Reviews in Aquaculture

REVIEWS IN Aquaculture

REVIEW OPEN ACCESS

The Fragmented Landscape of Shrimp Life Cycle Assessments: Uncovering Methodological Dependence and Analytical Blind Spots

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Received: 30 July 2025 | **Revised:** 11 December 2025 | **Accepted:** 27 January 2026

Keywords: critical review | life cycle analysis | prawn | reproducibility | seafood | sustainability

ABSTRACT

Life cycle assessment (LCA) of shrimp aquaculture is hampered by widely divergent results, with reported impacts varying by more than fiftyfold across key categories. This systematic review of 16 peer-reviewed LCAs provides quantitative evidence that much of this divergence is driven by analytical choices rather than on-farm performance: In this case study covering 37 farming cycles, methodological differences in shrimp LCAs induced larger changes in global warming estimates for identical farm data compared to different farming practices. This issue is compounded by a lack of transparency, with only five of the 16 studies providing sufficient data for full reproducibility. We find that this methodological dominance is amplified by analytical blind spots, as most studies neglect critical environmental pressures such as land use change, biodiversity loss, and antibiotic use. To build a robust and comparable evidence base, we recommend representative studies, specific methodological harmonisation, mandatory inclusion of neglected impact categories, and improved reporting transparency. These improvements are essential for LCA to accurately guide the sector towards more sustainability.

1 | Introduction

The global food system is responsible for roughly one quarter of global greenhouse gas (GHG) emissions and is the leading driver of global biodiversity loss [1]. 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 [2]. 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 [3].

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 [4]. In terms of value, shrimp are the second most valuable aquatic export globally, following salmonids [5]. They are also estimated to be the most consumed animal globally in terms of number of individuals [6]. The global production of shrimp and prawns (group 45 of the International Standard Statistical Classification of Aquatic Animals and Plants, FAO [7]) in brackish water aquaculture systems amounted to an annual average of 6.7 million tonnes 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 [8]. The second most produced species is the giant tiger prawn (*Penaeus monodon*), which comprises 11% of brackish water shrimp farming during the same period.

Shrimp farming comprises a variety of systems operating in diverse environments [9]. Intensive systems dominate global production, but extensive systems remain common, often occupying the fragile mangrove-fringed rim of intertidal coastal zones with brackish water [10]. Alongside growing demand, the sector faces criticism and pressure to mitigate energy use, freshwater consumption, mangrove deforestation, and pollution [11]. 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 (GW) [12]. Additionally, the high reliance on feed resources, such as fishmeal from capture fisheries and soybean meal, threatens aquatic and terrestrial biodiversity in globally telecoupled locations [13]. There is therefore a need to understand a diversity of environmental impacts throughout shrimp supply chains.

Life cycle assessment (LCA) is 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) [14], as a key tool in driving sustainability transitions. 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, even with harmonised methods [15]. However, many of these differences relate also to methodological choices [16, 17] that, in theory, could be harmonised. Such ambitions have, for example, been initiated by the 14044 [18, 19] International Organisation for Standardisation (ISO), with ISO 14040 and ISO 14044 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 [20], 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 [21–23]. 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 [24, 25].

This review builds on previous work by Henriksson et al. [17] and Bohnes and Laurent [26] to demonstrate that methodological inconsistencies are the dominant driver of reported environmental impacts among shrimp LCAs, often outweighing the influence of on-farm practices. This finding has profound implications on to which degree literature can guide policy, certification, and improvement efforts. To develop our argument, this paper is structured thematically. First, we provide an overview of available shrimp LCA research. Next, we critically evualuate how methodological choices systematically shape LCA outcomes. We then turn to examining critical environmental pressures that remain neglected. Finally, we conclude by offering a clear set of actionable recommendations for methodological harmonisation to build a more robust and representative science.

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 and giant tiger prawn. 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

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 other studies to avoid a 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 (Table 1).

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

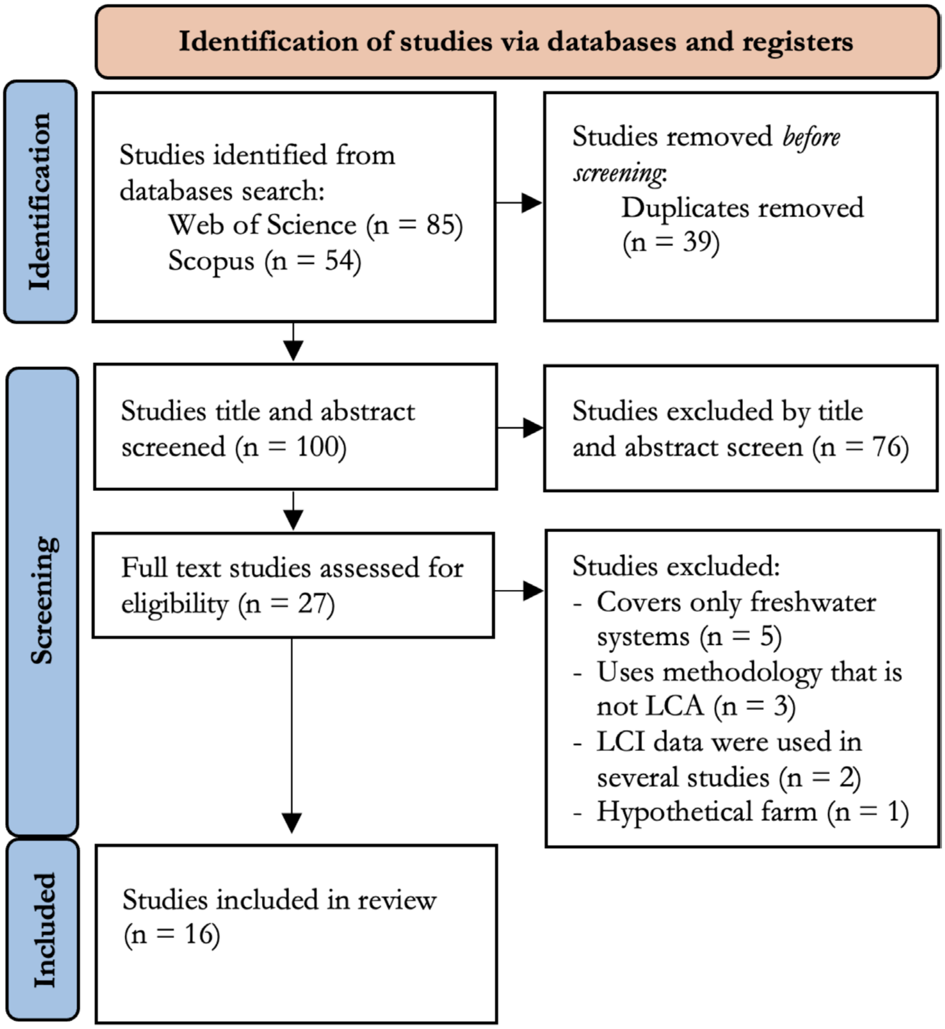

FIGURE 1 | PRISMA flowchart, showing the criteria for inclusion in the review, and the narrowing down from 139 initial studies to 16 included in the review.

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 impact assessment (LCIA), and interpretation). All quantitative data were extracted and, where necessary, harmonised to a common functional unit of 1 t of liveweight shrimp from cradle to farmgate to facilitate comparisons. Detailed data for each of the 37 cycles are provided in the Supporting Information.

