Reviews in Aquaculture

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Life Cycle Assessments of Bivalve Aquaculture: A Systematic Review and Meta-Analysis

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Received: 26 October 2025 | **Revised:** 29 May 2026 | **Accepted:** 4 June 2026

Keywords: bivalve aquaculture | blue foods | carbon sequestration | life cycle assessment (LCA) | sustainability assessment

ABSTRACT

Bivalve aquaculture is generally considered a low-impact food system with ecosystem co-benefits. Yet its net contributions to climate change (CC), eutrophication (E), and broader ecosystem stewardship remain uncertain. To address this, we analyzed 31 life cycle assessment studies of bivalve farming. Reported impacts varied substantially. Median values were 385 kg CO_2-eq t^{-1} for CC (interquartile range [IQR]: 164–612.2), 0.25 kg PO_4^{3-}-eq t^{-1} for E (IQR: 0.15–0.49), 0.014 kg N-eq t^{-1} for marine eutrophication (ME) (IQR: 0.00–0.50), 1.86 kg SO_2-eq t^{-1} for acidification (A) (IQR: 0.56–6.26), and 10,772 MJ t^{-1} for energy demand (ED) (IQR: 7231–16,383). High-impact processes were mainly linked to electricity and fuel use, plastic infrastructure, and transport. Reported co-benefits included nutrient removal and potential carbon storage in shells. Regression analysis showed that methodological choices influenced CC and ME, whereas species differences were significant only for ME. Meta-analysis revealed high heterogeneity across studies ($I^2 = 90\%$ for CC and 85% for E). Distinct species patterns emerged. Mussels showed lower CC but variable E outcomes. Oysters showed moderate CC but relatively higher E burdens. Clam showed more variable results and was sensitive to carbon accounting assumptions. Accounting for shell carbon sequestration influenced CC but had little effect on E. Overall, bivalve aquaculture shows variability across studies. Outcomes are strongly influenced by methodological choices and species differences. Claims of climate neutrality remain sensitive to methodology and should be evaluated alongside nutrient trade-offs. Standardized methods and broader geographic coverage are needed for robust sustainability assessments and comparisons.

1 | Introduction

Bivalve mollusks such as oysters, mussels, clams, and scallops are increasingly recognized not just as economic commodities, but as an important component of sustainable food systems [1–4]. Concerns over global food security, climate change (CC), and the environmental impacts of conventional livestock and high-trophic farmed species have attracted renewed scientific and policy interest as low-impact, nutrient-rich alternatives [5–7]. Bivalves require no feed inputs, enhance coastal water conditions, and may contribute to carbon sequestration through shell formation and enhanced sediment burial [8]. As a result, bivalves align closely with the need for climate-resilient and environmentally sound food sources. However, these environmental benefits are subject to important limitations and uncertainties. The role of shell formation (biocalcification) in carbon sequestration remains debated. This process can involve both carbon storage in shells and CO_2 release during calcification processes [9–12]. Additionally, these benefits depend on cultivation remaining within the ecological

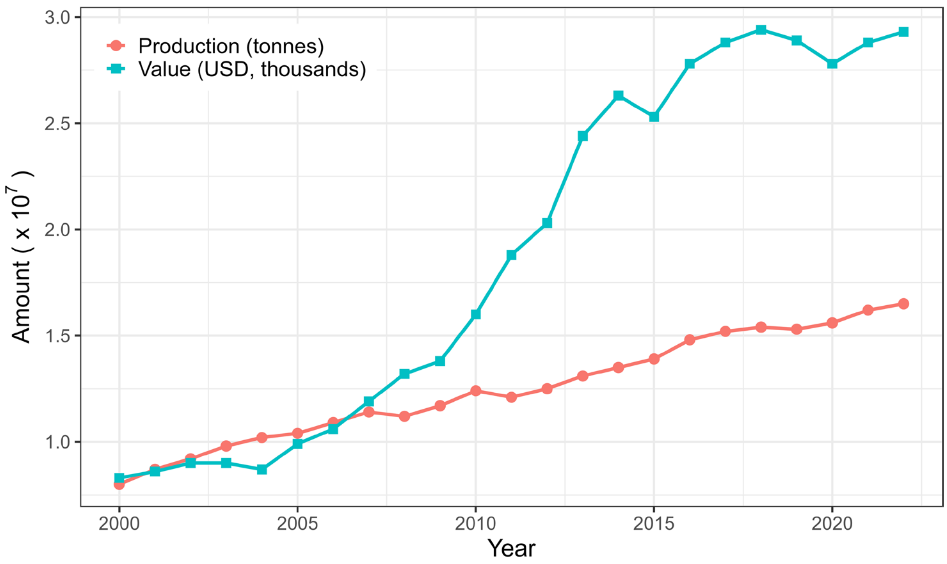

FIGURE 1 | Trends in global bivalve aquaculture production (t live weight) and value (thousand USD) from 2000 to 2022. *Source:* [30].

carrying capacity of local systems. Excessive extraction may reduce food availability for other species, including fish larvae, potentially leading to negative ecosystem effects [13, 14]. Representing nearly 3% of the global export value of aquatic foods [15], bivalves are mostly cultivated, accounting for about 89% of their production [16].

Bivalve aquaculture provides numerous ecosystem services that contribute to ecosystem processes and coastal resilience. Suspension feeding reduces particulate matter and dissolved nutrient concentrations through assimilation and immobilization of organic matter. This can reduce eutrophication symptoms and improve light-attenuating conditions. Bivalve biodeposition and excretion facilitate benthic–pelagic coupling and nutrient remineralization. These processes support nitrogen and phosphorus cycling. Under favorable hydrodynamic and substrate conditions, natural and farmed bivalve aggregations can enhance sediment cohesion and reduce resuspension. These aggregations include reefs, beds, and culture structures. Together, these processes help stabilize benthic habitats essential to estuarine and marine ecosystem integrity [16–18]. However, they can also increase benthic nutrient loading through deposition of feces and pseudofeces. This may alter sediment biogeochemistry and oxygen dynamics [19–21]. Beyond these sedimentary effects, such bivalve aggregations also increase habitat complexity and support a wide range of marine biodiversity [22]. In addition, new mussel production approaches are being developed with an explicit focus on ecosystem services. Examples include nutrient-catch culture designed to extract nutrients from eutrophic areas [23, 24] and the relay of mussels in biogenic reefs to enhance biodiversity and habitat complexity [25]. These ecological functions, along with minimal reliance on external inputs, illustrate the role of bivalve aquaculture in alleviating anthropogenic pressures. They also highlight its potential to support coastal ecosystem resilience [26–28]. In addition to their role in human consumption and ecosystem services, bivalves are receiving increasing attention as sustainable feed ingredients for aquaculture and livestock. This is largely due to their high protein content and favorable amino acid profile [4, 29].

