Environmental impacts of shrimp aquaculture – a systematic review of life cycle assessments

Authors:

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Abstract

Life Cycle Assessment (LCA) is increasingly used to evaluate the environmental impacts of shrimp aquaculture, a rapidly expanding global food sector. However, existing shrimp LCA studies report widely divergent results, varying by more than fiftyfold across key impact categories. This systematic review identified 16 peer-reviewed shrimp LCAs and investigates the reasons for these discrepancies. We reveal inconsistencies across all LCA stages, such as system boundaries (e.g., inconsistent inclusion of change and pond emissions), co-product allocation methods, background data sources, and impact assessment methodologies. Strikingly, only five studies provide sufficient data for reproducibility. We demonstrate that methodological choices more strongly influence LCA outcomes than actual differences in shrimp farming operations. Moreover, many studies neglect critical environmental concerns such as biodiversity loss, land use change and antibiotic use. To enhance LCA reliability and comparability, we recommend specific methodological harmonisation, suggest reporting needs for transparency, and identify priority geographic and system coverage for future LCAs. Such improvements are essential for LCA results to accurately inform sustainable shrimp farming practices.

Key words

Prawn; seafood; LCA; footprint; life cycle analysis; environmental outcomes; reproducibility, sustainability; global warming

1. Introduction

The global food system is responsible for roughly one quarter of global greenhouse gas (GHG) emissions (Poore and Nemecek 2018) and is the leading driver of global biodiversity loss (Ritchie et al., 2022). As the world's population is growing and becoming more affluent, the demand for animal-based food products is increasing rapidly, with aquaculture playing an important role in meeting this demand (Salin & Ataguba, 2018). As animal-based foods generally require considerably more resources than plant-based alternatives, the environmental burden of the food sector is expected to increase further (Godfray et al. 2018).

Among animal-based foods, aquaculture – the production of aquatic organisms such as fish, crustaceans, and algae in controlled environments – is the fastest-growing sector in relative terms and now exceeds capture fisheries in production volume (Gentry et al., 2019). In terms of value, shrimp are the second most valuable aquatic export globally, following salmonids (Thornber et al., 2020). Ecuador is the largest shrimp exporter, followed by India, Viet Nam, and Indonesia in 2022. Meanwhile, China is the largest importer, followed by the US, Japan, and Spain (FAOFishstatJ, 2025). Shrimp are also estimated to be the most consumed animal globally in terms of number of individuals (Blaxter et al., 2024).

Shrimp farming comprises a variety of systems operating in diverse environments (Emerenciano et al., 2022). Intensive systems dominate global production, but extensive systems remain common, often occupying the fragile mangrove-fringed rim of intertidal coastal zones in intertidal areas with brackish water (Maiti et al., 2021). The global production of shrimp and prawns (group 45 of the International Standard Statistical Classification of Aquatic Animals and Plants, FAOFishStatJ 2025) in brackish water aquaculture systems amounted to an annual average of 6.7 million metric tons in 2020-2022. Whiteleg shrimp (*Litopenaeus vannamei*) is the dominant species, accounting for 82% of global production. This prevalence can be attributed to the species' rapid growth, disease resistance, and consumer popularity (Funge-Smith and Briggs, 2003). China leads whiteleg shrimp production with 21% of global production by volume, followed by India (17%), Ecuador (17%), Indonesia (13%), and Viet Nam (13%). The second most produced species is the Asian tiger shrimp (*Penaeus monodon*), which comprises 11% of brackish water shrimp farming during the same period. For this species, the top producers are Viet Nam (37% of global production by volume), Indonesia (18%), China (12%), Bangladesh (9%), and Myanmar (7%).

Alongside growing demand, the sector faces criticism and pressure to mitigate energy use, freshwater consumption, mangrove deforestation, and pollution (Serpa & Duarte, 2008). Some of these, such as eutrophication, saltwater intrusion, or loss of fish habitat, negatively impact neighbouring social and ecological systems, while others contribute to global environmental concerns (such as global warming) (Ahmed and Ambinakudige, 2024). Additionally, the high reliance on feed resources, such as wild fish and soy, threatens aquatic and terrestrial biodiversity in globally telecoupled locations (Majluf et al., 2024). There is therefore a need to understand a diversity of environmental impacts throughout shrimp supply chains.

Life Cycle Assessment (LCA) a framework used to quantify various environmental impacts of a product or service and scale them to a functional unit. It is increasingly being adopted by policymakers, most notably in the European Union (EU) (Sala et al., 2021), as a key tool in driving sustainability transitions. However, LCA results for various food products reveal substantial discrepancies in environmental impacts on the farm level; estimated impacts can vary 50-fold among producers of the same product (Poore and Nemecek, 2018). Many of these differences relate to methodological choices (Henriksson et al., 2012; Bohnes et al., 2019) that, in theory, could be harmonised. Such ambitions have, for example, been initiated by the International Organisation for Standardisation (ISO), with ISO14040 and ISO14044 providing guidelines for conducting LCAs. These standards seek to promote reliable and transparent LCA results — qualities essential for scientific reproducibility, informed decision-making, and credible sustainability reporting. Scientific reproducibility, as defined by Popper (1959), could be translated to LCA in terms of the documented methodology and data values providing sufficient information for an independent practitioner to reproduce the LCA results. However, studies across multiple sectors have highlighted that poor documentation on unit process data, poorly documented system boundaries, and insufficient reporting of key methodological choices often compromise LCA reproducibility (Talon 2016; Dieterle et al., 2022; Philis et al., 2019). In addition to generic ISO standards for LCA, the EU's Product Environmental Footprint Category Rules (PEFCR) are intended to provide sector-specific guidelines on how to conduct LCAs. While there is a PEFCR for Unprocessed Marine Fish Products, no PEF standards exist for crustaceans as of now (The Marine Fish PEFCR project, 2025; Pedersen and Remmen, 2022).

Through this review, we seek to understand the reasons behind the large discrepancies in environmental impacts reported in shrimp LCAs. We hypothesise that while differences in shrimp farming practices are highly variable, most divergence stems from methodological inconsistencies. Through a systematic review of existing literature, we identify relevant peer-reviewed articles and unpack the key causes of diverging results. We use the identified inconsistencies to recommend improvements to increase LCA reliability. This work builds upon earlier reviews by Henriksson et al. (2012) and Bohnes and Laurent (2019) on methodological approaches in aquaculture LCAs. While they provided insights into aquaculture LCAs, our study specifically focuses on shrimp farming, emphasising a systematic review of existing peer-reviewed literature of brackish water systems to pinpoint the drivers of reported impact discrepancies and offer targeted recommendations for methodological harmonisation and enhanced transparency within this rapidly growing sector. Additionally, this review complements recent work by Pazmiño et al. (2024), which reviews shrimp LCAs to identify potential improvement measures in the sector. In contrast, our study focuses exclusively on brackish water shrimp aquaculture, avoiding the confounding of freshwater and brackish systems, and provides a more in-depth examination of underlying data and methodological choices. Moreover, we conduct a detailed analysis of all available data from the reviewed studies, including supplementary materials, to comprehensively unpack the key methodological inconsistencies across all LCA stages, quantify their influence on results, and offer specific, actionable recommendations for future shrimp LCAs.

2. Methods

2.1 Review Protocol and Scope

We conducted this systematic review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (figure 1). The primary aim was to identify and critically assess all relevant peer-reviewed LCA studies concerning the aquaculture of whiteleg shrimp (*Litopenaeus vannamei*) and giant tiger prawn (*Penaeus monodon*). These two species were prioritised as they are the most widely farmed shrimp species globally, and predominantly cultivated in brackish water systems within tropical coastal regions. This focus was chosen because the context and environmental consequences of these systems differ from freshwater aquaculture operations, such as those for the giant river prawn (*Macrobrachium rosenbergii*).

2.2 Literature Search and Study Selection

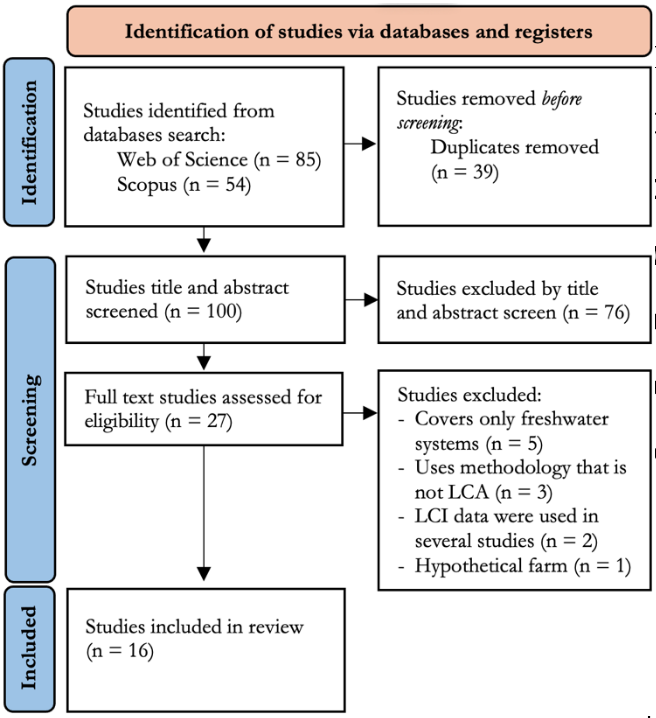

Figure 1 PRISMA flowchart, showing the criteria for inclusion in the review, and the narrowing down from 139 initial studies to 16 included in the review.