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 [43]), were compared against the reported GW and eutrophication impact estimates for each cycle. If not indicated otherwise, 'eutrophiation' in this paper refers to phosphate equivalent (PO_4-eq.). When including freshwater or marine eutrophication, this is explicitly stated. Different farm 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 [44]. For studies applying multiple allocation methods, we used economic allocation as this is the most commonly applied allocation method (Supporting Information). Due to inconsistent reporting, other relevant factors (e.g., freshwater consumption, land occupation, chemical inputs, stocking density, yield, survival rate, and various emissions) could not be evaluated. The relationships between inputs and environmental impacts of each cycle were analysed through a correlation analysis.

TABLE 1 | Overview of reviewed shrimp LCA studies.

Study no.	Authors	Year	Title of study
1	Al Eissa et al. [27]	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. [28]	2015	Environmental performance of brackish water polyculture system from a life cycle perspective: A Filipino case study
3	Belettini et al. [29]	2018	Carbon footprint in commercial cultivation of marine shrimp: A case study in southern Brazil
4	Cao et al. [30]	2011	Life cycle assessment of Chinese shrimp farming systems targeted for export and domestic sales
5	Chang et al. [31]	2017	Carbon footprint analysis in the aquaculture industry: Assessment of an ecological shrimp farm
6	Cortés et al. [32]	2021	Eco-efficiency assessment of shrimp aquaculture production in Mexico
7	Flores-Pérez et al. [33]	2023	Eco-efficiency assessment of disease-infected shrimp farming in Mexico using environmental impact assessment tools
8	Henriksson et al. [34]	2015	Comparison of Asian aquaculture products by use of statistically supported life cycle assessment
9	Henriksson et al. [35]	2017	Indonesian aquaculture futures—Evaluating environmental and socioeconomic potentials and limitations
10	Jonell et al. [36]	2015	Mangrove-shrimp farms in Vietnam-Comparing organic and conventional systems using life cycle assessment
11	Koniyo [37]	2022	Role of innovations/interventions to bring sustainability in aquaculture growth in Indonesia: Integration of life cycle assessment (LCA) framework
12	Lebel et al. [38]	2010	Innovation cycles, niches and sustainability in the shrimp aquaculture industry in Thailand
13	Mungkung et al. [39]	2006	Potentials and limitations of life cycle assessment in setting ecolabelling criteria: A case study of Thai shrimp aquaculture product
14	Sanchez et al. [40]	2023	Life cycle analysis of farmed shrimp of the species *Litopenaeus vannamei* in the province of Guayas
15	Sun et al. [41]	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. [42]	2014	Life cycle assessment of pacific white shrimp (*Penaeus vannamei*) farming system in Trang province, Thailand

Note: More information can be found in the Supporting Information.

To quantify the influence of methodological choices versus different farming practices, coefficients of variation (CV) for GW and eutrophication estimates were calculated for eight distinct shrimp farming cycles from one study that employed a consistent methodology [34]. 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 [27, 36].

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 fulfill the search requirements.

Due to the cut-off date in January 2024, the most recent studies covering novel systems are not included in this review.

3 | Temporal, Geographical, and Systemic Coverage of Existing LCAs

3.1 | Temporal, Geographical, and Systemic Distribution

The 16 studies were published between 2006 and 2023. Three quarters of the studies detailed primary data collection dates, which was, on average, 4 years before publication, making the average year of data collection 2013. Twenty-one percent of the cycles are based on data representing a single farm, while the remaining cycles represent horizontally averaged data of an average of 41 farms (Supporting Information). 81% assess monoculture systems and the remaining cycles assess polyculture systems. 60% evaluate whiteleg shrimp and 40% giant tiger prawn. A key distinction among the reviewed literature is its comparative nature. Of the 16 studies, 63% assess multiple distinct production cycles. The remaining studies assess a single production cycle each. Half of the studies define farming intensity (e.g., extensive, intensive), but often fail to clarify the specific criteria for these classifications, highlighting the lack of harmonised definitions [45].

The geographical focus of the reviewed literature is also misaligned with current global production locations, especially Ecuador (16.7% of global whiteleg shrimp production versus 3% of reviewed LCA cycles) and India (17.4% of global whiteleg shrimp production, but with only one LCA study on shrimp feed; Ramesh et al. [46]; 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 but had the highest representation with 27% out of all reviewed cycles. 94% of studies provided geographical specificity at least to the provincial level, with some detailing exact farm locations. Among the reviewed studies, 69% claimed adherence to the ISO 14040 and 14044 standards, while Study 5 self-defining as an LCA refers to ISO 14067 for carbon footprinting.

3.2 | Recommendations for a Representative Body of LCA Research

The existing literature fails to capture the current shrimp industry, both with regards to geography, year of production, species produced, and dominant production systems. Farming practices have drastically changed over the last decade 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 [47]. Furthermore, key producing countries are not represented in the existing literature. To address these gaps in the current body of research, future LCA studies must be strategically focused on three key areas:

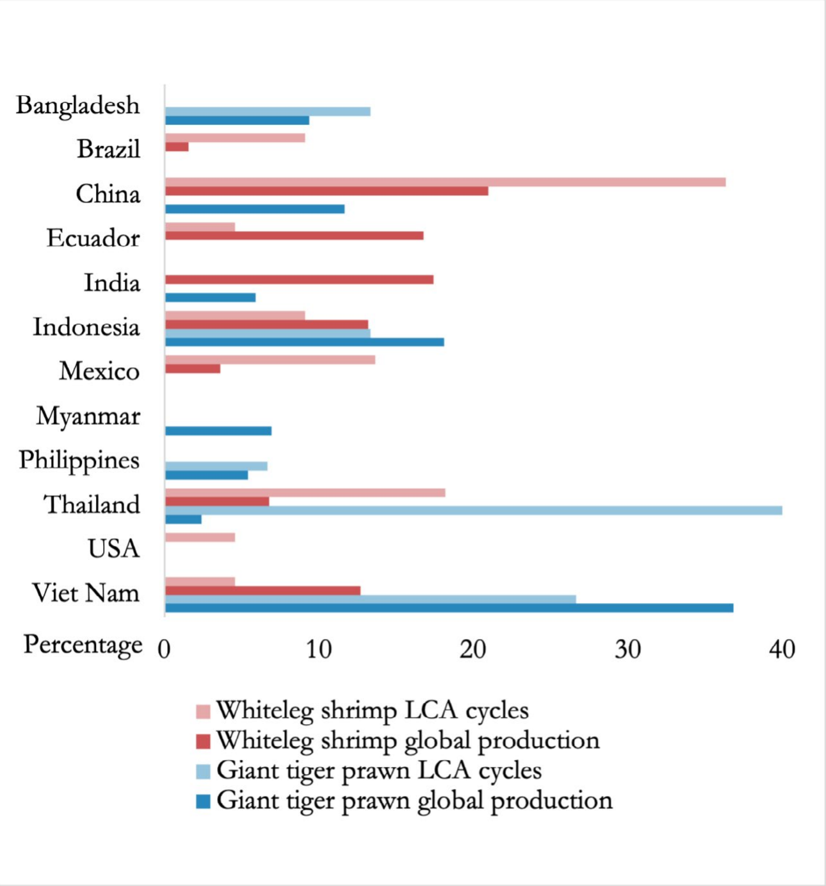

FIGURE 2 | Percentage comparison of number of LCA cycles and global shrimp aquaculture in brackish water. Production data from FAO FishStatJ [7], where the average of the three most recent available years (2020–2022) was used. Annuall whiteleg shrimp production had an average of 5.49 million tonnes and giant tiger prawn 723 thousand tonnes.