From 2000 to 2022, global bivalve aquaculture more than doubled in production volume and saw an even greater rise in economic value (Figure 1). Production increased from approximately 8 million to 16.5 million t live weight (LW), while value increased from \$8.4 billion to over \$29 billion. This divergence reflects rising unit prices, likely driven by premium markets, value-added products, and growing recognition of sustainability benefits. Further, the global distribution of bivalve production and value across major species and regions is illustrated in Figure 2. Asia dominates in both volume and diversity, with China alone producing about 12.4 million t in 2015, representing 66% of national marine aquaculture output [31]. Meanwhile, Europe and North America generate higher economic returns per unit production despite lower production volumes. This likely reflects specialization in value-added or niche markets [32, 33]. In contrast, Africa, Oceania, and parts of South America account for relatively limited production. In these regions, both aquaculture and wild harvesting play important roles. For example, community-based oyster projects in Mozambique focus on farming [34], while wild oyster harvesting remains a major activity in parts of West Africa [35]. Further, aquaculture initiatives include green-lipped mussel farming in New Zealand [36] and mussel exports from Chile's Los Lagos region [37].

Despite the relatively low environmental footprint of bivalves compared to finfish and crustaceans [38], reported full life cycle impacts vary across studies. A crucial distinction is that most environmental impacts in finfish and crustacean aquaculture arise from the feed supply chain. In contrast, bivalves are unfed and rely on natural primary production [39, 40]. For bivalves, potential trade-offs include localized benthic impacts, energy use in seed production/collection and harvesting, and emissions related to transportation and processing [41–43]. These impacts vary considerably across species, farming systems, and regional contexts [44].

Bivalve aquaculture encompasses a wide range of production techniques. These include intertidal and subtidal bottom culture, suspended longline systems, fixed and floating cages, and raft-based grow-out [6]. These systems differ in terms of

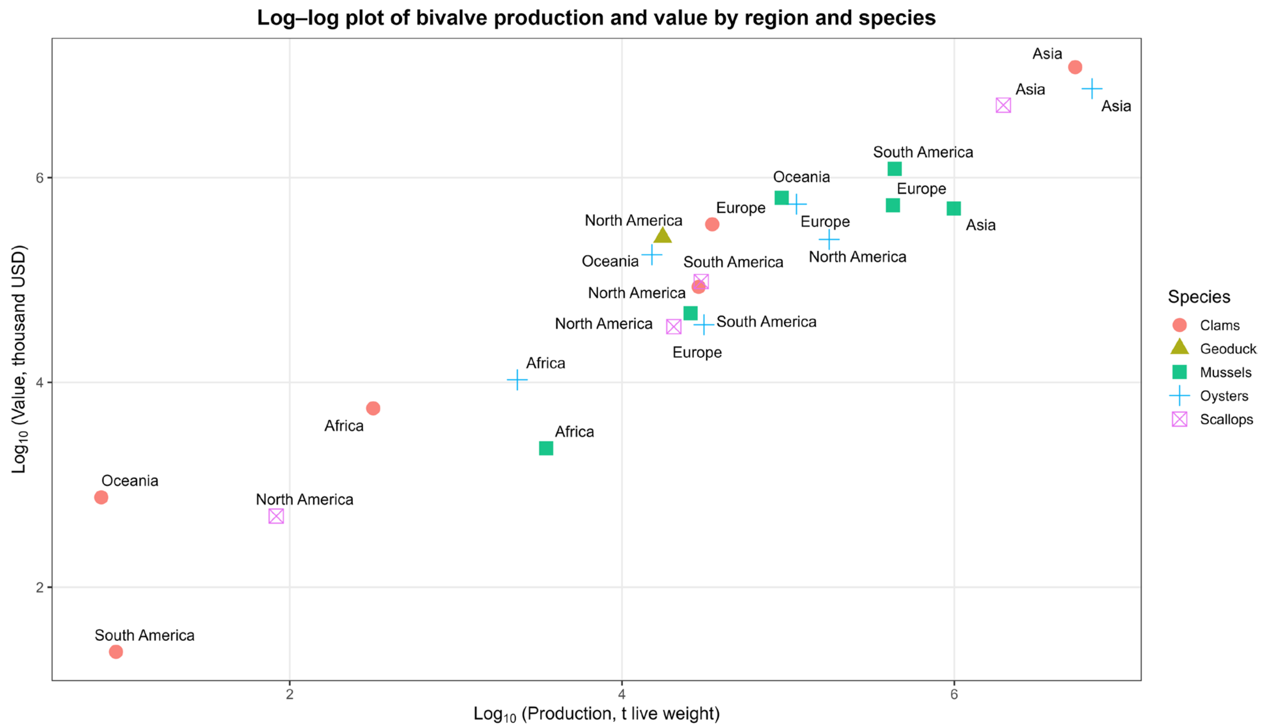

FIGURE 2 | Log–log plot of bivalve aquaculture production (t live weight) versus value (thousand USD) by region and species, 2022. *Source:* (Food and Agriculture Organization, 2024—Global Aquaculture Production dataset via FishStatJ).

infrastructure, material use, operations, and environmental interactions. Seed sourcing strategies also vary from hatchery-based to wild-collected spat. Each approach has distinct implications for energy use, genetic diversity, and ecological outcomes [44, 45]. Hatchery systems typically allow for greater control and disease resistance but may involve higher energy inputs. Conversely, wild spat collection may reduce energy use but can increase the risk of overexploitation or inconsistent supply. As outlined in Table 1, bivalve production techniques differ by species, reflecting biological requirements and regional practices [46–52]. Local practices may also reflect site-specific conditions such as water depth and exposure to wind and waves. Labor costs and regulatory regimes further shape the feasibility and adoption of different farming systems [53, 54]. These differences complicate the environmental assessment of bivalve farming, especially in emerging aquaculture regions where practices are evolving, and data availability remains limited.

Life cycle assessment (LCA) is a robust framework for evaluating environmental impacts across the production chain [55, 56]. LCA studies on bivalve aquaculture have been conducted globally and typically examine key impact categories such as greenhouse gas emissions, eutrophication, energy demand, and water use [57–60]. However, inconsistencies in functional units, system boundaries, allocation rules, and life cycle impact assessment methods have limited cross-study comparability and hindered the development of best practices. In addition, a particular area of uncertainty within bivalve LCAs involves carbon dynamics. Bivalves contribute to carbon storage through shell formation (biocalcification). Biocalcification removes dissolved inorganic carbon from seawater while releasing a molecule of CO_2 during the process. The magnitude of CO_2 release associated with calcification varies with environmental conditions such as temperature, salinity, and background carbonate chemistry. Conversely, the biocalcification reaction simultaneously reduces total alkalinity (TA), which can lower the capacity of seawater to absorb atmospheric CO_2. However, bivalves also emit CO_2 via respiration, shell formation and bio-deposition (feces and pseudofeces). The net climate effect of these processes remains debated [9, 12]. In addition, their classification as carbon sequestration, storage, or transformation pathways varies across the literature.