We employed an iterative process to develop a comprehensive literature search strategy designed to ensure inclusivity while maintaining specificity. The final search string applied to the Scopus and Web of Science databases was: (shrimp OR prawn) AND (aquaculture OR farming OR production) AND (LCA OR "life cycle assessment" OR "life cycle analysis"). This search was conducted without filters or date restrictions to maximise coverage and was finalised on January 19, 2024. Additionally, the reference lists of all identified relevant articles were manually screened for further pertinent studies; this process yielded no new records.

Studies were included if they were peer-reviewed, applied LCA methodology to assess environmental impacts, and focused on either whiteleg shrimp or giant tiger prawn aquaculture in brackish water systems. Studies were excluded if they: (i) covered only freshwater systems; (ii) used a methodology that was not LCA; (iii) used primary data that was also used in several other studies (to avoid duplication of datasets); or (iv) assessed a purely hypothetical farm. The initial database search yielded 85 records from Web of Science and 54 from Scopus, which, after removal of 39 duplicates, resulted in 100 unique records for screening (figure 1). Title and abstract screening led to the exclusion of 76 records. The remaining 27 full-text articles were assessed for eligibility, from which 16 studies were eligible for this review.

2.3 Data Extraction and Synthesis

From the 16 selected studies, a total of 41 production "cycles" were initially identified. A "cycle" is defined as an LCA conducted for a unique dataset of inputs, emissions, products, and practices specific to a particular farming system, intensity, species, or geographical context within a study. For example, study 15 examines three distinct farming cycles in China using recirculating aquaculture systems (RAS), biofloc technology (BFT), and high-performance ponds (HPP).

For studies where primary data collection was supplemented with data from existing studies (e.g., studies 1 and 10), only those cycles based on the primary data collected by the respective authors were included in our dataset to avoid pseudo replicates. One cycle from study 8 was excluded because it combined giant tiger prawn and giant river prawn, making it difficult to isolate the impacts relevant to this review's scope. After these refinements, a final dataset of 37 distinct production cycles was analysed.

For each included cycle, detailed information was extracted (where reported) pertaining to general context and the four LCA phases outlined in ISO 14040/14044 (goal and scope definition, life cycle inventory (LCI), life cycle inventory analysis (LCIA), and interpretation). All quantitative data were extracted and, where necessary, harmonised to a common functional unit of one tonne of liveweight shrimp at farmgate to facilitate comparison and subsequent correlation analysis. Detailed data for each of the 37 cycles are provided in the Supplementary Material (SM).

2.4 Analysis of Methodological Choices, Reproducibility, and Input-Impact Relationships

To investigate the influence of methodological choices, data on on-farm energy use and Feed Conversion Ratios (FCRs, defined as the weight of feed given divided by the weight gained; Fry et al., 2018), were compared against global warming and eutrophication impact results for each cycle. Different energy inputs such as electricity and diesel were standardised to megajoules, while acknowledging that this approach does not account for conversion efficiency differences between energy carriers (Frischknecht et al., 2015). For studies applying multiple allocation methods, we used economic allocation as this is the most common allocation method (SM). Due to inconsistent reporting, other relevant factors (e.g., water consumption, land occupation, chemical inputs, stocking density, and field emissions) could not be evaluated. The relationships between inputs and environmental impacts of each cycle were analysed through a correlation analysis.

To quantify the influence of methodological choices versus different farming practices, coefficients of variation (CV) for global warming (GW) and eutrophication impacts were calculated for nine distinct shrimp farming cycles from one study that employed a consistent methodology (Henriksson et al., 2015a). These CVs were later contrasted against the percentage change in impacts observed in three identified instances where identical farm-level inventory data were re-analysed using different LCA approaches (Al Eissa et al., 2022; Jonell and Henriksson, 2015)).

2.5 Limitations of the Review Methodology

This systematic review has certain limitations primarily related to the literature search process. Firstly, the search was confined to two major academic databases: Scopus and Web of Science. While these databases provide extensive coverage of peer-reviewed literature, relevant studies indexed exclusively in other specialised or regional databases might not have been captured. Similarly, the review was restricted to English-language publications. This means that pertinent research published in other languages would have been excluded, potentially limiting the geographical or contextual scope of the findings if significant non-English literature exists on this topic. However, an informal search of the same terms in Spanish, Portuguese, Mandarin, and Hindi did not reveal any relevant studies that fulfil the search requirements.

Due to the cut-off date in January 2024, the most recent studies covering novel systems, such as Arbor et al. (2024) looking at microalgae-based wastewater treatments and Sun et al. (2025) identifying tunnel greenhouse aquaculture systems, are not included in this review.

3. Results

3.1 Study characteristics

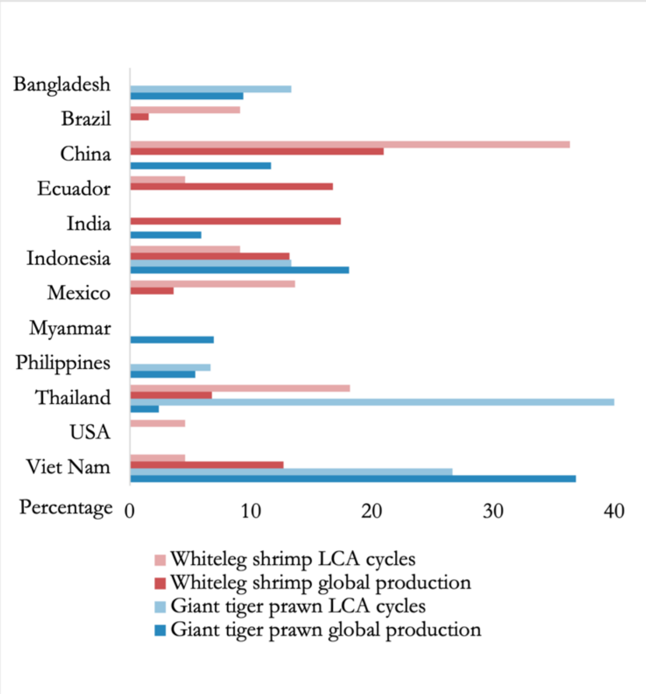

Figure 2 Percentage comparison of number of LCA cycles and global shrimp aquaculture in brackish water. Production data from FAO FishStatJ (2025), where the average of the three most recent available years (2020-2022) was used. Annuall whiteles shrimp production had an average of 5.49 million tonnes and giant tiger prawn 723 thousand tonnes.

The 16 studies under review were published between 2006 and 2023. For the twelve studies that detailed primary data collection dates, the median time between data collection and publication was four years. The average year of data collection across these eleven studies was 2013. This temporal gap draws into question the relevance of some findings to current shrimp farming practices, which have evolved significantly due to growing demand, disease outbreaks, improved farm management strategies, and technological innovations. The COVID-19 pandemic, for example, prompted a shift towards more efficient systems due to input and labour shortages (Nguyen et al., 2024).

The 37 analysed production cycles exhibit considerable heterogeneity. Eight cycles are based on data representing a single farm, while other cycles represent horizontally averaged data from up to 106 farms (SM). Of the 37 cycles, 30 assess monoculture systems and seven polyculture systems. Twenty-two cycles evaluate whiteleg shrimp (*Litopenaeus vannamei*) and 15 evaluate giant tiger prawn (*Penaeus monodon*).

A key distinction among the reviewed literature is its comparative nature. Of the 16 studies, ten are internally comparative, meaning they assess multiple distinct production cycles using a consistent internal methodology. This structure is critical as it allows for the isolation of impacts due to farming practices from those due to methodological choices. The remaining six studies each assess a single production system.

Eight studies define farming intensity (e.g., extensive, intensive) but fail to clarify the specific criteria for these classifications, highlighting the lack of harmonised definitions (Oddson 2020). The geographical focus of the reviewed literature is also misaligned with current global production locations, especially Ecuador (16.7% of global whiteleg shrimp production; one LCA, study 14) and India (17.4% of global whiteleg shrimp production, no shrimp LCA study, but one LCA study on shrimp feed; Ramesh et al., 2024; figure 2). Thailand, on the other hand, is nowadays only responsible for 2.4% of giant tiger prawn and 6.8% of whiteleg shrimp production and had the highest representation amongst all countries in exiting LCA studies (ibid.). Among the reviewed studies, 11 claimed adherence to the ISO 14040 and 14044 standards, with study 5 self-defining as an LCA but referencing ISO 14067 for carbon footprinting. The following sections systematically evaluate how each study adheres to the stages outlined in ISO 14040/14044, and which methodological choices were made.