- Prioritise contemporary and emerging systems: Future research should evaluate contemporary systems which include (super-)intensive ones (e.g., RAS and BFT), where infrastructure can be a major driver of emissions [48] in combination with energy and feed inputs, emerging techniques like offshore and closed-loop farming, and the impacts of recent innovations, such as improved feed formulations and certification schemes.
- Align research with global production hotspots and species: Efforts should be redirected from historically overrepresented regions, such as Thailand, whose data often reflects a dated industry structure [49], to the world's current major producing countries and regions. Prioritising studies for whiteleg shrimp in India and Ecuador or giant tiger prawn in China, which are almost entirely absent from the peer-reviewed LCA literature.
- Model context-specific environmental impacts: Simply studying the right regions is insufficient; LCAs must model how region-specific factors fundamentally alter environmental impacts. For example, the land-use implications of models like rice-shrimp farming in Viet Nam [50] are essential for accurately quantifying LULUC emissions. Similarly, diverse regional regulations in India [51] can dictate on-farm inputs, such as energy for mandatory water treatment, while the unique coastal ecosystem dynamics in Ecuador [52] will determine the actual impact of effluent, which a generic model would miss. Using generic, one-size-fits-all data for these factors undermines the assessment's validity.

4 | Methodological Dominance: How Analytical Choices Shape Results

4.1 | Inconsistencies Across the LCA Framework

4.1.1 | Study Goals

An LCA must begin with a clear statement of its objectives and the rationale for the assessment. All reviewed studies adhere to this ISO 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 (Supporting Information).

4.1.2 | Scope—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 FU at farmgate. The FU was defined as either 1 kg (25% of studies) or 1 t (75% of studies) of shrimp at the farmgate. 31% of studies also included supplementary FUs for processed products to meet specific study goals covering the broader value chain (Supporting Information). For this review, we harmonised all inventory data and impact estimates to 1 t of liveweight shrimp from cradle to farmgate.

4.1.3 | Scope—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 one third of the studies explicitly include infrastructure even though 75% of studies can be assumed to have varying levels of infrastructure use due to their semi-intensive and intensive nature. 81% explicitly include transport, while all studies can be assumed to transport certain inputs, such as feed or postlarva (Supporting Information).

The treatment of land use and land use change (LULUC) was a major inconsistency and a key driver behind discrepancies in results. Only 13% of studies quantified farm-level LULUC emissions from mangrove conversion, despite 94% of studies covering systems in areas of historic mangrove coverage. 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 (Supporting Information). 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 inclusion 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. However, only Study 1 explicitly included LULUC impacts from feed in its system boundaries.

4.1.4 | Scope—Coproduct Allocation Methods

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 50% of the studies explicitly specify their coproduct allocation method. Monetary value was the most common adopted allocation denominator (38%), followed by mass (19%) and energy (6%) (Supporting Information). 19% of the studies applied multiple allocation methods, providing direct insight into the influence of this choice (Supporting Information). The results showed that the choice of allocation method alters GW estimates 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.

4.1.5 | Scope—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 69% of the studies provide detailed documentation (Supporting Information). The profound influence of some of these choices is also demonstrated through sensitivity analyses. For instance, Study 1 assumed all its soybean meal originated from the US, while a sensitivity analysis reveals that sourcing from Argentina or Brazil would increase the associated GW impacts by 1240% or 960%, respectively. These discrepancies are primarily due to LULUC emissions associated with deforestation of the Amazon rainforest. 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%.

4.1.6 | Modelling Approaches

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 demands. A fundamental issue is that the two approaches are generally not comparable. In this review, only 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 75% of studies, the specific LCA framework is not explicitly stated.

4.1.7 | Impact Assessment Categories and Methodologies

The number of impact categories assessed ranged from zero to eleven, with an average of four. Most studies included GW (81%), terrestrial acidification (56%), and eutrophication (50%). As shown in Figure 6, 10 different impact categories only appeared once, suggesting a fragmented picture of the full environmental performance of shrimp across the LCA studies (Supporting Information). Noteworthy is that no study evaluated endpoint impacts (damage to human health, damage to ecosystem quality, and damage to resource availability) which provide an aggregated and more simplified view of LCA estimates.

To classify and characterise environmental emissions and resource uses towards specific environmental impact categories, different impact assessment methodologies are used. The CML-IA baseline methodology was applied in 56% of the studies, while ReCiPe was applied in 19% (Supporting Information). Study 8 applied a method that explicitly cited its foundational components, such as Heijungs et al. [53] (the scientific basis for the CML method), the USEtox model for toxicity, and GWP factors from the IPCC 5th Assessment Report. Study 5 did not apply a broad, multi-category LCIA methodology. Instead, it followed the ISO/TS 14067 [54] and PAS 2050 [55] standards to conduct a standalone carbon footprint assessment.

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. The former, which applies the CML-IA Baseline [56] finds comparable outcomes for GW estimates and terrestrial acidification, but lower eutrophication estimates under IMPACT 2002+. Notably, the study's Supporting Information shows this discrepancy (e.g., 64.9 vs. 28.0 kg PO_4-eqivalent for the intensive system) occurred even though the authors reported the same units for both methods. This highlights how different characterisation models can create large numerical divergences. However, the study's relative comparison was consistent, as both methodologies identified the intensive farming system as having the higher eutrophication estimates. Discrepancies also arise from different versions of the Intergovernmental Panel on Climate Change (IPCC) [57]. Assessment reports (AR) that underpins GW in most impact assessment methodologies. For example, the GW potential over 100 years (GWP100) for biogenic 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 choice of underlying data [58]. Among the reviewed studies, Study 8 calculated specific freshwater ecotoxicity factors using the USEtox model [59].

4.1.8 | Primary Data

Data collection 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. All studies use primary data for the grow-out stage, which was a requirement for inclusion in our review. However, they demonstrate significant inconsistencies in the primary data sampling methods and documentation, and individual cycles are based from data of between a single and 106 farms.

Several studies employed what they described as 'representative' farm selection 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).

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. Furthermore, sample selection can suffer from a systemic survivorship bias. Sampling methods that rely on farm records inherently favour well-managed, successful operations, leading to underestimated sector-wide impacts. Field observations from major production hubs like the Mekong Delta, for instance, suggest that nearly one-third of all shrimp production cycles fail [60]. By exclusively assessing successful cycles, the current body of LCA literature, except for Study 7, may fail to account for the substantial resources consumed and emissions generated by these failed production events, thus presenting an incomplete and overly optimistic view of the sector's true environmental footprint.