In this review, carbon sequestration is defined in line with IPCC terminology as the process of increasing the carbon content of a carbon pool other than the atmosphere [61]. However, its interpretation in the literature varies, particularly with respect to atmospheric CO_2 removal. The lack of standardized approaches for accounting for these carbon fluxes leads to inconsistent impact estimates across studies. Previous work has highlighted broader methodological inconsistencies in bivalve LCAs, including variation in functional units, allocation methods, system boundaries, and impact assessment approaches [62, 63]. However, carbon accounting challenges remain unsolved. This variability highlights the importance of a systematic examination of how existing LCAs have handled carbon fluxes. Rather than resolving these uncertainties outright, this systematic review maps the methodological approaches used to account for carbon-related processes. It highlights inconsistencies, emerging best practices, and areas in need of methodological harmonization. By doing so, the review evaluates how methodological choices shape results across studies. These choices include system boundaries, functional units, allocation rules, and approaches to carbon and nutrient fluxes. The review also supports efforts to standardize LCA methods for more consistent assessments of bivalve aquaculture.

TABLE 1 | Common bivalve species and their production methods.

Common name	Scientific name	Spawning techniques	On-growing techniques	Harvesting methods
Eastern oyster	*Crassostrea virginica*	Hatchery	FLUPSY, on-/off-bottom culture, suspended systems	Hand, mechanical, dredging
Pacific oyster[a]	*Magallana gigas* (*Crassostrea gigas*)	Hatchery, wild spat	FLUPSY, on-/off-bottom, suspended systems	Hand, mechanical, dredging
Kumamoto oyster	*Magallana sikamea* (Crassostrea sikamea)	Hatchery	Off-bottom, suspended culture	Hand harvesting
Portuguese oyster	*Magallana angulata* (*Crassostrea angulata*)	Hatchery, wild spat	Similar to *M. gigas*, sometimes hybridized	Hand, mechanical
European flat oyster	*Ostrea edulis*	Hatchery, natural spat	On-/off-bottom, suspended systems	Dredging, hand harvesting
Sydney rock oyster	*Saccostrea glomerata*	Hatchery, natural spat	On-/off-bottom, longlines, sticks	Manual, mechanical
Hard clam/quahog	*Mercenaria mercenaria*	Hatchery	Intertidal/subtidal plots	Hand harvesting
Manila clam[a]	*Ruditapes philippinarum*	Hatchery, limited wild spat	Intertidal/subtidal planting	Hand harvesting, hydraulic dredging
Soft-shell clam	*Mya arenaria*	Natural spawning	Intertidal planting	Hand digging
Geoduck clam	*Panopea generosa*	Natural spawning	Intertidal and subtidal planting	Manual digging
Blue mussel[a]	*Mytilus edulis*	Natural spat, some hatchery	Bottom culture, longlines, rafts, bouchot	Boat-based mechanical harvesting
Mediterranean mussel[a]	*Mytilus galloprovincialis*	Natural spat	Suspended raft culture, longlines	Boat-based mechanical harvesting
Pacific blue mussel	*Mytilus trossulus*	Natural spat	Rope culture on longlines (typically small-scale/regional)	Boat-based mechanical harvesting
Green-lipped mussel	*Perna canaliculus*	Hatchery, wild spat	Longline systems (industrial scale)	Boat-based harvesting
Atlantic sea scallop	*Placopecten magellanicus*	Hatchery, natural spawning	Bottom cages, ear-hanging, suspended containment, enhancement	Hand, mechanical, boat-based
Japanese scallop	*Mizuhopecten yessoensis*	Hatchery	Bottom cages, ear-hanging, suspended containment	Hand collection, boat-based
Bay scallop	*Argopecten irradians*	Hatchery	Floating cages, bottom plots	Hand harvesting, raking

[a]Species explicitly represented in the reviewed LCA case studies. Additional species are included to provide a broader global aquaculture context on cultivation and harvesting practices. Oyster, mussel, and clam production systems are discussed further in the Section 3.

In response to this fragmented landscape, a systematic literature review offers a structured and transparent method for mapping the current body of knowledge. A previous review [44] concentrated mainly on methodological interpretation within LCA and did not include a quantitative synthesis of environmental outcomes. While valuable for identifying trends and gaps, it lacked a systematic protocol. This included predefined eligibility criteria, transparent database screening, and quantitative synthesis needed to consolidate evidence comprehensively. Since then, numerous LCA studies have been published, expanding in geographic scope, methodological complexity, and thematic focus. These studies include assessments of underrepresented species and regions. They also incorporate novel impact categories such as biodiversity and ecotoxicity, and advances in carbon accounting methods related to shell formation, respiration, and dissolved fluxes. This growing and increasingly diverse body of research highlights the need for an updated, methodologically robust synthesis to guide future environmental assessments in bivalve aquaculture. The findings aim to inform more sustainable production practices, improve environmental accounting, and support evidence-based policy development.

Accordingly, this study undertakes a systematic review guided by three primary objectives. First, it maps the geographic, species-specific, and methodological distribution of production practices reported in the literature, including farming methods, allocation approaches, software, and life cycle impact assessment methods. Second, it evaluates how environmental impacts are assessed and interpreted, with a focus on commonly reported impact categories such as CC (often reported in LCA studies as global warming potential, GWP), eutrophication, marine eutrophication, energy demand, and acidification. Third, it identifies methodological limitations that constrain cross-study comparisons and the robustness of sustainability evaluations.

2 | Methods and Materials

2.1 | Systematic Literature Review

This study adopts the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) [64] framework. PRISMA is a widely used guideline that promotes rigor, transparency, and reproducibility in synthesizing the fragmented literature on environmental assessments of bivalve aquaculture. The review systematically identifies, screens, and analyzes existing LCA studies in accordance with the objectives outlined in the Introduction.

In addition to synthesizing reported results, this review also maps the methodological approaches applied in bivalve LCAs. It further examines how prevailing practices, such as monoculture systems and site-specific intensification, may limit the range of environmental interactions and ecosystem services considered in current LCA studies.

2.2 | Data Collection

In alignment with the PRISMA methodology, the literature search was systematically conducted across three databases: Web of Science, Scopus, and Google Scholar. The search was carried out in August 2025, using comprehensive keyword combinations designed to identify studies on bivalve aquaculture and environmental assessment. The authors discussed and agreed upon the inclusive search terms, and an example of a search string employed in the Web of Science was as follows:

Topic: ("bivalv*" OR "mussel*" OR "oyster*" OR "ostrea*" OR "clam*" OR "scallop*" OR "shellfish*" OR "geoduck*") AND Topic: ("life cycle*" OR "LCA" OR "life cycle assessment" OR "life cycle analysis" OR "inventor*" OR "LCI" OR "material flow analysis" OR "sustainab*" OR "sustainability assessment" OR "environment*" OR "environmental assessment" OR "product system").