Study no.	Authors	Year	Title of Study
1	Al Eissa et al.	2022	Effects of feed formula and farming system on the environmental performance of shrimp production chain from a life cycle perspective
2	Aubin et al.	2014	Environmental performance of brackish water polyculture system from a life cycle perspective: A Filipino case study
3	Belettini et al.	2018	Carbon footprint in commercial cultivation of marine shrimp: A case study in southern Brazil
4	Cao et al.	2011	Life cycle assessment of Chinese shrimp farming systems targeted for export and domestic sales
5	Chang et al.	2017	Carbon footprint analysis in the aquaculture industry: Assessment of an ecological shrimp farm
6	Cortés et al.	2021	Eco-efficiency assessment of shrimp aquaculture production in Mexico
7	Flores-Pérez et al.	2023	Eco-efficiency assessment of disease-infected shrimp farming in Mexico using environmental impact assessment tools
8	Henriksson et al.	2015	Comparison of Asian Aquaculture Products by Use of Statistically Supported Life Cycle Assessment
9	Henriksson et al.	2017	Indonesian aquaculture futures – Evaluating environmental and socioeconomic potentials and limitations
10	Jonell et al.	2015	Mangrove-shrimp farms in Vietnam-Comparing organic and conventional systems using life cycle assessment
11	Koniyo et al.	2022	Role of Innovations / Interventions to Bring Sustainability in Aquaculture Growth in Indonesia: Integration of Life Cycle Assessment (LCA) Framework
12	Lebel et al.	2010	Innovation cycles, niches and sustainability in the shrimp aquaculture industry in Thailand
13	Mungkung et al.	2006	Potentials and Limitations of Life Cycle Assessment in Setting Ecolabelling Criteria: A Case Study of Thai Shrimp Aquaculture Product
14	Sanchez et al.	2023	Life Cycle Analysis of Farmed Shrimp of the Species Litopenaeus Vannamei in the Province of Guayas

15	Sun et al.	2023	Comparative life cycle assessment of whiteleg shrimp (Penaeus vannamei) cultured in recirculating aquaculture systems (RAS), biofloc technology (BFT) and higher-place ponds (HPP) farming systems in China
16	Tantipanatip et al.	2014	Life cycle assessment of pacific white shrimp (penaeus vannamei) farming system in trang province, Thailand

Table 1: Overview of reviewed shrimp LCA studies. More information can be found in the supplementary material (SM).

3.3 Goal and scope definition

3.3.1 Study goal

According to the ISO 14044 standard, an LCA must begin with a clear statement of its objectives and the rationale for the assessment. All reviewed studies adhere to this requirement, defining a wide array of goals. In general, these objectives focused on conducting comparative assessments between different farming systems, species, or geographies; identifying environmental hotspots within specific systems; or evaluating the impacts of targeted scenarios such as the use of innovations, different feeds, polyculture practices, or the effects of disease outbreaks (SM).

3.3.2 Functional units

The functional unit (FU) is the unit of reference to which all environmental impacts are scaled. All studies under review use a mass-based functional unit (FU) at farmgate, a rare point of consensus. The FU was defined as either 1 kilogram (four studies) or 1 tonne (12 studies) of shrimp at the farmgate. Five studies also included supplementary FUs for processed products to meet specific study goals covering the broader value chain (SM). For this review, we harmonised all impact results to one tonne of liveweight shrimp at the farmgate to facilitate comparison.

3.3.3 System boundaries

The system boundary defines which unit processes and emissions are to be included in the LCA study. All studies under review include the grow-out stage, in which post-larvae shrimp are raised to market size. However, only four studies explicitly include infrastructure and 13 include transport (SM).

The treatment of land use and land use change (LULUC) was a major inconsistency and a key driver of discrepancies. Only studies 10 and 11 quantified farm-level LULUC emissions from mangrove conversion, but their differing methodologies and resulting impacts highlight the problem. In study 10, the direct calculation of LULUC was responsible for 94% of the system's GW impacts, making it one of the highest outlier in the dataset (SM). In contrast, study 11 incorporated LULUC by applying a pre-calculated emission factor from existing literature, which resulted in GW impacts that were comparable to other studies that did not include farm-level LULUC. This demonstrates how the specific methodological choice for quantifying LULUC can have a more significant effect on the result than the decision to include it in the first place.

The treatment of LULUC associated with feed ingredients was more opaque as several LCI background databases (e.g., ecoinvent) used in the studies account for LULUC for some crops, while only studies 1 and 8 detailed the assumed origins of feed ingredients. This is particularly relevant for ingredients sourced from regions like Brazil and Argentina, where soy farming is associated with high levels of LULUC. This inconsistent inclusion of LULUC represents a major driver behind discrepancies in reported impacts.

3.3.4 Coproduct allocation

Coproduct allocation refers to how environmental burdens are divided among multiple products originating from the same unit process, or among multiple uses of one product. Only half of the studies explicitly specify their coproduct allocation method, thus failing to comply with ISO 14044. Among those that did, economic allocation was the most common adopted (six studies), followed by mass (three studies) and energy (one study) (SM). Three studies applied multiple allocation methods, providing direct insight into the influence of this choice (SM). The results showed that for the exact same farm-level inventory data, the choice of allocation method could alter GW impacts by up to 58% (study 9) and eutrophication impacts by up to 59% (study 8). Critically, there was no predictable pattern where one allocation method consistently produced higher or lower results, demonstrating the unpredictable influence of this methodological choice.

3.3.5 Assumptions

LCA studies are data intensive and therefore often rely upon assumptions to fill data gaps and/or solve unknown fates and origins. These assumptions are another major driver of discrepancies, yet only eleven studies provide detailed documentation (SM). The profound influence of these choices is also demonstrated through sensitivity analyses. For instance, study 1 assumed all its soybean meal originated from the U.S., while a sensitivity analysis reveals that sourcing from Argentina or Brazil would increase the associated GW impacts by 1,240% or 960%, respectively. These discrepancies are primarily due to LULUC. Similarly, study 4 reports that assumptions about electricity mix is highly influential, with a switch from coal to hydropower or nuclear energy having the potential to reduce GW impacts of farmed shrimp by 25-50%. These examples show that assumptions can have fundamental influence on LCA conclusions.

3.3.6 Impact assessment methodologies and categories

To classify and characterise environmental emissions and resource uses towards specific environmental impact categories, different impact assessment methodologies are used. CML methodology was applied in nine studies, while ReCiPe was applied in three. One study applied foundational models and methods, and another study ISO/TS 14067 and PAS 2050 (SM). Different impact assessment methodologies use different cause-effect pathways and units to quantify how emissions and resource use contribute to specific impact categories. Studies 4 and 13 compare impact results for different methodical choices. Study 4, which applies the CML-IA Baseline (Guinée 2002) finds comparable outcomes for GW impacts and terrestrial acidification, but lower eutrophication estimates under IMPACT 2002+. Discrepancies also arise from different versions of the Intergovernmental Panel on Climate Change' (IPCC) (Kikstra et al., 2022) Assessment Reports (AR). For example, the global warming potential over 100 years (GWP100) for methane increased from 25 in AR4 to 27 in AR6. Meanwhile, the characterisation factors for different freshwater ecotoxicity impacts can differ with orders of magnitudes depending upon the underlying data (Nyberg et al. 2024). Among the reviewed studies, study 8 calculated specific freshwater ecotoxicity factors using the USEtox model (Rosenbaum et al., 2008).

The number of impact categories assessed ranged from none to eleven, with an average of four. Most assessments included global warming (13 studies), eutrophication (eleven studies), and terrestrial acidification (nine studies). As shown in figure 6, ten different impact categories only appeared once, suggesting a fragmented picture of the full environmental performance of shrimp across the LCA studies. Noteworthy is that no study evaluated endpoint impacts (e.g., damage to human health or ecosystems) (SM).

3.3.7 Modelling approach

A critical omission was the failure to declare the specific LCA modelling approach; attributional or consequential. Attributional LCA is a methodology that quantifies the environmental impacts associated with the lifecycle of a product or service, attributing all emissions and resource extractions directly to the product or service being studied, and is typically used for reporting past impacts or comparing environmental performances and identifying critical impact areas. In contrast, consequential LCA assesses the environmental impacts of a decision by modelling the changes in the entire product system, including market interactions and marginal effects. In this review, only two studies (2 and 10) explicitly state they use an attributional methodology, while study 15 self-identifies as using a consequential LCA approach. For the remaining twelve studies, the specific LCA framework is not explicitly stated, a fundamental issue as attributional and consequential approaches are generally not comparable.

3.4 Life cycle inventory

3.4.1 Primary data

All studies use primary data for the grow-out stage (these have been extracted and harmonised to the same FU in the SM), which was a requirement for inclusion in our review, but demonstrate significant inconsistencies in their primary data sampling methods and documentation, ranging from detailed case studies of single farms to broader, multi-farm surveys of up to 106 farms per cycle. Ten cycles relied on individual farms for data collection. Other studies employed what they described as "representative" without further details. More robust approaches involved random sampling designs of farm clusters for large datasets, as seen in a study collecting data from up to 100 farms per cycle across four Asian countries (study 8), or using random sample size determination to select 106 farms in Thailand (study 16). Some studies adopted targeted sampling strategies, such as selecting 76 commercial farms specifically affected by the white spot syndrome virus in Mexico (study 7). Data collection primarily involved on-site interviews and questionnaires filled out by farm owners, sometimes drawing from existing governmental databases or previous studies and interviews spanning several years.