4.1.9 | Secondary Data

The reviewed studies relied on a diverse array of secondary sources, including published literature, government reports, online resources, and structured LCI databases (Supporting Information). Half of the 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. One quarter of studies relied solely on ecoinvent, while the other 25% used it in combination with other LCI databases, such as the Agri-footprint database, LCA Food database, and national government databases. The predominant European or North American origin of many LCI databases poses specific challenges for shrimp production that is mainly conducted in Asia and Latin America, where regional conditions can differ substantially from database defaults [61, 62]. Studies therefore supplemented global databases with local data for aspects like electricity mixes, local emission factors, and specific farming conditions. Examples of this include Study 3, which sourced its electricity mix data directly from Empresa de Pesquisa Energética, a Brazilian national energy research company. Similarly, Study 4 replaced default database values with specific Chinese regional data, using an emission factor for its coal-dominated electricity grid (890 kg CO_2-eqivalent per MWh) that was sourced from a publication by the Chemical Industry Press. One fifth of the studies simply referred to the LCI databases within different versions of SimaPro (Supporting Information), and Studies 12 and 16 did not specify background LCI database(s) used.

4.1.10 | Unit Process Data Reporting for Grow Out Cycles and Feed Mills

The unit process data—the quantified inputs and outputs for each production cycle—form the foundation of any LCA. Our analysis of these data across the reviewed studies reveals two critical findings: immense variability in the scale of inputs and outputs, and systematic inconsistencies in what is reported. While most studies provided detailed inventories, Studies 3 and 5 only reported inputs in terms of associated CO_2-equivalent, making it implausible to reproduce or fully analyse their inventory data.

For the remaining studies, Figure 3 provides a visual overview of the system boundaries, illustrating how inconsistently critical inputs and emissions were documented. To analyse this further, Table 2 provides a harmonised, quantitative synthesis of the life cycle inventories, summarising the key physical flows required to produce 1 t of shrimp. This table serves as the foundational evidence for the methodological dominance and analytical blind spots that are central to this review's thesis.

As shown in Table 3, feed and energy are the most consistently reported parameters, yet they show a high degree of variation. Total on-farm energy use ranges from zero in extensive systems to over 100 GJ per tonne at farmgate in an intensive biofloc system. Feed inputs show similar variability and a critical lack of transparency. While 88% of the studies reported the use of feed pellets or the lack of pellet inputs in two extensive studies, only 50% provided primary data on feed ingredients. Within this subset, feed compositions vary widely, with fishmeal comprising 20%–42% of pellet ingredients and soybean meal 11%–30%. Geographical information on the origin of feed ingredients were also largely lacking, with only Studies 8 and 9 detailing the geographical origins the ingredients used, while Study 1 made assumptions. This represents a significant data gap, as the sensitivity analysis of Study 1 concluded that geographical origin is a highly influential variable. The resulting FCRs for (semi-)intensive monoculture systems ranged from 1.0 to 2.0. One intensive monoculture system which suffered from a disease outbreak had an FCR of 3.0, and systems which added or solely relied on less efficient feed inputs such as mollusks and low value fish, had FCRs of up to 12.

This variability is directly linked to the trade-off between on-farm and off-farm impacts. The intensification of shrimp farming has shifted land occupation from the farm-level (water area) to the feed production level [63–65]. This is starkly illustrated by the inventory data: Study 10, an extensive system, reported up to 4.4 ha (44,000 m^2) of direct land use with no feed or electricity inputs, while Study 1, a super-intensive system, documented only 84 m^2 of water area but required 1.5 t of feed and 921 kWh on-farm for the same functional unit.

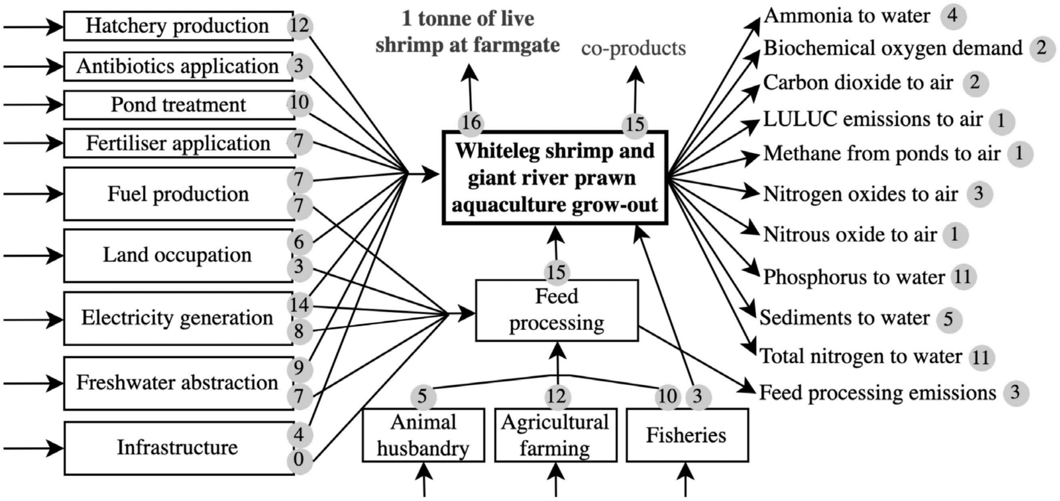

FIGURE 3 | Inputs and outputs to and from feed processing and shrimp grow-out. Unit processes are represented by boxes and flows by arrows. Circled numbers indicate how many of the 16 studies detail primary data, including zeroes (e.g., no feed applied and therefore zero energy use for feed processing).

TABLE 2 | A Comparative synthesis of life cycle inventories for the production of 1 t of Shrimp (Liveweight at Farmgate).

Parameter	Unit	Range	Mean	Median	Studies out of 16 reporting
Feed inputs					
Total pelleted feed	kg	0–3000	1577	1500	15
Key ingredient: fishmeal	% of pellet	3–46	27.9	28.6	8
Key ingredient: soymeal	% of pellet	11–30	22.3	24.9	8
Energy use					
On-farm electricity	kWh	0–30,278	3504	1215	14
Total on-farm energy	MJ	0–109,000	19,656	13,623	14
Energy in feed production	MJ per 1 t	720–32,313	4434	1460	8
Pond amendments, fertilisers, therapeutics and biocides					
Lime (all forms)	kg	10.7–2274	728	614	5
Urea/manure	kg	6–2277	534	87	4
Antibiotics	g	0–4.5	1.8	1.4	3
Disinfectants (e.g., chlorine)	kg	0.5–103	22.8	4.7	4
Land use					
Direct land occupation (farm)	m^2	84–44,000	9430	2380	6
Direct farm emissions					
Nitrogen to water (total N)	kg N	−78 to 76	34.7	21.2	11
Phosphorus to water (total P)	kg P	−8 to 52.5	7.2	2.9	10
Methane from pond	kg CH_4	382.2	—	—	1
Land use change	t CO_2-eq	18.2 to 25.7	22.0	22.0	1

Note: The full list is available in Supporting Information.

While pond amendments like lime and fertilisers were documented in 63% and 44% of the studies respectively, the data for biocides is much sparser. Most critically, the table reveals a near-total data vacuum regarding therapeutic agents. Antibiotic use was quantified in only 19% of the studies, 13% of which explicitly stating none were used (Supporting Information). This low reporting rate contradicts research from regions like Viet Nam, where studies have found that one in four shrimp farmers use antibiotics [66], indicating that their use is not being widely accounted for in the LCA literature.