The search strategy prioritized broad taxonomic and common terms to maximize coverage across bivalve species. Additional genus-level terms (e.g., *Crassostrea*, *Magallana*, *Mytilus*, *Ruditapes*) were tested during search development. However, these terms increased retrieved records by less than 3% and did not substantially improve the identification of relevant studies. Therefore, the final search string was retained to ensure clarity, consistency, and reproducibility.

The syntax was adjusted appropriately for Scopus and Google Scholar, yielding 40,964 records from Web of Science, 38,926 from Scopus, and 80 additional relevant records from Google Scholar (Figure 3). After removing duplicates and retracted articles, a total of 54,615 unique records were retained for screening. The screening process followed a three-stage approach (title, abstract, full-text). Inclusion criteria were defined as follows: (1) relevant documents published in English, including books, reports, conference papers, and original articles; (2) documents available until August 2025; (3) original research applying LCA or closely related methods; and (4) studies addressing the environmental impacts of any bivalve species using quantifiable indicators. Exclusion criteria included: (1) studies limited to physiological, biochemical, or technological aspects (e.g., growth rates, feed trials, or water chemistry) without system-level LCA modeling; (2) research on ecosystem services, policy, or biodiversity that did not apply LCA; (3) articles unavailable in full text or not written in English; (4) LCA studies unrelated to bivalves or using assessment frameworks not focused on LCA-based environmental impacts; and (5) studies that excluded farm-level bivalve production data in the system boundary (e.g., analysis beginning only from post-harvest or product distribution).

All references were imported into Zotero for citation management [65]. Duplicates were removed, and titles and abstracts were independently screened by three reviewers. Full-text assessments were conducted for eligible studies, with discrepancies resolved through consensus. Ultimately, 31 studies met the inclusion criteria and were retained for synthesis. Of these studies, 20 provided sufficient data for CC and 12 for eutrophication analysis. These studies were therefore included in the respective meta-analyses. Extracted data were organized in an Excel spreadsheet for comparative analysis (Supporting Information).

2.3 | Data Analysis

2.3.1 | Data Extraction and Coding

Data from 31 LCA case studies on bivalve aquaculture were systematically extracted using a structured Excel framework (Supporting Information). Extracted information included five categories: (i) study characteristics, such as bibliographic details, species, country, functional unit, and system boundary;

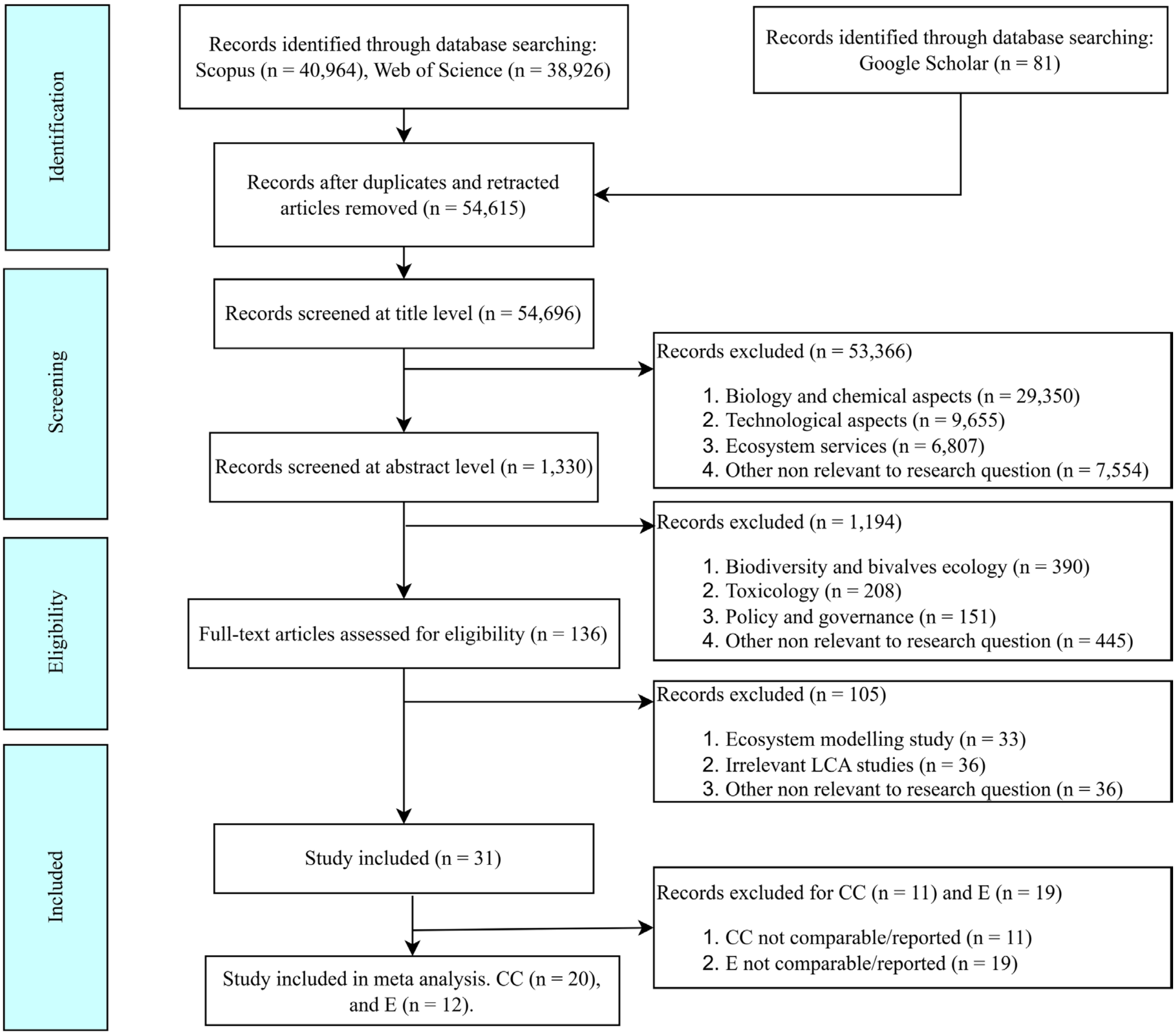

FIGURE 3 | PRISMA flow diagram of the systematic literature review process for selecting LCA studies on bivalve aquaculture. Climate change (CC) expressed in kg CO_2-eq, and eutrophication (E) expressed in kg PO_4^{3-}-eq.