These diverse sampling methodologies, particularly the use of single-farm data or inadequately defined "representative" samples, can significantly introduce bias and limit the generalisability of reported environmental impacts across the broader shrimp aquaculture sector. Certain sampling methods potentially prioritise better-managed farms with good records, which potentially result in underestimated sector-wide impacts. These differences in sampling strategy mean that observed variations in environmental impacts may be artefacts of the sampling method rather than true differences in farming performance. Fifteen studies provided geographical specificity at least to the provincial level, with some detailing exact farm locations. Three studies failed to specify data collection years, creating temporal ambiguity.

3.4.2 Secondary data

The reviewed studies relied on a diverse array of secondary sources, including published literature, government reports, online resources, and structured LCI databases. Details on the databases and versions of these used are available in the SM. Eight studies utilised the ecoinvent database in some capacity, including v2.2, v3.0, v3.01, and v3.7.1, while one study did not specify the version employed. Four studies relied solely on ecoinvent, while the four others used it in combination with other LCI databases, such as Agri-footprint database, LCA Food database, and national government databases. For instance, studies supplemented global databases with local data for aspects like electricity mixes, local emission factors, and specific farming conditions. Examples include study 3, which sourced electricity mix data from Empresa de Pesquisa Energética (EPE), a Brazilian national energy research company and study 4 adapted secondary data to Chinese regional conditions, referencing a publication by the Chemical Industry Press. This demonstrates the necessity of integrating more specific local data to enhance the accuracy and regional representativeness of life cycle assessments.

Three studies simply referred to the LCI databases within different versions of SimaPro (SM). Studies 12 and 16 did not specify background LCI databases used (SM).

Inconsistent data sourcing introduces discrepancies in LCA outcomes. The predominant European or North American origin of many LCI databases (Henriksson et al., 2014) poses specific challenges for shrimp production that is mainly conducted in Asia and Latin America, where regional conditions can differ substantially from database defaults (Ossés de Eicker et al., 2010).

3.4.3 Unit process data - Grow out cycles and feed mills

Unit process data for the grow-out cycles represent the quantified inputs and outputs associated with one cycle. While most studies detailed inputs and outputs in total units, studies 3 and 5 only reported inputs and outputs in terms of associated CO_2-equivalent, making it impossible to reproduce the results of these studies. Of the remaining 14 studies, all reported energy and feed use, but other critical inputs were inconsistently documented (figure 4; SM). Freshwater inputs were reported in nine studies and land occupation in six. Chemical treatments for water and pond soil such as chlorine, calcium carbonate, and limestone were documented in ten studies, while fertilisers and productivity enhancement inputs, such as urea and manure, appeared in seven studies. Notably, only one study reported types and amounts of antibiotic use, while two studies explicitly stated that no antibiotics were used (SM).

The intensification of shrimp farming has shifted land occupation and its associated impacts from the farm-level to the feed production level (Davis et al., 2021; Henriksson et al., 2018; Froehlich et al., 2018). Study 10, for example, where data were collected in an extensive system in 2010, reported up to 4.4 hectares of land use without any external feed inputs, while study 1, which was published in 2022, documented only 84 m^2 of land use and 1.5 tonnes of feed for the same functional unit of one tonne of shrimp at the farmgate. Of the 16 examined studies, 14 reported the use of feed pellets, with 13 of these quantifying the total amounts used. Three studies reported supplementary feed inputs alongside pelleted feeds, including lower-value fish and rice bran. In study 2, only molluscs were employed as a feed input, while no feed inputs were applied in study 10. Four studies lacked documentation of feed ingredients, and two studies relied on feed formulas from previously published research from different contexts. The remaining eight studies provided primary data on feed ingredients and their quantities. Within this subset of eight studies, five documented water consumption associated with pellet production and six reported energy use data (SM). Only study 8 detailed the geographical origins of feed ingredients, while study 1 made assumptions about ingredient origins. Feed compositions vary, with fishmeal comprising 20-42% of pellet ingredients and soybean meal 11-30%. Feed Conversion Ratios (FCRs) of monoculture cycles with pellet inputs ranged from 1.0 to 3.6. Higher FCRs are caused by the addition of less nutritious feeds, such as rice bran.

While all studies report product outputs at the farm gate and co-products from polyculture systems, the documentation of emissions and waste varied considerably (figure 4; SM). Total emissions of nitrogen and phosphorus were reported by eleven studies. Other emissions (figure 3) were reported by less than half of the studies, despite the impact they can have on the LCIA results, as seen in the case of the inclusion of LULUC emissions in study 10. Emissions from feed processing plants were addressed in three studies (figure 4; SM).

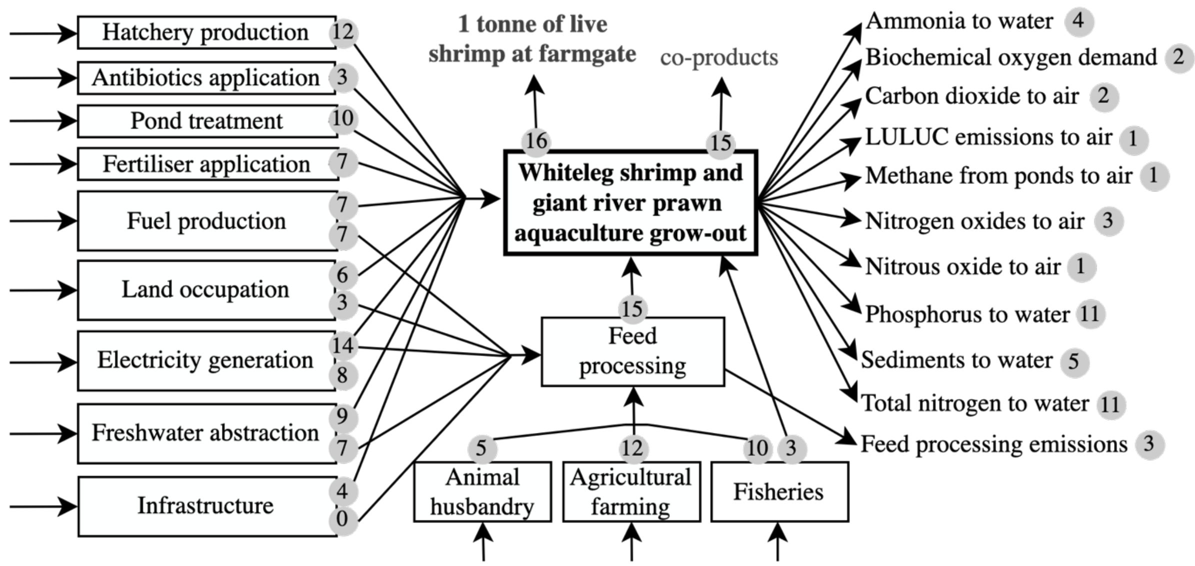

Figure 3: Inputs and outputs to and from feed processing and shrimp grow-out. Unit processes are represented by boxes and flows by arrows. Circled numbers indicate how many of the 16 studies that detail primary data, including zeroes (e. g. no feed applied and therefore zero energy use for feed production).

3.5 Life cycle impact assessment

The multiplication of varying set of lifecycle inventory results with an accumulation of methodological inconsistencies detailed in the preceding sections explains the divergence LCIA results. By scaling impact assessment results to a functional unit of one tonne of liveweight shrimp at the farmgate, the results from the different studies can be compared (figure 4, SM):

- GW impacts (reported in 33 cycles) ranged from 901 kg to 47,997 kg of carbon dioxide equivalent (CO_2-eq) per tonne of shrimp, with a standard deviation of 7,968 kg CO_2-eq t^{-1} shrimp.
- Eutrophication results (reported in 28 cycles) ranged from -32 to 160 kilograms of phosphate equivalent (PO_4-eq.) per tonne of shrimp, with a standard deviation of 52 kg PO_4-eq. t^{-1} shrimp.
- Terrestrial acidification (reported in twenty cycles) ranged from 4 to 89 kilograms of sulphur dioxide equivalent (SO_2-eq.) per tonne of shrimp, with a standard deviation of 27 kg SO_2-eq. t^{-1} shrimp.