Similarly, the documentation of farm emissions is highly variable. While total emissions of nitrogen and phosphorus to water were reported by 11 studies, other critical emissions are systematically overlooked (Table 3 and Supporting Information). As detailed in the table, direct methane emissions from ponds and emissions from LULUC were each separately quantified only in single occasions. Given that these two sources can be dominant drivers of an aquaculture system's climate impact—as seen with LULUC, which accounted for 94% of GW impacts in Study 10, and direct pond emissions, which amounted to 382 kg of methane per tonne in the single study that quantified them—their systematic omission means that the majority of the literature is likely presenting a materially incomplete and underestimated assessment of the sector's true GW potential.

4.1.11 | Life Cycle Impact Assessment (LCIA)

The addition and multiplication of varying sets of lifecycle inventory data with an accumulation of methodological inconsistencies easily results in divergence in LCIA results. Thus, by scaling the impact assessment results to a functional unit of 1 t of liveweight shrimp at the farmgate, the results from the different studies can be compared with each other and to pivotal inventory flows (Figure 4 and Supporting Information):

- GW ($n = 33$) had a mean of 8795 kg of carbon dioxide equivalent (CO_2-eq.) per tonne of shrimp. The data showed high variability, with a standard deviation of 9078 kg CO_2-eq. t^{-1} and a full range from 901 to 47,997 kg CO_2-eq. t^{-1}
- Eutrophication ($n = 26$) had a mean of 69 kg of phosphate equivalent (PO_4-eq.) per tonne of shrimp. The dataset had a standard deviation of 56 PO_4 kg-eq. t^{-1} and ranged from −32 to 160 PO_4 kg-eq. t^{-1}. Furthermore, two studies included marine eutrophication and three studies freshwater eutrophication which are not included here due to differing characterisation of nitrogen and phosphorus.
- Terrestrial acidification ($n = 20$) had a mean of 33 kg of sulphur dioxide equivalent (SO_2-eq.) per tonne of shrimp, with a standard deviation of 23 kg SO_2-eq. t^{-1} and a range from 4 to 80 kg SO_2-eq. t^{-1}

TABLE 3 | Completeness, transparency and reproducibility evaluation of 11 key aspects among the reviewed shrimp LCAs.

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

Note: Blue means data are reported. Red means data are not transparently reported.

4.1.12 | Completeness and Consistency Analysis

The interpretation phase of an LCA requires completeness and consistency checks to validate the results [67, 68]. A completeness check verifies that all process stages, elementary flows, and environmental data relevant to the system boundary have been included. A consistency check ensures that all assumptions, data quality, and methodological choices are applied uniformly throughout the study and are appropriate for the stated goal.

These essential checks were almost entirely absent from the reviewed literature. While Studies 4 and 8 conducted a consistency check, none of the 16 studies performed an explicit completeness check. This lack of formal verification is a significant finding that can be tied back to the different approaches to emission accounting. In the absence of a standardised framework, these omissions allow wide-ranging and methodologically diverse approaches to persist without being flagged as critical inconsistency.

4.1.13 | Uncertainty and Sensitivity Analyses

Incorporating uncertainty parameters and calculating rages of results enhances the robustness of LCA outcomes by accounting for error and variability in unit process data, emission models, and characterisation factors [69, 70]. Monte Carlo simulations were applied by 38% of the studies to propagate uncertainties among parameters (Supporting Information), 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 1260 to 108,000 kg CO_2-eq. t^{-1} frozen peeled tail-on giant tiger prawns at European ports due to uncertainties in unit process data and characterisation factors.

Sensitivity analyses (Supporting Information) were conducted in 44% of the studies to identify key contributing variables and improve the reliability of results [71]. 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. This shows how methodological decisions and background data can overshadow actual farming practice differences in determining environmental performance outcomes.

4.1.14 | Conclusions, Limitations, and Recommendations

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 (56%), such as lowering the FCR and reducing fishmeal. Fifty

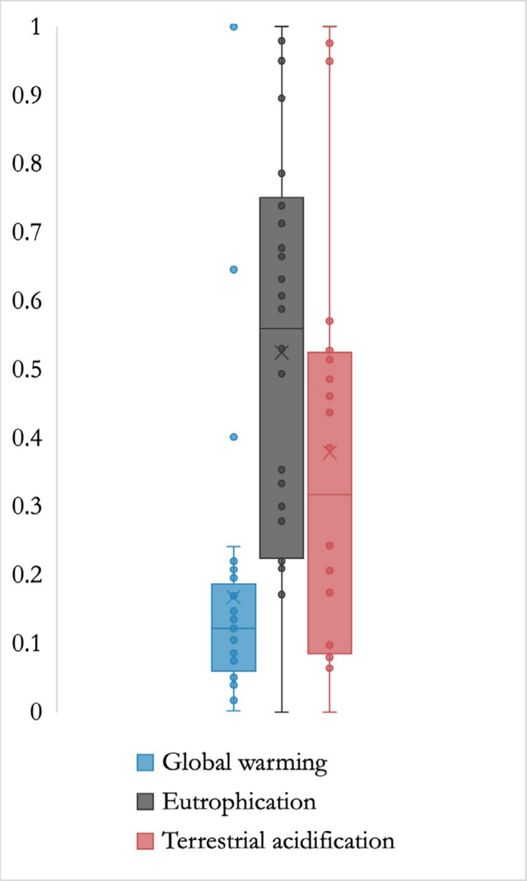

FIGURE 4 | Normalised LCA results from all reviewed cycles, with the lowest reported value among impact results being 0 and highest being 1. Boxes represent the interquartile range with median (line) and mean ('X'). Whiskers extend to 1.5× IQR, showing individual data points and outliers.

percent of the studies recommended the optimisation of energy consumption or use of renewable energy and energy conserving technologies. Changes in wastewater discharge and recycling of excessive nutrients were recommended by 38%.

Only 31% of the studies (Studies 8–11, 13, and 15) explicitly acknowledged limitations in their methodologies, such as the lack of inadequate region-specific data (Study 15). One quarter of the studies also recommended methodological improvements for LCA practitioners, 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).

4.2 | When Methodology Matters More Than Practice

4.2.1 | Reproducibility Assessment

We 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 and detailed sampling methodology—a level of transparency lacking in all reviewed studies.

The quantitative assessment (Table 3) reveals a stark picture: Only 5 of the 16 studies fulfilled all 11 criteria for complete reproducibility, while two studies only lacked one aspect. Considerable lack of transparency hampers the reproducibility of Study 3, which reports the highest GW discrepancies despite the apparent absence of LULUC accounting. These findings align with broader challenges in LCA, where methodological inconsistencies, documentation gaps, and restricted access to proprietary data are recognised barriers to reproducibility [21, 72–73].

4.2.2 | Regression Analysis of Inputs and Impacts

Shrimp LCAs consistently name feed production and on-farm energy consumption as primary drivers behind many environmental impacts [74]. While intensification can improve resource-use efficiency [63, 65, 75], our analysis reveals that variations in system boundaries and modelling choices complicate these relationships. We found no correlation across studies between GW estimates and on-farm energy use ($r = 0.05$, $R^2 = 0.002$, $n = 30$) and only a weak negative correlation with FCR ($r = -0.20$, $R^2 = 0.04$, $n = 33$).

However, when excluding Study 10, which uniquely included significant LULUC emissions, the correlation between GW and energy use strengthened ninefold (from $r = 0.05$ to $r = 0.45$, $n = 28$). This contrast suggests that while energy is a key driver in systems where land impacts are ignored, it stops being a reliable key driver when system boundaries are extended. Consequently, the 'weak' correlation across the full dataset is not merely statistical noise, but an indication that current LCA literature largely overlooks the sector's LULUC emissions.