(ii) methodological aspects, including allocation, software, and impact methods; and (iii) environmental outcomes, such as CC, eutrophication, and energy demand. It also included (iv) ecosystem service treatment, such as nutrient removal, carbon sequestration, and (v) data transparency, including the availability of inventory data. In practice, many studies did not clearly distinguish between aquaculture systems and site type (e.g., longlines may be deployed in either nearshore or offshore contexts). As a result, categories sometimes overlap. We therefore coded site information where available, but broadly combined it within the aquaculture system variable for analysis, as site type could not reliably stand alone as a separate category. With respect to ecosystem services, only biocalcification (CO_2 fluxes from shell formation) was coded, as this was the sole service explicitly addressed in more than two reviewed LCA studies. Each study was coded as "yes" (included) or "no" (not included). For "yes" cases, details were extracted on whether carbon fixed in shells was credited and whether CO_2 release during calcification was included. We also recorded how the long-term fate of shell carbon was handled. This distinction is important because sequestration only occurs if shell-derived carbon is retained in a sink, such as sediment burial, rather than rapidly released. The full coding is provided in Supporting Information.

All results were standardized to a functional unit of 1 t live weight (LW, farm gate). Where studies reported results in different functional units, conversions were applied following study descriptions or appropriate biomass ratios to ensure consistency. For studies reporting environmental impacts per kilogram of bivalve seed, conversion to harvest-level impacts was explored using reported yield ratios. These ratios describe kilograms of harvest per kilogram of seed [66]. However, this approach does not account for downstream processes such as grow-out, maintenance, and harvesting, which are major contributors to environmental impacts. Therefore, seed-only studies were not included in the meta-analysis and regression modeling.

Seed-to-harvest yields vary by species and system; mussels typically range between 25 and 40 kg harvest per kg seed [26], while oysters can exceed 80–120 kg harvest per kg seed [67] in suspended culture systems. Where reported, species-specific yields were directly applied for descriptive interpretation. It should also be noted that these yields are expressed as LW including shell, whereas edible weight (EW) (soft tissue fraction) is lower and varies by species, season, and processing method, commonly ~15%–25% of LW for mussels and oysters [68–70].

Where studies reported multiple scenarios, each scenario was treated as an independent case for descriptive analysis and content synthesis. These scenarios included alternative farming systems, allocation strategies, and methodological assumptions. However, for regression and meta-analysis, only harmonized and non-overlapping scenarios aligned with farm-gate system boundaries were included to avoid pseudo-replication.

2.3.2 | Descriptive Summary of Case Studies

Categorical variables (species, country of origin, production method, software, allocation strategy, and impact assessment method) were summarized as frequencies and percentages. Continuous variables (impact results such as CC, eutrophication, and energy demand) were summarized using mean and standard deviation as well as median and interquartile range (IQR) to account for skewed distributions. The descriptive analysis enabled the identification of dominant trends in study design (e.g., Europe-based production, reliance on SimaPro, and frequent use of CML/ReCiPe), as well as heterogeneity in reported environmental outcomes.

2.3.3 | Content Analysis of Key Findings

A qualitative content analysis was conducted to synthesize the key findings from LCA studies on bivalve aquaculture, including mussels, oysters, and clams. First, key results were systematically extracted from each study, capturing both quantitative indicators (e.g., percentage contributions to CC, nutrient removal rates) and qualitative observations, where available (e.g., operational inefficiencies and socio-economic considerations). These findings were then reviewed and inductively coded into preliminary categories according to their thematic similarity, such as "energy use," "infrastructure and materials," "nutrient reduction," and "carbon sequestration." In the final stage, related categories were consolidated into four overarching analytical themes to enable robust cross-study comparison: (1) ecosystem services and carbon sequestration, (2) energy and material hotspots, (3) supply chain and operational efficiency, and (4) comparative performance and future sustainability. This thematic synthesis approach helped identify recurrent environmental hotspots, context-specific variations, and opportunities for improvement. It also maintained traceability to the original references across production systems and geographic settings.

2.3.4 | Regression Modeling of Environmental Outcomes

To examine factors influencing environmental outcomes, linear regression models were fitted for each impact category with sufficient sample size (CC, eutrophication, marine eutrophication, and acidification). The dependent variables (impact category values) were log-transformed prior to analysis to improve normality and reduce heteroscedasticity. Predictor variables included species (binary indicators for mussel and oyster, with other species as the reference category), production context (European vs. non-European), farming method (longline vs. other systems), multifunctionality approach (not required vs. allocation-based), and impact assessment methodology (ReCiPe vs. other methods). All categorical variables were coded as binary dummy variables (1 = presence of the specified condition, 0 = reference category). Model fit was evaluated using R^2, and statistical significance was assessed at $p < 0.05$. Multicollinearity was assessed using variance inflation factors (VIF). VIF values > 5 were considered indicative of problematic multicollinearity [71]. Variables exceeding this threshold were excluded from the respective regression models where necessary.

Given that the dataset was compiled from multiple independent LCA studies, the regression analysis was conducted as a pooled cross-study regression rather than a formal meta-regression. Where studies reported multiple scenarios (e.g., alternative system configurations or methodological assumptions), only harmonized and non-overlapping scenarios aligned with farm-gate system boundaries were retained to minimize pseudo-replication. These scenarios were treated as independent observations to capture methodological variability across the literature. However, it is acknowledged that observations originating from the same study may share underlying assumptions and data sources and, therefore, may not be fully statistically independent. As such, the regression results should be interpreted as exploratory and indicative of general patterns. They should not be treated as strictly inferential estimates derived from a hierarchical or mixed-effects framework.

2.3.5 | Meta-Analysis of Climate Change and Eutrophication

To integrate findings across studies and quantify pooled effects, random-effects meta-analyses were conducted for two key categories: CC and eutrophication. Random-effects models were selected to account for variability in study designs and methodological assumptions across studies. The analysis was performed using log-transformed impact values (natural logarithm) derived directly from reported LCA results, allowing comparison across studies without the use of fixed reference values. This approach avoids structural bias associated with benchmark-based standardization and facilitates comparison of relative impact magnitudes across studies. Because variance was not consistently reported across studies, uncertainty was addressed by assuming a coefficient of variation of 30%. This corresponds to an approximate standard deviation of 0.3 on the log scale. Because study-specific variance estimates were rarely reported, this assumption was applied uniformly across studies and may affect confidence interval precision without substantially altering overall trends. This value was selected as a pragmatic and conservative assumption within the range of uncertainty typically reported in environmental assessments. For example, the Intergovernmental Panel on CC recommends indicative uncertainty ranges (typically ±10%–50%) when empirical data are unavailable [72]. Although this guidance primarily applies to greenhouse gas emissions, similar default uncertainty ranges are often used in LCA when study-specific variance is not reported. This is also reflected in databases such as ecoinvent [73]. This assumption does not capture study-specific variability and therefore represents a simplifying approximation.