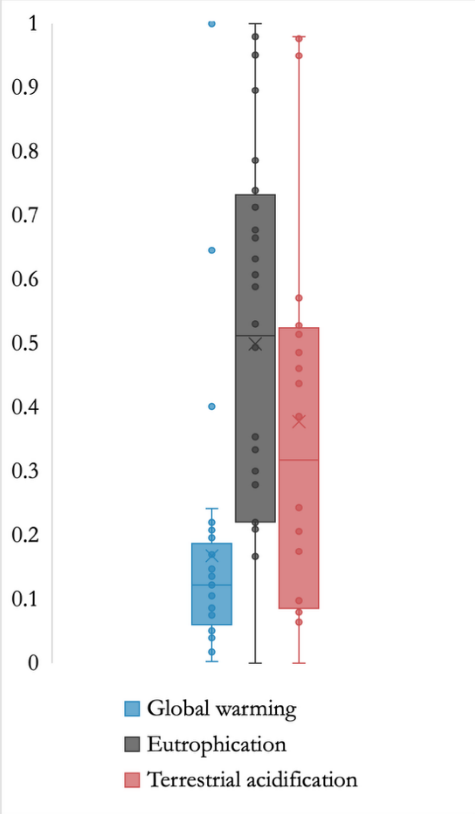

Figure 4 Normalised LCA results from all reviewed cycles, with the lowest reported value among impact results being 0 and highest being 1. Boxes represent the interquartile range with median (line) and mean ('X'). Whiskers extend to 1.5x IQR, showing individual data points and outliers.

Eutrophication showed the greatest spread, terrestrial acidification displayed moderate spread, while GW demonstrated the lowest spread, but with two outliers (SM, figure 4). The relatively low spread in GW may be attributed to more harmonised emissions models and characterisation factors (section 3.5.2).

3.6 Interpretation

3.6.1 Completeness and consistency analysis

The interpretation phase of an LCA requires checks to ensure all relevant information is included (completeness) and that the methodology aligns with the study's goals (consistency). These checks, mandated by ISO 14044, are essential for validating results. However, they were almost entirely absent from the reviewed literature. Only studies 4 and 8 conducted a consistency check, and none of the 16 studies performed an explicit completeness check as defined by ISO 14044 (Henriksen et al., 2019; Dong and Liu, 2022).

3.6.2 Uncertainty and sensitivity analyses

Incorporating uncertainty ranges enhances the robustness of LCA outcomes by accounting for error and discrepancies in unit process data, emission models, and characterisation factors (Ziyadi and Al-Qadi, 2019; Heijungs 2024). Six studies used Monte Carlo simulations to propagate uncertainties among parameters (SM), showing that shrimp LCAs can result in very high variation in impacts: Study 8 shows that the GW results of black tiger shrimp production in Eastern Bangladesh could range from a minimum of 1,260 to a maximum of 108,000 kg CO_2-eq. t^{-1} frozen peeled tail-on monodon shrimp at European ports due to uncertainties in unit process data and characterisation factors.

Seven studies include sensitivity analyses (SM) to identify key contributing variables and improve the reliability of results (Guo and Murphy, 2012). These analyses explicitly tested aspects including feed compositions (such as fishmeal content and the origin of ingredients, study 1, allocation methods (studies 1; 8-10), FCR and impact assessment methodologies (study 4), and pond size and production-site distance from the sea (study 2). For study 10, the sensitivity analysis revealed that carbon loss assumptions during mangrove transformation strongly influenced results, with a 64% reduction in GW impacts when using conservative estimates (25% carbon loss) and an 87% increase when assuming complete carbon loss. Study 4 investigated how shifting the Chinese electricity mix from coal-dominated to less CO_2-intensive alternatives (such as natural gas, nuclear, or hydropower) would affect global warming, showing potential reductions of 25-50%. These examples show how methodological decisions and background data can overshadow actual farming practice differences in determining environmental performance outcomes.

3.6.3 Conclusions, limitations, and recommendations

Regarding study findings, studies that included a broader range of metrics found that aspects like LULUC and chemical applications substantially influenced environmental profiles. The most common recommendations covered changes in feed production and application (nine studies), such as lowering the FCR and reducing fishmeal. Eight studies recommended the optimisation of energy consumption or use of renewable energy and energy conserving technologies. Changes in wastewater and nutrient management Changes in wastewater discharge and recycling of excessive nutrients were recommended by six studies.

Only studies 8-11, 13 and 15 explicitly acknowledged limitations in their methodologies, such as the lack of inadequate region-specific data (study 15). Four studies also recommended methodological improvements for LCA practitioner including: combining quantitative LCA with qualitative "hurdle criteria" to address impacts not captured by traditional metrics (study 13); adopting statistically supported approaches to quantify data uncertainty (study 8); integrating spatiotemporal considerations (study 10); and expanding data on LULUC emissions (study 9).

3.7 Correlation analysis of key inputs and environmental impacts

Shrimp LCAs consistently name feed production and on-farm energy consumption as primary sources of environmental impact (Pazmiño et al., 2024). While intensification can improve resource-use efficiency (Tamariska et al., 2024; Davis et al., 2021; Henriksson et al., 2018), our analysis reveals that pervasive methodological inconsistencies obscure these expected relationships. We found no correlation across studies between GW impacts and on-farm energy use ($r=0.04$, $R2=0.0016$, $n=30$) and only a weak negative correlation with FCR ($r=-0.21$, $R2=0.043$, $n=33$). Excluding study 10, which included LULUC and therefore had some of the highest GW results, strengthened the correlation between GW and energy use tenfold (from $r=0.04$ to $r=0.40$, $n=28$), suggesting methodological noise is indeed to blame for the lack of expected relationships. For eutrophication, correlations were also weak for both on-farm energy use ($r=0.35$, $R2=0.121$, $n=28$) and FCR ($r=0.24$, $R2=0.058$, $n=27$).

Figure 5 visualises these counterintuitive patterns. Again, the two extensive farming cycles (23 and 24 from study 10) report the highest GW impacts because of LULUC while having the lowest eutrophication impacts. The stark contrast in eutrophication impacts between cycles from studies 8 and 9 and the rest of the dataset highlights how different modelling approaches (sections 3.5.1 and 3.5.2) can dramatically affect results.

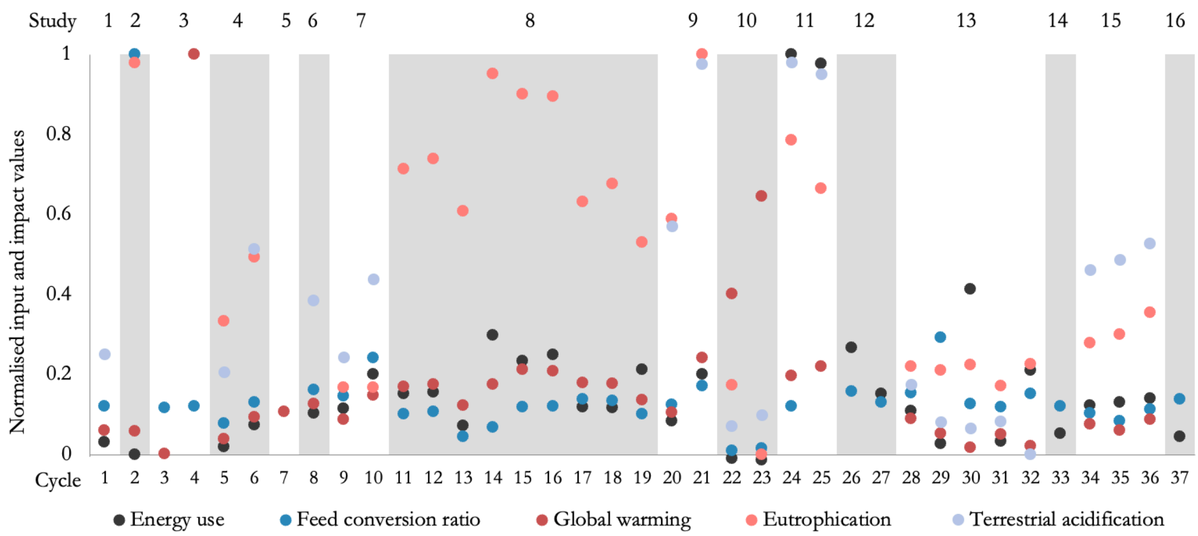

Figure 5 Normalised data on energy use, FCR, global warming and eutrophication impacts obtained from 37 shrimp LCA cycles detailed in 16 studies. Same background colour of adjacent cycles indicates that these cycles originate from the same study. Overlapping points have been jittered for better visibility.

3.8 Reproducibility

This review assessed reproducibility based on the transparency of calculation methodologies, acknowledging that true reproducibility would also require documentation of primary data collection processes, such as providing surveys — a level of transparency lacking in all reviewed studies. While all studies clearly documented FUs and system boundaries, and 13 documented primary data origins, significant reporting gaps existed across other fundamental aspects. Only half of the studies reported their allocation methods, nine detailed their underlying assumptions, and only seven provided emission models sufficient for replication. Furthermore, two studies described themselves as LCAs without conducting any impact assessment, and two only reported aggregated CO_2-eq., making independent verification impossible.