Furthermore, correlations were weak between eutrophication and both on-farm energy use ($r = 0.31$, $R^2 = 0.09$, $n = 26$) and FCR ($r = 0.35$, $R^2 = 0.19$, $n = 25$). Figure 5 visualises these distinct patterns. The two extensive farming cycles (23 and 24 from Study 10) report the highest GW estimates due to the inclusion of LULUC emissions, yet simultaneously report the lowest eutrophication estimates. This highlights a clear trade-off rather than an anomaly: extensive systems are driven by land-use impacts, whereas intensive systems are driven by nutrient loading and energy inputs. The contrast between cycles from Studies 8 and 9 and the rest of the dataset further illustrates how different modelling approaches can shift a system's environmental profile.

These findings indicate that comparing LCA results across methodologically diverse studies is fraught with risk. Averaging results from studies with different boundaries—such as combining LULUC-inclusive extensive systems with energy-intensive systems that ignore land use—can lead to skewed conclusions. This is exemplified by meta-analyses of diets, such as Clune et al. [76], which include Study 10 in their averaged GW estimates for shrimp. Because Study 10 accounts for LULUC while others do not, its inclusion disproportionately influences the aggregate figure, conflating the environmental impact of shrimp's methodological choices with actual agronomic variance.

The analysis of input-impact relationships is limited by the inconsistent reporting of farm performance data. Critical output metrics, especially shrimp yield and survival rates, were insufficiently documented across the reviewed literature to permit a formal correlation analysis. This is a significant omission because yield acts as the denominator for efficiency; it determines how effectively inputs and burdens are diluted per functional unit. In intensive systems, high energy and feed inputs are only justified by high yields; if survival rates drop, the impact per kilogram spikes. Conversely, in extensive systems, low yields can magnify the impact of land occupation,

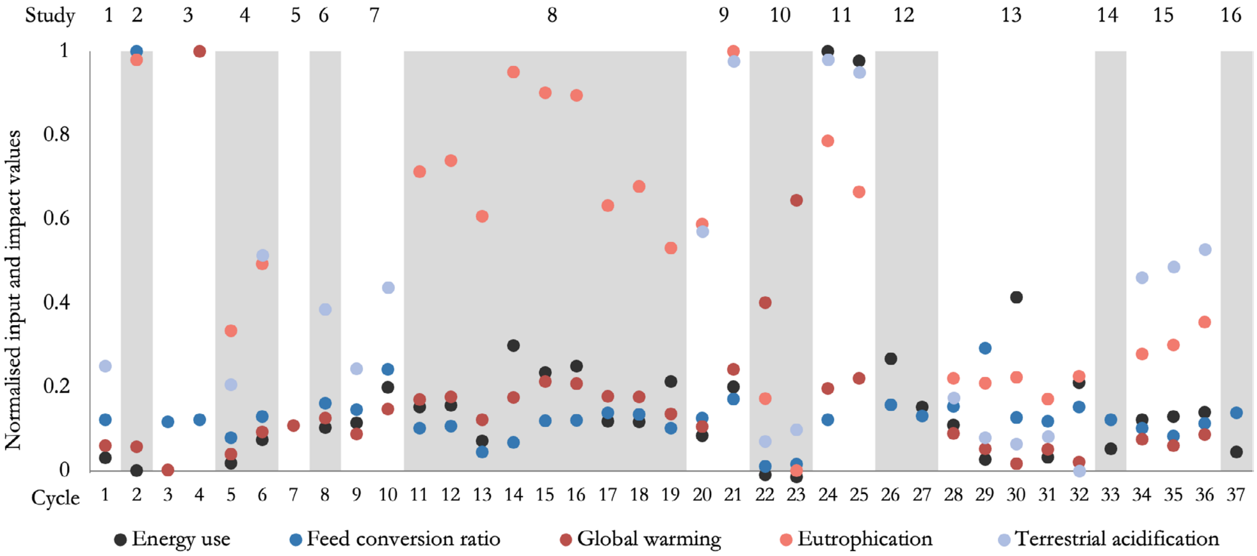

FIGURE 5 | Normalised data on energy use, FCR, global warming and eutrophication impacts obtained from 37 shrimp LCA cycles detailed in 16 studies. Same background colour of adjacent cycles indicates that these cycles originate from the same study. Overlapping points have been jittered for better visibility.

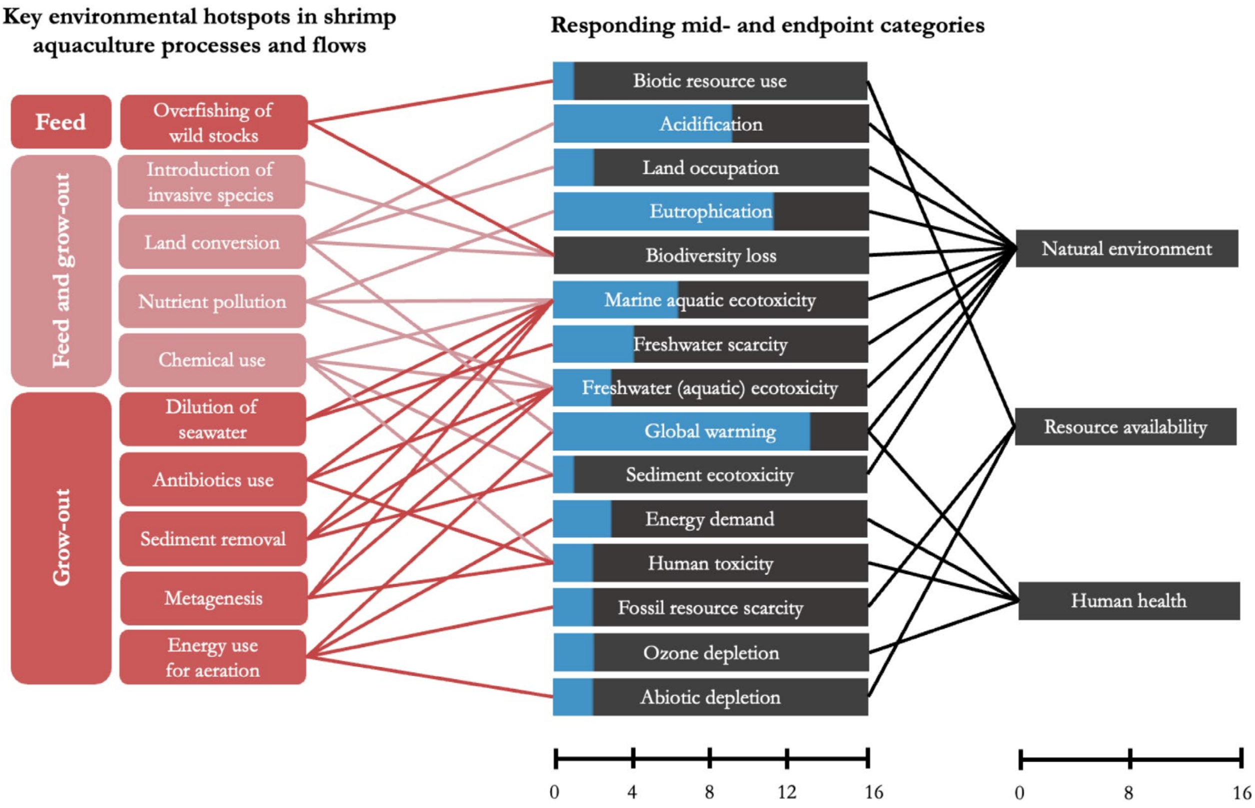

FIGURE 6 | Environmental challenges of shrimp aquaculture and the responding impact categories. Blue shading of mid- and endpoint categories indicates the proportion of the 16 reviewed studies which address the particular category. Lines represent causal relationships between mid- and end-point categories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

making even low-input systems environmentally costly on a per-kilogram basis. Without transparent yield data, these efficiency dynamics remain opaque.