Uncertainty was further propagated using a Monte Carlo simulation (200 iterations) to estimate confidence intervals around pooled results. Pooled estimates were derived from log-transformed values and subsequently back-transformed to original units for interpretation. Between-study heterogeneity was assessed using the Q statistic and the I^2 index, with $I^2 > 50\%$ considered substantial heterogeneity. The LCA studies included in this review primarily represent three bivalve groups: mussels, oysters, and clams. Subgroup analyses were conducted to test systematic differences by (i) species (mussels, oysters, and clams) and (ii) carbon sequestration treatment (explicitly included vs. excluded in system boundaries). Sensitivity analyses were conducted to evaluate robustness by (i) excluding sequestration scenarios and (ii) removing extreme values. Cockles were retained only in the descriptive summary because only one study met the inclusion criteria. They were therefore excluded from comparative interpretation and quantitative synthesis. Furthermore, observations with non-positive values were excluded, as the log transformation is undefined for such cases. Results were synthesized and visualized using forest plots of pooled effect sizes.

All descriptive statistics, regression analyses, and meta-analyses were performed in SPSS version 30.0.0.

3 | Results

3.1 | Characteristics of the Included Studies

The characteristics of the 31 LCA case studies on bivalve aquaculture included in this review are summarized in Table 2. The results indicated that mussels (53.1%, $n = 17$) and oysters (31.3%, $n = 10$) dominated, reflecting their global production importance, while clams (12.5%, $n = 4$) and cockles (3.1%, $n = 1$) were rarely assessed. No LCA studies were identified for scallop or geoduck aquaculture systems; available scallop studies were limited to capturing fisheries and were therefore excluded from this review. Most studies were conducted in Europe (71%). Italy alone accounted for 32.3% ($n = 10$), while another 38.7% ($n = 12$) were distributed across Sweden ($n = 3$), Spain ($n = 5$), Ireland ($n = 1$), Portugal ($n = 1$), France ($n = 1$), and Belgium ($n = 1$). Only 29% ($n = 9$) of studies originated from non-European contexts. These included the United States ($n = 2$), Brazil ($n = 1$), Malaysia ($n = 1$), Chile ($n = 1$), China ($n = 3$), and Algeria ($n = 1$).

Farming methods were diverse but unevenly represented: rope-based longline (38.7%, $n = 12$) and raft-based (16.2%, $n = 5$) systems were most common. Less frequently studied systems included unspecified suspended systems (12.9%, $n = 4$), seabed or intertidal on-bottom cultivation (9.7%, $n = 3$), and hatchery-based grow-out (9.7%, $n = 3$). Shore-fixed structures such as trestles or racks (6.4%, $n = 2$), and mixed or integrated systems including integrated multi-trophic aquaculture (IMTA) (6.4%, $n = 2$) were also less common. Multifunctionality was treated inconsistently across studies. In most cases, it arose from the joint production of edible tissue and shell, with the latter containing most of the biomass carbon. Approximately one-quarter of studies applied mass allocation (25.8%, $n = 8$), while nearly 40% did not report any allocation approach.

Most studies used SimaPro (71%, $n = 22$), while OpenLCA, Gabi, or unspecified tools were less common. Impact assessment methods were dominated by CML (36.1%, $n = 13$) and ReCiPe (33.3%, $n = 12$), while others relied on Eco-indicator 99, ILCD, IPCC, or custom frameworks. This concentration on a limited set of tools and methods improves comparability across studies but also highlights the limited methodological diversity in the literature.

3.2 | Content Analysis of Key Findings From LCA Studies

Bivalve aquaculture generally exhibits low environmental impacts while also providing ecosystem services such as nutrient removal and carbon sequestration. However, LCA studies reveal considerable variability in environmental performance depending on farming practices, material choices, and supply chain configurations.

This section presents a thematic synthesis of key findings across bivalve LCA studies, structured around major environmental dimensions rather than individual species. Given the diversity of farming systems, production stages, and methodological approaches, results are organized into cross-cutting themes, while similarities and differences between species (mussels, oysters, and clams) are highlighted within each theme where relevant.

3.2.1 | Ecosystem Services and Carbon Sequestration

Across species, LCA studies consistently identify ecosystem service provision as a distinctive attribute of bivalve aquaculture, in contrast to many other food production systems. Across multiple LCAs, mussel, oyster, and clam farming have been associated with nutrient removal, eutrophication mitigation, and the potential for carbon storage in shells [74–77]. In the Baltic Sea, LCA modeling showed that mussel farming can reduce nutrient loads and improve water transparency [75]. These benefits remained largely independent of end-product valorization scenarios, such as mussel meal, biogas, or compost production. However, such ecosystem services depend on farming remaining within local ecological carrying capacities. Similarly, [74] reported that using mussels as fertilizer can substitute for synthetic nutrient inputs in agriculture and reduce eutrophication. This effect was strongest when fresh or inert storage minimizes nitrogen loss. However, these benefits may be offset in practice by the high salt content of marine biomass, which can impose agronomic limitations and increase treatment costs if not carefully managed. A study by [76] applied LCA to clam farming and quantified that CO_2 sequestered in shells exceeded emissions from farming operations, indicating a potential net sink effect under certain operational conditions. The role of shells in carbon balance emerges repeatedly across LCAs, with mussels and clams storing carbon as calcium carbonate [57, 77]. For instance, [57, 78] found that shell biocalcification in Mediterranean mussel farming can substantially offset GHG emissions. In their Class A systems, which do not require depuration, the offset was between

TABLE 2 | Summary of the characteristics of 31 bivalve aquaculture LCA studies included in this review.

Factors	Categories	% (*n*) or value
Species	Mussels	53.1 (17)
	Oysters	31.3 (10)
	Clam	12.5 (4)
	Cockles	3.1 (1)
Country	Italy	32.3 (10)
	Other Europe (Sweden, Spain, Ireland, France, Belgium, and Portugal)	38.7 (12)
	Outside Europe, the United States, Brazil, Malaysia, Chile, China and Algeria	29 (9)
Farming method	Rope-based longline	38.7 (12)
	Raft-based	16.2 (5)
	Suspended culture	12.9 (4)
	Fixed/shore-based	6.4 (2)
	Hatchery based	9.7 (3)
	Intertidal/seabed	9.7 (3)
	Mixed/integrated	6.4 (2)
Multifunctionality	Specified: mass allocation	25.8 (8)
	Specified: economic allocation	3.2 (1)
	Specified: cut-off allocation	3.2 (1)
	Mentioned, but treatment unclear	29.1 (9)
	Not reported	38.7 (12)
Software	SimaPro	71 (22)
	Open LCA	12.9 (4)
	Gabi	3.2 (1)
	Not specified	12.9 (4)
Impact assessment methodology	ReCiPe (all versions)	33.3 (12)
	CML (all versions)	36.1 (13)
	Eco-indicator 99	5.6 (2)
	Other single methods (ILCD, EPD 2018, IPCC 2013, PEF)	19.4 (7)
	Custom/combined approaches (ISO 14040 with nutrient flow modeling and ecosystem service evaluation)	2.8 (1)
	Not reported	2.8 (1)

Note: Totals may exceed 31 as some studies contributed to multiple categories; full study details and corresponding references are provided in Supporting Information.