The quantitative assessment (table 2) reveals a stark picture: only five of the 16 studies fulfilled all eleven criteria for complete reproducibility, while two studies only lacked one aspect. Lack of transparency hampers the reproducibility of study 3, which reports the highest GW discrepancies, casting doubt on its findings, particularly given the apparent absence of LULUC accounting. Conversely, the value of transparency is highlighted by study 13. Its exemplary documentation allowed for the identification of a detectable allocation error, where trawling impacts were overestimated by attributing 94.63% to broodstock instead of the correct ~57%. This error was only identifiable because of the study's transparency, proving that proper documentation enables critical evaluation and scientific self-correction. These findings align with broader challenges in LCA, where methodological inconsistencies, documentation gaps, and restricted access to proprietary data are recognised barriers to reproducibility (Dolan & Heath, 2012; Dieterle et al., 2022; Vafi and Brandt, 2014).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Functional units	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue
System boundaries	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue
Allocation	Blue	Blue	Red	Blue	Red	Red	Red	Blue	Blue	Blue	Blue	Red	Blue	Red	Red	Red
Primary data collection	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Red	Blue	Red	Red	Blue
Unit process data	Blue	Blue	Red	Blue	Red	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue
Background data documentation	Blue	Blue	Red	Blue	Blue	Red	Blue	Blue	Blue	Blue	Blue	Red	Blue	Blue	Blue	Red
Clearly stated assumptions	Blue	Blue	Blue	Blue	Blue	Blue	Red	Blue	Blue	Blue	Red	Red	Blue	Red	Blue	Red
Farm level emissions	Blue	Red	Blue	Blue	Red	Blue	Blue	Blue	Blue	Blue	Red	Red	Blue	Blue	Blue	Red
Emission models	Red	Blue	Red	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Red	Red	Blue	Red	Red	Red
Impact categories	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Red	Blue	Red	Blue	Red
Characterisation	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Red	Red	Blue	Red	Blue	Red
Reproducibility score (criteria met / total criteria)	$\frac{10}{11}$	$\frac{10}{11}$	$\frac{6}{11}$	$\frac{11}{11}$	$\frac{8}{11}$	$\frac{8}{11}$	$\frac{9}{11}$	$\frac{11}{11}$	$\frac{11}{11}$	$\frac{11}{11}$	$\frac{7}{11}$	$\frac{3}{11}$	$\frac{11}{11}$	$\frac{5}{11}$	$\frac{8}{11}$	$\frac{4}{11}$

Table 2: Completeness, transparency and reproducibility evaluation of eleven key aspects among the reviewed shrimp LCAs. Blue means data are reported. Red means data are not transparently reported.

4. Discussion

It is crucial to emphasise that LCA is a relative, not an absolute, measure of environmental impact (Henriksson et al., 2015b), meaning that LCA provides comparative insights rather than definitive totals, and its primary strength lies in comparing different systems or identifying relative environmental hotspots within a consistent methodological framework. This review substantiates earlier findings from broader aquaculture LCA reviews (Bohnes and Laurent, 2019; Henriksson et al., 2012), revealing that the current body of shrimp LCA literature is defined by deep methodological inconsistencies that limit its utility and comparability. This is not to undermine the individual strengths of certain studies under review, which may have had specific aims unrelated to comparability; rather, it is an observation about the field as a whole, and therefore the ability to draw generalised conclusions about the environmental impacts of this type of shrimp aquaculture system.

4.1 The dominance of methodological choice in shaping LCA outcomes

The primary strength of LCA lies in comparing products or systems, a practice only valid when conducted within a consistent methodological framework as stipulated by ISO 14040. Across the ten studies that assessed and compare multiple farming cycles using a consistent internal methodology, the average CV across the farming cycles compared for GW results was 23.6%. In the most comprehensive single study, which analysed nine distinct production cycles (study 8), this variation attributable to farming practices was even lower, with a CV of 15.2%.

In contrast, when identical farm-level inventory data were re-analysed using different LCA approaches, the resulting impacts changed dramatically. Study 10 recalculated two cycles of study 8 in addition to its own cycles, and study 1 recalculated one cycle of study 10 in addition to its own cycle. In these three instances, GW results changed by an average of CV=41.6%. When study 1 recalculated data for an extensive system from study 10, the GW impact decreased by 47% (from 19,800 to 10,503 kg CO_2-eq.), the acidification impact was reduced to zero, and the eutrophication impact inverted from a positive 1.44 to a negative -11.66 kg PO_4-eq. For the exact same farm inventory, the reported environmental profile is therefore largely a function of the analyst's choices. This has profound implications for consumer-facing initiatives such as product labelling and certification. An eco-label awarded based on these LCA results may be rewarding favourable methodological choices rather than genuinely superior on-farm environmental performance, misleading consumers and undermining the credibility of such schemes.

The correlation analysis revealed surprisingly weak relationships between key inputs like on-farm energy use and GW impacts (r=0.04) or between Feed Conversion Ratios (FCR) and GW impacts (r=−0.21). This does not imply that feed and energy are unimportant; rather, it proves that pervasive methodological variations introduce substantial statistical noise, obscuring these fundamental input-impact relationships when data are aggregated across studies. Consequently, any meta-analysis that simply averages results from methodologically diverse LCAs risks drawing conclusions from figures that are not fundamentally comparable. This is exemplified by how directly averaging the data of study 10, which uniquely and showed

LULUC emissions with studies lacking such comprehensive LULUC accounting, would disproportionately skew overall findings, as could be observed in analyses performed by studies like Clune et al. (2017).

Specific methodological decisions have different influence on this divergence. The choice of co-product allocation method alone can alter reported GW and eutrophication results by up to 59%. Decisions regarding system boundaries, particularly the inclusion or exclusion of LULUC, can be even more influential, increasing GW results by as much as 94% in one case (study 10). This problem is compounded by a critical lack of transparency and reproducibility. Only five of the 16 studies fulfilled all eleven criteria deemed necessary for complete reproducibility, with one study failing to meet eight of the criteria. This opacity prevents scientific scrutiny and self-correction. This lack of reproducibility undermines the cumulative nature of scientific knowledge (Popper, 1959) and erodes trust in LCA as a robust tool for sustainability assessment.

Despite these significant challenges, it is important to recognise the value of the existing body of research. The reviewed LCAs have consistently identified feed composition and on-farm energy consumption as the primary environmental hotspots across a wide range of production systems. This provides a crucial and foundational understanding for guiding improvement efforts. Furthermore, several of the reviewed studies exemplify methodological rigour with high transparency and reproducible results, offering a foundational blueprint for developing more comprehensive and standardised environmental evaluation frameworks in the future.

However, the collective utility of these studies for comparison or policy is hindered by a more fundamental issue this review has quantified: the influence of methodological choice on reported impacts is greater than the influence of actual on-farm practices. This analytical dominance is so profound that it can invert the environmental profile of an identical farm—transforming it from a net source of eutrophication to a net mitigator based solely on the modelling choice. It obscures expected biophysical relationships, making it impossible to draw meaningful conclusions from cross-study comparisons. Furthermore, it means that specific, often opaque, decisions, such as the inclusion of LULUC or the assumed origin of feed ingredients, can single-handedly determine a product's perceived sustainability, rendering many comparative assertions unreliable.

This review's findings demonstrate that the current, narrow focus of most shrimp LCAs is a key source of this unreliability. The widespread and systematic omission of critical impact pathways creates a vacuum of data and guidance. This vacuum is inevitably filled by the inconsistent assumptions and variable system boundaries that have been shown to dominate the results. Therefore, for shrimp LCAs to evolve into a robust tool capable of guiding policy and practice, its scope must be fundamentally expanded and harmonised. Future assessments, and any prospective PEFCR for crustaceans, must move beyond a narrow set of midpoints to systematically and transparently quantify the interconnected impacts of LULUC, the biodiversity footprint of farms and feed, chemical and antibiotic inputs with their associated ecotoxicity and human health risks, and direct GHG emissions from ponds.

4.2 Blind spots: The neglected environmental dimensions of shrimp aquaculture

The environmental critique of aquaculture extends beyond the commonly assessed impact categories of global warming, eutrophication, and acidification, encompassing a wider range of environmental pressures (Ahmed and Thompson, 2019; DeWeerdt, 2020; Martinez-Porchas and Martinez-Cordova, 2012; Mavraganis et al., 2020; Pazmiño et al., 2024; figure 6). However, the current literature systematically do not allow for or omits critical environmental impacts. Biodiversity loss, for instance, is a highly relevant, yet overlooked, aspect in the reviewed shrimp LCAs. Here more work needs to be done to develop biodiversity impact assessment methodologies for marine environments. Furthermore, various toxicity categories were calculated by only five studies, despite the documented widespread use of chemicals in shrimp aquaculture. Neither did any study evaluate endpoint impact indicators, such as effects on human health or ecosystems, thereby limiting the ability of LCA to provide a holistic assessment of shrimp aquaculture's sustainability. This selective focus creates a partial and potentially misleading picture of environmental performance of shrimp aquaculture (figure 6).