4.2.3 | The Dominance of Methodological Choice in Reported Outcomes

This review substantiates earlier findings from broader aquaculture LCA reviews [17, 26], revealing that the current body of shrimp LCA literature is defined by methodological inconsistencies that limit its utility and comparability. Rather than focusing on totals in isolation, the primary strength of LCA lies in comparing different systems or identifying relative environmental hotspots within a consistent methodological framework [77].

To isolate the variation attributable to on-farm practices, we analysed the 10 studies that assessed multiple production cycles using a consistent internal methodology. By calculating the coefficient of variation (CV) for GW estimates within each of these studies and averaging the results, we found a mean within-study variation of 24%. 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%.

In contrast, when identical farm-level inventory data were reanalysed 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 estimates exhibited a CV of 42% due to the change in methodology. When Study 1 recalculated data for an extensive system from Study 10, the GW estimates 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 varies significantly depending on the modelling framework applied, determining how accurately the assessment reflects the true environmental cost.

Specific methodological decisions have different influence on this divergence. This issue is compounded by a lack of transparency and reproducibility which prevents scientific scrutiny and self-correction, hindering the cumulative nature of scientific knowledge [20] and limiting the reliability of the current state of shrimp LCA knowledge in its unharmonised form as a tool for sustainability assessment.

Despite these challenges that we outlined, the existing body of research retains significant value. The reviewed LCAs have consistently identified feed composition and on-farm energy consumption as the primary environmental hotspots within the assessed system boundaries. While this dominance may be partly influenced by the exclusion of biological foreground processes (such as pond emission fluxes), these consistent findings provide a solid foundation for guiding improvement efforts. Furthermore, the methodologically rigorous studies within the review offer a blueprint for developing more standardised environmental evaluation frameworks in the future.

4.2.4 | Recommendations for Harmonised Frameworks

With respect to the different goals of different LCA studies, most policy makers and actors in the food industry desire more comparability among results. Thus, to allow shrimp LCAs to more effectively guide policy, inform certification schemes, and inform dietary choices, a concerted effort towards methodological harmonisation is desired. The following recommendations for establishing more consistent LCAs and improving transparency:

- Adopt recognised existing frameworks: While ISO 14040 and 14044 provide general dos and don'ts, they are generic frameworks that are not adapted to specific sectors. The EU's PEF methodology, in the meantime, offers sector-specific standardisation and is available for marine fish [78], providing comprehensive guidelines on system boundaries, co-product 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.
- Benchmark results via complementary open-access platforms: We recommend the adaptation of harmonised LCA platforms, in particular the HESTIA platform [79, 80] to enable LCA practitioners to benchmark shrimp aquaculture performance against other studies and commodities. Such a platform provides harmonised background data, models, and fills data gaps, hence enabling researchers and individual shrimp farmers to analyse their data as well as to benchmark their results against other studies and food commodities, facilitating harmonised cross-study comparisons across different systems, products, and regions. Such benchmarking has the potential to help identify which shrimp farming systems that are most environmentally efficient, potentially influencing consumer adoption of more sustainable diets [81]. Making these tools accessible also empowers individual farmers to quantify their own footprints, allowing them to benchmark their performance against regional averages, identify resource inefficiencies, and validate their sustainability credentials for buyers.
- Conduct sensitivity analyses: To make the influence of critical aspects, such as assumptions and methodological choices more transparent, we recommend that future shrimp LCAs and any forthcoming PEFCR should require a minimum set of sensitivity analyses. Based on the major drivers of variability identified in this review, these sensitivity analyses should at least consider: co-product allocation method; assumptions regarding the geographical sourcing of feed ingredients and underlying calculations of high-impact inputs; uncertainty surrounding direct farm-level emission models; and LULUC emissions related to mangrove and other deforestation.

5 | Analytical Blind Spots: What Shrimp LCAs Do Not Yet Capture

This section argues that this methodological dominance is a direct consequence of the field's exclusion of critical, system-defining environmental pressures that go beyond GW, eutrophication, and acidification ([74, 82–85]). These ‘analytical blind spots’ create a vacuum of data and standardised methods, which is inevitably filled by the inconsistent assumptions and variable system boundaries shown to dictate results. This selective focus, which also omits endpoint impact indicators such as effects on human health or ecosystems, creates a partial and potentially misleading picture of the environmental performance of shrimp aquaculture (Figure 6).

5.1 | 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.

5.1.1 | Land Use and Land Use Change

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 estimates. This omission is critical, as emissions from mangrove conversion in Southeast Asia alone are estimated at 691.8 Tg of CO_2-equivalent annually [86]. 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 [87]. This demonstrates how a single methodological choice regarding system boundaries—a choice necessitated by the analytical blind spot around LULUC—can have more influence than any potential on-farm efficiency gain, materially altering the assessment's conclusions.

5.1.2 | 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 [63, 88]. 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 1240% 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 [89], highlighting the need for high levels of detail and transparency. In the absence of standardised reporting on origins, an opaque practitioner assumption about a single feed ingredient becomes a dominant, and potentially decisive, variable in the final assessment. We should add something on fishmeal and oil.

5.1.3 | Biodiversity Impacts

Biodiversity loss, representing a major component of ecosystem damage, is one of the key consequences of these pressures, and LCA is increasingly used to estimate biodiversity impacts across complex value chains [90]. Yet, it remains 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 soybeans, and the potential introduction of invasive species or genetic pollution from escaped stock.

LCA methodologies for biodiversity assessment have known limitations, such as inadequate spatial differentiation [91], difficulty in modelling habitat fragmentation [92], and gaps in addressing diverse taxonomic groups [93, 94]. However, methods to quantify terrestrial biodiversity loss are advancing, while marine biodiversity metrics are lagging [95]. The EU's Environmental Footprint 3.1 methodology is now the leading guide recommended for developing comparable PEFCRs, but 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 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.

5.2 | Overlooked 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. The lack thereof represents another set of blind spots that materially affect assessments by presenting an incomplete and biased risk profile.

5.2.1 | Antibiotics and Ecotoxicity

This review reveals a critical failure to assess antibiotic use in shrimp aquaculture. Only Study 8 quantified antibiotic inputs, despite calls for more comprehensive modelling of pharmaceutical emissions and their toxicity-related effects in LCA [96]. This is not just a matter of direct ecotoxicity, but 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 [97]. By omitting this impact pathway, current LCAs systematically underrepresent the potential human health burden of shrimp production, meaning the assessments are not just inconsistent but are also materially incomplete.