20% and 36%. In the Class B system, which undergoes depuration, the offset was approximately 13%. In their modeling, Class B's higher emissions were largely driven by the additional depuration treatment burden. Global scaling suggested a potential net sequestration of −162 Gg CO_2 annually, with higher shell-to-meat ratios driving CC towards negative values. However, sequestration offsets only a fraction of fuel-related greenhouse gas emissions in [43].

Further, Irish Pacific oyster farming has been reported to have relatively low life cycle impacts while actively removing nutrients (3.05 kg N and 0.35 kg P t^{-1} of oysters) and sequestering carbon (70.52 kg C), further reinforcing the role of bivalves as ecosystem service providers [79]. In contrast, [80] deliberately excluded carbon sequestration credits in mussel LCA. This was based on the assumption that shell carbon is eventually re-emitted rather than permanently stored. The study also assumed that broken shells returned to the ocean do not constitute a stable sink. Their analysis, therefore, emphasized farming-related emissions (543 kg CO_2-eq t^{-1}), highlighting the methodological divergence in whether shell carbon storage should be treated as a genuine sink or temporary holding pool.

3.2.2 | Energy and Material Hotspots

Across different bivalve species and production systems, electricity and fuel use dominate environmental burdens. Suspended mussel culture in Algeria showed electricity contributing 38.1% of CC and fuel 19.5% [81]. In a separate study on Manila clam hatchery production in Italy, electricity accounted for over 80% of impact categories [82], noting that this study covers only the hatchery phase and is not directly comparable to full production systems. In oyster farming, the grow-out (including the fattening and pre-fattening phases), along with depuration stages, is particularly significant hotspots due to intensive handling, high material use, and diesel-powered transport between sites [58, 60, 83, 84]. Infrastructure and material choices can be equally impactful: cotton mesh bags in mussel farming accounted for up to 99% of certain category impacts [85], while offshore mussel farms saw anchors, mooring chains, and buoys drive most supply chain impacts [86]. Non-recyclable plastics, including high-density polyethylene (HDPE) socks, were also repeatedly cited as significant contributors [58, 87].

Similarly, [88] identified nylon ropes, polyethene float balls, polypropylene ropes, diesel, and electricity use as major GHG contributors in oyster production. The study also showed that substituting polypropylene ropes could reduce emissions, although at higher costs. Further, energy use emerged as a central driver of environmental impacts, with aquaculture stages accounting for 88.9% of impacts and electricity consumption alone contributing 89.6% of the total footprint, highlighting energy sourcing as a decisive sustainability factor [89]. Likewise, plastic use was identified as a critical sustainability issue in oyster farming, with recommendations to transition toward polypropylene (PP) netting or polyhydroxyalkanoates (PHAs) as more environmentally sound alternatives compared with other plastics [90].

Similarly, in cockle farming, long-lived infrastructure and equipment (*capital goods*) were reported as the main contributors to most impact categories, while short-lived consumables and fuel use (*operational goods*) dominated ozone depletion potential due to frequent fiberglass boat operations. Fiberglass materials have had the most impact, whereas eutrophication was mainly linked to polypropylene [91]. However, this finding should be interpreted cautiously, as reporting on the treatment of capital goods and their allocation over service life was inconsistent or not clearly specified across the reviewed studies. Further, key environmental hotspots in mussel farming include high energy and iron use for capital goods and significant diesel consumption in auxiliary boats [42, 92].

3.2.3 | Supply Chain and Operational Efficiency

Across species and production stages, geographic sourcing, transport distances, and operational practices strongly influence environmental outcomes. Importing oyster seed from France to Italy had higher impacts than local production, emphasizing the benefits of shorter supply chains [84]. Recycling mussel shells—evaluated as their use as a substitute for agricultural lime or cement clinker—proved favorable only when processing facilities were within 323 km of the source [93]. In this case, climate benefits were attributed to avoided emissions from conventional materials rather than to treating the shells themselves as a permanent carbon sink. Relocating oyster pre-fattening to lagoon environments reduced CO_2 emissions by 12% [58].

Seed sourcing is another critical supply-chain factor. In clam aquaculture, wild seed systems showed lower global warming and energy demand than hatchery-produced seed, largely because larval rearing is electricity-intensive. However, increasing climate and habitat pressures may constrain continued reliance on wild seed, making a gradual shift toward hatchery production more likely. This highlights the importance of decarbonizing hatchery operations through renewable electricity and improved fuel efficiency [94].

Operational efficiency, defined as the ability to minimize environmental impacts relative to input use and production output, remains a major area for improvement. Using Data Envelopment Analysis (DEA) applied to LCA results, [95] reported an average environmental efficiency of 55%. This indicates substantial variability in farm performance and the presence of best-practice benchmarks. The analysis suggested that environmental impacts could be reduced by up to 60% or more in some categories without reducing production, primarily through improved resource use efficiency, such as optimizing energy use, reducing fuel consumption, and improving farm management practices. Key improvement strategies include optimizing fuel use in auxiliary boats, reducing material and energy inputs, and adopting best-performing operational practices identified across farms. Energy-efficient depuration, optimized boat use, and renewable power adoption could further lower footprints [75, 92, 96]. The study by [97] disaggregated cradle-to-gate emissions for Chinese Pacific oyster farming. Hatchery operations (37.99%) and sea farming (38.75%) were nearly equal contributors, while algae cultivation was negligible (1.43%). This emphasizes the importance of stage-specific efficiency improvements across the supply chain.

Organic certification and recycling improvements yielded only modest environmental gains, while decarbonizing the electricity mix had the greatest potential to reduce impacts [98]. The authors noted that neglected subsystems (e.g., product processing and development), trade-offs between impact categories, and the lack of major technological innovations limited overall improvement potential, highlighting the need for stage-specific improvements across the production chain.

3.3 | Reported Environmental Impacts of Bivalve Aquaculture

Per t of LW, bivalve aquaculture exhibits a wide range of reported environmental impacts across different categories (Table 3). CC ($n = 70$) averaged 422.035 ± 332.689 kg CO_2-eq t^{-1}, with a median of 385 kg CO_2-eq t^{-1} (IQR: 164.025–612.250). These comparatively low values largely reflect the fact that bivalves are unfed and rely on natural primary production. In contrast, feed production is typically the dominant impact driver in finfish and crustacean aquaculture. At the same time, results also vary substantially with methodological assumptions, particularly regarding whether shell carbon sequestration is

TABLE 3 | Environmental impacts of bivalve aquaculture per t live weight (farm gate).