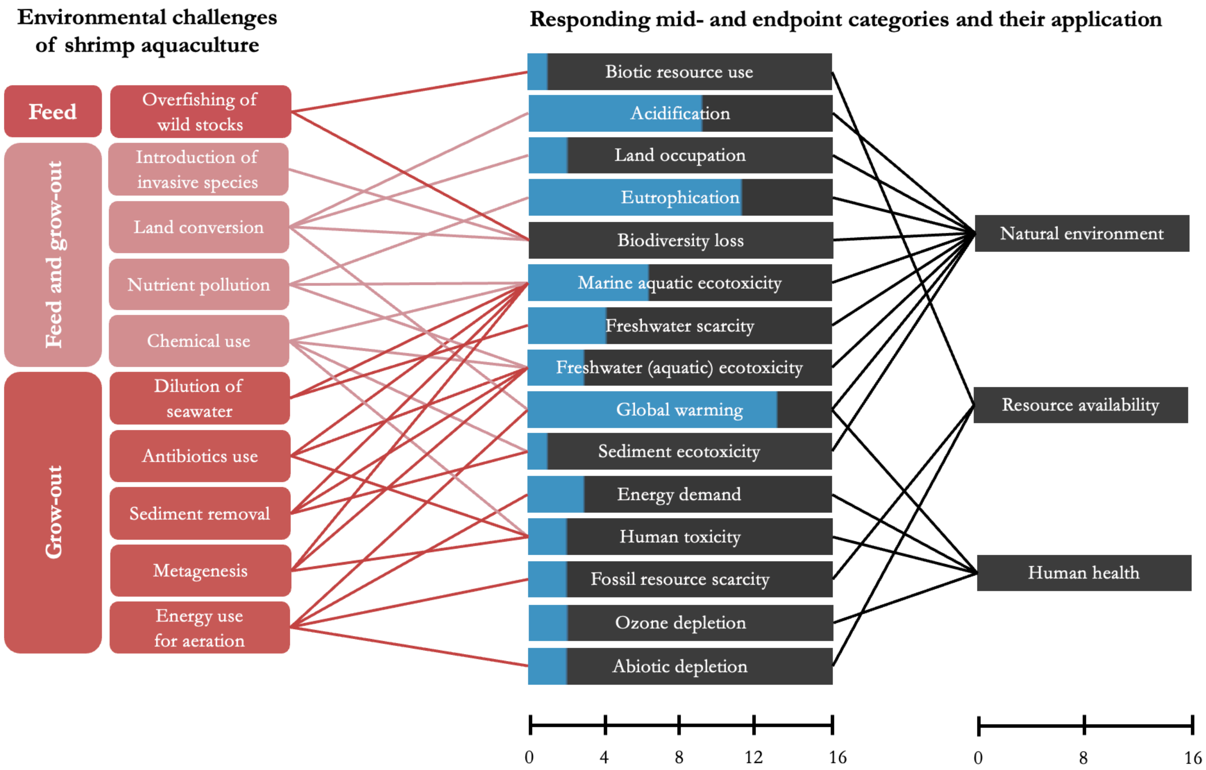

Figure 6 Environmental challenges of shrimp aquaculture and the responding impact categories. Blue shading of mid- and endpoint categories indicates the proportion of the 16 reviewed studies which address the particular category. Lines represent causal relationships between mid- and end-point categories and potential environment impacts of particular phases of the aquaculture cycle.

4.2.1 The interconnected footprint of land, feed, and biodiversity

The environmental footprint of shrimp aquaculture is often viewed through the narrow lens of the farm boundary, yet its most profound impacts are frequently interconnected and telecoupled. This review finds that the literature systematically fails to account for these linked pressures, with three areas of particular concern:

LULUC: The conversion of coastal ecosystems, particularly carbon-rich mangrove forests, for shrimp ponds is a profound environmental transformation. Yet only studies 10 and 11 included farm-level LULUC impacts, with study 10 finding that they could contribute up to 94% of a system's GW footprint. This omission is critical, as emissions from mangrove conversion in Southeast Asia alone are estimated at 691.8 teragrams of CO_2-equivalent annually (Sasmito et al., 2025). Current approaches to land-use assessment also exhibit high methodological discrepancy, with research demonstrating that the attribution of LULUC emissions remains a nuanced challenge influenced by data sources, historical land-use patterns, and regional dynamics (Caro et al., 2018). To address this gap, future shrimp LCAs and any prospective Product

Environmental Footprint Category Rules (PEFCRs) for aquaculture must mandate standardised LULUC accounting. This should align with established frameworks like PAS 2050 (BSI, 2011), requiring the use of region-specific carbon stock data and sensitivity analyses to address inherent uncertainties.

Feed formulations and origins: The intensification of shrimp farming has shifted this environmental burden from direct land occupation at the farm site to global feed supply chains (Clawson et al., 2024; Davis et al., 2021). However, the impacts of feed are poorly quantified due to inconsistent reporting of ingredients and, crucially, their geographical origins. The reviewed studies demonstrate variation in feed compositions, with fishmeal comprising 20–42% of pellet ingredients and soybean meal 11–30%. The sensitivity analysis in study 1, which showed a potential 1,240% increase in GW impacts for soybean meal sourced from Brazil versus the U.S., underscores the critical importance of geographical specificity. Furthermore, minor variations in reporting feed composition can lead to threefold differences in estimates of wild fish use (Roberts et al., 2024), highlighting the need for high levels of detail and transparency. Therefore, future LCAs and any aquaculture PEFCRs must involve transparent reporting of all feed ingredients, their proportions, and their geographical origins, along with sensitivity analyses for high-impact ingredients.

Biodiversity impacts: Biodiversity loss is the ultimate consequence of these pressures, and LCA is increasingly used to estimate biodiversity impacts across complex value chains (Bromwich et al., 2025), yet it remains entirely unquantified in shrimp LCA studies. While several studies recognised the role of shrimp farming in biodiversity loss, they excluded its quantification due to a lack of inventory data and characterisation factors or lack of methods to assess these impacts. The sector drives biodiversity loss through multiple pathways, including direct habitat destruction from mangrove conversion, pollution from effluent, pressure on both wild fisheries for fishmeal, terrestrial ecosystems for crops like soy, and the potential introduction of invasive species or genetic pollution from escaped stock.

While methods to quantify terrestrial biodiversity loss are advancing, marine biodiversity metrics is lagging (Crenna et al., 2020). While the European Union's Environmental Footprint 3.1 methodology is now the leading guide recommended for developing comparable PEFCRs, an examination reveals that this framework is not yet equipped to address the primary biodiversity impacts of coastal aquaculture. Omitting these key impact categories creates a systemic flaw in current assessments. An LCA that neglects off-farm

LULUC and biodiversity impacts may incorrectly favour an intensive system with a small local footprint over an extensive one, even if the former's feed is sourced from recently deforested land in a global biodiversity hotspot. This analytical blind spot could lead to counterproductive policy incentives that reward practices that appear sustainable locally while being devastating globally. While LCA methodologies for biodiversity assessment have known limitations, such as inadequate spatial differentiation (Winter et al., 2017), difficulty in modelling habitat fragmentation (Kuipers et al., 2019), and gaps in addressing diverse taxonomic groups (Damiani et al., 2023; Martínez-Ramón et al., 2024), researchers should begin incorporating biodiversity impacts using existing frameworks like ReCiPe. Documenting key water quality parameters related to biodiversity (such as biochemical oxygen demand, nitrogen, and phosphorus levels), or classifying feed sources by sustainability certification would be a significant step forward.

4.2.2 Unaccounted chemical contamination and gaseous emissions

Beyond the interconnected footprint of feed and land, LCAs must also quantify critical chemical and gaseous pressures originating from the farm itself.

Antibiotics and ecotoxicity: This review reveal a critical failure to assess antibiotic use in shrimp aquaculture. Only one study (study 8) quantified antibiotic inputs, despite calls for more comprehensive modelling of pharmaceutical emissions and their toxicity-related effects in LCA (Emara et al., 2019). This is not just a matter of direct ecotoxicity, which itself was only assessed in five studies. The development of antimicrobial resistance (AMR) is a profound threat to human health and may be a more severe long-term impact than direct toxicity (Nyberg et al., 2021). Empirical research underscores these risks: study 8 highlighted toxicity inputs including pesticides, metals, and pharmaceuticals, while other studies identified up to 20 different antimicrobial products in use in Viet Nam (Luu et al., 2021). Chemical residues in water, sediments, and harvested shrimp potentially promote antibiotic-resistant bacteria and resistance genes (Shao et al., 2021). Future LCAs should systematically incorporate these inputs. This will require establishing trusted, potentially anonymised, data-sharing frameworks for sensitive farm-level data and developing methods to assess not only direct toxicity but also the critical downstream impacts of AMR. If primary data collection of these sensitive inputs is not feasible, assumptions should be made rather than leaving out these highly influential inputs.