5.2.2 | Pond Emissions

Direct GHG emissions from the pond itself, particularly methane and nitrous oxide, 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 10 times more methane than the coastal marsh ecosystems they often replace [98], and the 2019 Refinement to the 2006 IPCC Guidelines [99] underscores the substantial potential for GHG fluxes from aquaculture wetlands. Similarly, Hu et al. [100] identified aquaculture as a key anthropogenic source of nitrous oxide, driven by microbial nitrification and denitrification processes in nutrient-rich waters.

This analytical blind spot extends equally to eutrophying emissions. The fate of nitrogen and phosphorus in pond sediments—whether they are buried, volatilised, or discharged into surrounding waterways—determines the system's true eutrophication potential. However, most LCAs lack dynamic modelling of these nutrient fluxes, relying instead on simple export coefficients or ignoring sediment-water interactions entirely. The lack of standardised emission models for both gaseous (air) and dissolved (freshwater/marine) pollutants drives significant discrepancies in reported impacts. Consequently, we encourage future PEFCRs to not only require the inclusion of these emissions but to standardise the models used to quantify them, moving beyond static assumptions to dynamic models that account for site-specific sediment management and water chemistry.

5.3 | Recommendations for Addressing Analytical Blind Spots

To address the analytical blind spots that amplify methodological dominance, the environmental scope of future shrimp LCAs and any prospective PEFCR for aquaculture must be expanded. The absence of standardised, mandatory methods for critical impacts creates a vacuum that practitioners fill with individual choices, making the final result reflect the analyst's methodology more than the farmer's performance. Therefore, the following recommendations are designed to re-align LCA results with biophysical reality by systematically quantifying previously neglected impacts.

- Undertake comprehensive land, feed, and biodiversity accounting: Future LCAs must include mandatory, standardised accounting for both farm-level and feed-related LULUC emissions, aligned with frameworks like PAS 2050 [55]. Assessments should require transparent reporting of all feed ingredients, their precise proportions, and their geographical origins. To account for biodiversity, practitioners should integrate existing frameworks like ReCiPe and supplement quantitative assessments with proxy indicators, such as water quality parameters and sustainability certifications for feed sources.
- Incorporate ecotoxicity and antimicrobial resistance: Assessments must quantify all chemical inputs, including therapeutic agents like antibiotics. When sensitive farm-level data is unavailable, practitioners should use justified assumptions based on the farming system and geography rather than omitting the impact category entirely. This ensures that potential risks from ecotoxicity and antimicrobial resistance are acknowledged.
- Implement a tiered approach for pond emissions: To account for direct GHG emissions from ponds, a routine and hierarchical approach is required. This involves a tiered system: as a minimum baseline (Tier 1), practitioners should apply methodologies from the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*; with farm-specific data, an intermediate (Tier 2) approach can use parsimonious predictive models based on parameters like water temperature and stocking density [15, 101]; and for data-rich assessments, an advanced (tier 3) approach should leverage detailed biogeochemical process models like the Pond-NP framework [102].
- Require sensitivity analyses for less frequently included blindspots: As many of these approaches and models are not yet standardised, future LCAs should include a minimum set of sensitivity analyses. These should test the impact of different assumptions made about blind spots, core model parameters such as carbon loss from soil or biomass, the chosen reference state (natural versus managed ecosystem), and metric used (species richness versus ecosystem functionality) for biodiversity impacts and the IPCC tier level.

6 | Conclusion

This systematic review provides quantitative evidence that the current body of LCA literature for shrimp aquaculture is defined by methodological inconsistencies that prevent reliable cross-study comparisons. The central finding of this analysis is that methodological choices are the dominant driver of reported environmental impacts, which vary more than 50-fold. For identical farm-level data, differences in analytical approach induced an average change of 41.6% in GW estimates, a figure that significantly outweighs the 15.2% variation attributable to differences in on-farm practices. This analytical dominance is so pronounced that it obscures expected biophysical relationships between inputs and impacts and can even invert a farm's environmental profile based solely on the analyst's modelling choices.

This issue is compounded by a critical lack of transparency, with only five of the 16 reviewed studies providing sufficient data for full reproducibility. We argue that the dominance of methodology is a direct consequence of the field's analytical blind spots. The widespread and systematic omission of critical environmental pressures—such as LULUC, biodiversity loss, antibiotic use, and direct pond emissions—creates a methodological vacuum.

This vacuum is inevitably filled by the inconsistent assumptions and variable system boundaries that have been shown to dictate results. Furthermore, the existing literature fails to reflect the modern shrimp industry, with a notable temporal lag in data and a geographical misalignment that underrepresents major production regions like India and Ecuador.

Based on these results, the primary inference is that the current body of research is an unreliable foundation for benchmarking performance, guiding policy, or developing robust sustainability strategies. To transition shrimp LCA from a collection of disparate studies into a coherent and trustworthy evidence base, a concerted effort focused is essential.

While this review focuses on shrimp, its findings offer critical lessons that extend to the broader field of food system LCA, particularly for animal agriculture. The problems identified are not unique to crustaceans but are symptoms of systemic challenges in assessing complex biological production systems. The critical role of feed as a telecoupled environmental hotspot, for instance, is a shared challenge across industrial animal production. Any LCA of a fed animal product that lacks transparency on feed composition and origin risks fundamentally misrepresenting the product's true environmental burden. Furthermore, the problem of ‘analytical blind spots’ is universal. In terrestrial systems, analogous blind spots may include soil carbon dynamics, methane from manure management, or local biodiversity impacts from grazing Goglio et al. [103]. The key lesson for all food LCA practitioners is the need to move beyond a narrow, conventional set of impact categories to identify and incorporate the system-specific pressures that may dominate the total environmental footprint.

Ultimately, the challenges identified here—methodological dominance amplified by analytical blind spots and geographical misalignment—are systemic issues in the LCA of complex agricultural products. Adopting the comprehensive approach recommended in this review will support the shrimp aquaculture sector—and food systems at large—in moving towards a truly sustainable future that balances global food demands with environmental responsibilities.

Author Contributions

Alena Calvo: conceptualisation, data curation, formal analysis, investigation, methodology, visualisation, writing – original draft. **Patrik J. G. Henriksson:** conceptualisation, funding acquisition, methodology, resources, supervision, validation, visualisation, writing – review and editing. **E. J. Milner-Gulland:** conceptualisation, resources, supervision, validation, writing – review and editing. **Henry Travers:** conceptualisation, supervision, validation, writing – review and editing. **Joseph Poore:** conceptualisation, funding acquisition, resources, supervision, validation, writing – review and editing.

Funding

We would like to thank all funders who supported this research through their contributions to the CGIAR Trust Fund as well the Login5 Foundation and the Heinrich Böll Foundation. P.J.G.H. is co-funded by FORMAS Inequality and the Biosphere (2020-00454) and CAPS Projects (2023-01805), the European Union's Horizon Europe Research and Innovation Programme under grant agreement no. 101182025, IKEA Foundation, Gordon and Betty Moore Foundation (GBMF11613), and Walton Family Foundation (00104857) and the David and Lucile Packard Foundation (2022-73546). The authors would like to thank them for their support.

Conflicts of Interest

Joseph Poore undertakes freelance consulting work conducting and reviewing LCAs and advising on LCA methodology, and Patrik J. G. Henriksson is a co-author of three of the 16 reviewed studies.

Data Availability Statement

All data generated or analysed during this study are included in this published article and its supplementary information files.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** raq70132-sup-0001-supinfo.xlsx.