Pond emissions: Direct greenhouse gas emissions from the pond itself, particularly methane (CH_4) and nitrous oxide (N_2O), represent a significant data gap that leads to a systematic underestimation of the sector's climate impact. This review found only a fraction of studies report these emissions, despite research showing they can be substantial, with shrimp ponds potentially emitting ten times more methane than the coastal marsh ecosystems they often replace. To move beyond this critical omission, LCA practitioners must actively incorporate predictive models to quantify these biogeochemical fluxes. While the IPCC provides foundational, default methodologies for estimating these emissions from aquaculture within its guidelines for wastewater, more specialised models are needed to capture the unique dynamics of these systems. For instance, the Pond-NP nutrient dynamic model developed by Zhang et al. (2024) quantifies the complex nitrogen cycle, estimating a significant loss to the atmosphere through processes like denitrification. This work underscores a crucial point for LCA: nutrient inputs that do not end up in harvested biomass are lost to the surrounding environment, partly as gaseous emissions, including potent greenhouse gases.

Therefore, we recommend a proactive, tiered approach for practitioners to ensure these emissions are accounted for. As a baseline, practitioners should use the established methodologies in the 2019 Refinement to the 2006 IPCC Guidelines. This involves applying default emission factors to the nitrogen load from uneaten feed and excretion to estimate N_2O, and adapting the wastewater methodology, which links CH_4 production to the pond's biochemical oxygen demand (BOD), to estimate methane. When more farm-specific data is available, practitioners should use these parameters to apply parsimonious predictive models. This practice is supported by research such as Znachor et al. (2023) which shows that GHG fluxes can be estimated from a limited set of readily available data like water temperature and depth. Key data to collect include feed inputs, stocking density, water exchange rates, and management practices during both the culture and non-culture periods, as the latter can be a hotspot for emissions.

For high-quality LCAs, practitioners should leverage outputs from detailed biogeochemical process models like Pond-NP, a framework that has been used to analyse complex economic and GHG relationships in other aquaculture contexts. Adopting this hierarchical approach, grounded in IPCC guidance, will bridge a major analytical gap and ensure that LCA can provide a more complete and accurate assessment of shrimp aquaculture's climate footprint.

4.3 Recommendations for future LCAs

To transition shrimp LCAs from a collection of disparate studies into a robust evidence base for sustainability, expansions in methodology and scope are necessary.

4.3.1 Methodological harmonisation

The EU's PEF methodology offers a promising pathway towards standardisation It has been applied in other food sectors (Hietala et al., 2023) and marine fish, providing comprehensive guidelines on system boundaries, allocation, and data quality. Its requirement to assess 16 impact categories would also significantly expand the scope beyond the narrow focus of current shrimp LCAs. For a future PEF standard for crustaceans, we suggest that the system boundaries should include all flows in figure 3 and other recommendations herein. Nonetheless, PEF's European origin may present challenges in its direct applicability in major non-EU shrimp-producing regions where production conditions and data availability differ substantially.

Complementary open-access platforms, like HESTIA (www.hestia.earth; Poore 2021), provide a harmonised data and modelling platform that can further help structured unit process data and associated meta-data. It enables researchers to analyse their own farm-level data using consistently using pre-defined emission models and gap filling. Moreover, it also allows users to compare their results against other studies and food commodities, facilitating harmonised cross-study comparisons across different systems, products, and regions. Such comparisons have the potential to help identify which shrimp farming systems that are most environmentally efficient, potentially influencing consumer adoption of more sustainable diets (Ran et al., 2022).

4.3.2 Representativeness in geography and practice

The current body of shrimp LCA research provides a picture of where the industry was, but is largely blind to where it is today and where it is going, while farmers are facing increasing environmental and socioeconomic pressures (Macusi et al., 2022). This makes our current knowledge a poor tool for guiding sustainable development of the sector. Using outdated and not geographically adapted literature to guide the current industry can even have highly counter-productive consequences. With an average data collection year of 2013, the literature largely fails to capture the modern, intensified industry. It does not adequately address newer, super-intensive systems (e.g RAS and BFT), integrated multi-trophic aquaculture (IMTA), or the impacts of certification schemes. Several emerging farming techniques, such as hybrid BioRAS systems, offshore shrimp farming, and various closed-loop land-based production systems, remain entirely absent from current LCA literature. Similarly, the impacts of improved feed formulations aimed at reducing antibiotic use are insufficiently evaluated, despite their growing adoption, particularly as economic shocks like the COVID-19 pandemic have driven farmers toward greater resource efficiency (Nguyen et al. 2024). The finding that infrastructure can be a major driver of GHG emissions, accounting for up to 14% of total emissions in super-intensive systems (Huang et al., 2024), an element often downplayed in older studies, underscores the need for updated assessments.

There is a significant misalignment between the regions covered by existing LCAs and the world's major shrimp producers. For example, data from Thailand is overrepresented but dated, reflecting a pre-2012 industry structure before a major disease outbreak reshaped its production (Prompatanapak & Lopetcharat, 2020). Meanwhile, major producers like India and Ecuador are almost entirely absent from the peer-reviewed LCA literature. This geographic imbalance is highly problematic, as production practices, regulatory environments, and ecosystem sensitivities vary dramatically by region. For instance, farming in India is shaped by diverse regional regulations (Kumar et al., 2023), while Ecuador's industry operates within unique coastal ecosystem dynamics (Viera-Roma et al., 2024). The environmental consequences of expanding shrimp farms into Egyptian deserts, utilising previously non-productive land (Soliman & Yacout, 2016), are vastly different from converting carbon-rich mangroves in Indonesia, where a hectare of converted mangrove can release thousands of tonnes of CO_2-equivalent (Sasmito et al., 2019). Similarly, Viet Nam's government supports a transition to rice-shrimp farming, a model whose impacts have not been analysed from an LCA lens yet, despite studies on farmers' willingness to adopt improved practices (Ngoc et al., 2021). Only through a continuous cycle of updated and geographically diverse LCAs can the field keep pace with this dynamic industry and provide relevant guidance for its sustainable development.

4.3.3 Sensitivity analyses

To make the influence of critical assumptions more transparent, we recommend that future shrimp LCAs, and any forthcoming PEFCR, should mandate a minimum set of sensitivity analyses. Based on the major drivers of variability identified in this review, these analyses should test the influence of several key factors. Practitioners should first assess the impact of the chosen co-product allocation method by comparing the results against at least one alternative, such as contrasting economic with mass-based allocation, to demonstrate the robustness of the conclusions. It is also essential to test assumptions regarding the geographical sourcing of high-impact inputs, for instance by evaluating how sourcing key feed ingredients like soybean meal from different plausible regions with varying LULUC and biodiversity risks. Similarly, given the uncertainty surrounding direct farm-level emissions, the sensitivity of results to different emission models or factors for pond-level greenhouse gases should be evaluated.

Sensitivity analyses are also paramount for complex and developing modelling areas like LULUC and biodiversity. For studies including farm-level LULUC, an analysis of the core parameters of the model—such as the assumed percentage of carbon loss from soil and biomass upon conversion—is critical to frame the uncertainty of this high-impact factor. As methodologies for assessing biodiversity impacts are incorporated for both farm and feed stages, it is crucial to test the sensitivity of results to key methodological choices, which can significantly alter outcomes. This should include assessing the sensitivity to the chosen reference state (e.g., a 'natural' versus a 'managed' ecosystem baseline), the choice of biodiversity metric (e.g., comparing models based on species richness with those reflecting ecosystem functionality), and the taxonomic scope of the assessment (e.g., comparing impacts on well-studied taxa versus broader species groups). Systematically performing and reporting on these sensitivity analyses would provide a much clearer picture of how methodological choices influence the results, enhancing the credibility and utility of future studies.

5. Conclusion

LCA is an increasingly utilised tool for evaluating the environmental performance of shrimp aquaculture, and a body of research now exists, identifying key areas like LULUC, feed, and energy as key impact drivers. However, this literature is marked by substantial methodologically induced discrepancies in reported impacts, often differing by more than fiftyfold across key categories, and does not reflect current production systems and regions. A lack of transparent reporting currently limits the reliability and comparability of many shrimp LCAs. While individual studies offer valuable insights, the collective picture is fragmented, making it challenging to benchmark performance accurately or develop robust, evidence-based sustainability strategies. To realise the full potential of LCA as a guide for sustainable shrimp farming, addressing these shortcomings is crucial. We recommend a concerted effort focused on:

- Enhancing Transparency: Ensuring full and explicit documentation of all assumptions, allocation approaches, system boundaries, calculation methods, and unit process data.
- Adopting Harmonised Methodologies: Progressing towards standardised frameworks, potentially leveraging the PEF guidelines, including the development of PEFCRs, or platforms like HESTIA, to improve cross-study comparability.
- Broadening Environmental Scope: Systematically incorporating critical impacts like LULUC, biodiversity, antibiotics and water treatment chemicals, and pond emissions, using standardised assessment approaches.
- Expanding Geographic and System Coverage: Prioritising assessments in underrepresented major producing regions and incorporating emerging intensive farming systems.

This will support the shrimp aquaculture sector in moving towards a truly sustainable future, balancing global food demands with environmental responsibilities.

6. Conflict of Interest

Joseph Poore undertakes freelance consulting work, conducting and reviewing LCAs and advising on LCA methodology.

7. Acknowledgements

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1079 **9. Abstract Art**

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Abstract art: Different global warming results for farmed shrimp in reviewed LCA studies