Impact categories	Number of cases (n)	Mean ± standard deviation	Median (interquartile range: 25th–75th percentile)
Climate change (kg CO_2-eq t^{-1})	70	422.035 ± 332.689	385.000 (164.025–612.25)
Eutrophication (kg PO_4^{3-}-eq t^{-1})	33	0.334 ± 1.086	0.258 (0.15–0.495)
Freshwater eutrophication (kg P-eq t^{-1})	23	0.063 ± 0.103	0.024 (0.019–0.032)
Marine eutrophication (kg N-eq t^{-1})	28	−1.73 ± 5.972	0.014 (0.006–0.504)
Acidification (kg SO_2-eq t^{-1})	23	2.817 ± 2.855	1.86 (0.56–6.26)
Energy demand (MJ t^{-1})	7	11272.479 ± 4955.745	10,772 (7231–16,383)

Note: The number of cases (n) varies across impact categories because not all studies reported every impact indicator. Negative values of eutrophication may reflect net nutrient removal effects associated with bivalve aquaculture.

credited. Nutrient-related categories showed greater variability and, in some cases, net benefits. For eutrophication ($n = 33$), the mean value was 0.334 ± 1.086 kg PO_4^{3-}-eq t^{-1}, with a median of 0.258 kg PO_4^{3-}-eq t^{-1} (IQR: 0.15–0.495). The results suggest that nutrient removal associated with bivalve harvest may offset modeled impacts. However, this interpretation should be treated cautiously as nutrient removal occurs at a local scale, whereas LCA impacts are typically assessed at regional or global scales.

This trend was also evident in marine eutrophication ($n = 28$). Values averaged −1.730 ± 5.971 kg N-eq t^{-1}, while the median was close to zero (0.014 kg N-eq t^{-1}; IQR: 0.006–0.504). This suggests highly site-specific outcomes. For example, mussel farming in the Baltic Sea showed a net negative marine eutrophication impact (−18.35 kg N-eq t^{-1}), indicating that nutrient removal exceeded emissions [75], whereas organic mussel production in Spain reported a positive marine eutrophication impact (+5.27 kg N-eq t^{-1}), reflecting net nutrient release and thus a higher environmental burden [98]. Freshwater eutrophication ($n = 23$) averaged 0.063 ± 0.103 kg P-eq t^{-1}, with a median of 0.024 kg P-eq t^{-1} (IQR: 0.019–0.032), mainly linked to electricity production, hatchery-related inputs, and hatchery effluents, rather than direct farming activities. At the same time, bivalves actively remove nutrients from the water column through filtration, and several studies have highlighted their capacity to reduce local nitrogen and phosphorus loads. However, this ecosystem service is not consistently integrated into LCA impact calculations and remains methodologically challenging to reconcile across spatial scales.

Acidification ($n = 23$) averaged 2.817 ± 2.855 kg SO_2-eq t^{-1}, with a median of 1.86 kg SO_2-eq t^{-1} (IQR: 0.56–6.26), highlighting moderate but variable contributions depending on farming practices and infrastructure. For example, longline systems use lighter infrastructure with lower material inputs and therefore show low acidification values ([89]: 0.047 kg SO_2-eq t^{-1}). In contrast, raft systems require heavier construction and maintenance, resulting in much higher impacts ([84]: 9.29 kg SO_2-eq t^{-1}). Energy demand ($n = 7$) averaged 11272.47 ± 4955.74 MJ t^{-1}, with a median of 10,772 MJ t^{-1} (IQR: 7231–16,383), indicating considerable variation across studies and highlighting the importance of site-specific energy use and material intensity in farm operations.

The large standard deviations and wide IQRs across categories indicate substantial variability in reported impacts. These descriptive statistics represent the distribution of reported case values, while pooled estimates derived from meta-analysis are presented separately in Section 3.5.

3.4 | Factors Influencing Environmental Impact Outcomes

Linear regression models were fitted to identify predictors of environmental impacts in bivalve aquaculture systems (Table 4). Regression models explained approximately 26%–33% of the variance in CC, eutrophication, and acidification, and 74% for marine eutrophication.

For CC, impact assessment methods had a significant effect, with ReCiPe associated with higher CC values ($\beta = 0.572$, $p = 0.024$). Other predictors, including species, production context, farming method, and multifunctionality, were not significant. For eutrophication, none of the predictors considered was statistically significant ($p > 0.05$). For marine eutrophication, results from the reduced model showed that both species and methodological choices were significant drivers. Mussel systems were associated with significantly lower marine eutrophication values ($\beta = -6.740$, $p < 0.001$). Studies applying the ReCiPe impact assessment method also reported substantially lower values ($\beta = -7.459$, $p < 0.001$). For acidification, no predictors were statistically significant ($p > 0.05$).

Overall, these results suggest that methodological choices play a more consistent role than system or geographic variables in explaining variation across impact categories. However, some observations were derived from the same studies and may therefore not be fully independent. Accordingly, regression results should be interpreted cautiously.

3.5 | Meta-Analysis of Climate Change and Eutrophication in Bivalve Farming

The meta-analysis revealed contrasting patterns for CC and eutrophication in bivalve farming. Unlike the descriptive

TABLE 4 | Factors influencing the environmental impacts of bivalve farming.

	Climate change (CC)				Eutrophication (E)				Marine eutrophication (ME)				Acidification (A)			
	β	SE	p	VIF	β	SE	p	VIF	β	SE	p	VIF	β	SE	p	VIF
Species (Mussel = 1)	0.270	0.418	0.521	4.314	1.219	0.704	0.096	3.651	**−6.740**	**1.414**	**< 0.001**	1.031	0.840	1.097	0.455	2.958
Species (Oyster = 1)	0.792	0.418	0.063	4.100	0.792	0.750	0.301	3.139					0.384	1.208	0.754	2.902
Country (Europe = 1)	0.511	0.285	0.078	1.085	0.509	0.518	0.336	1.299	−3.105	2.304	0.193	1.115	0.835	0.822	0.325	1.343
Farming (Longline = 1)	−0.429	0.272	0.119	1.518	0.225	0.538	0.680	2.135					−0.337	0.776	0.670	1.526
Multifunctionality (not required = 1)	−0.437	0.357	0.225	1.442	0.697	0.576	0.238	1.609					−0.342	0.935	0.719	1.535
Impact assessment method (ReCiPe version = 1)	**0.572**	**0.247**	**0.024**	1.380	0.574	0.607	0.353	2.057	**−7.459**	**1.260**	**< 0.001**	1.083	1.395	0.976	0.172	2.902
Constant	4.826	0.454	< 0.001		−2.948	0.678	< 0.001		4.127	2.439	0.106		−1.056	1.088	0.346	
R2	0.331				0.286				0.744				0.256			

Note: Dependent variables were log-transformed prior to analysis. β = regression coefficient; SE = standard error; VIF = variance inflation factor. Statistically significant coefficients ($p < 0.05$) are shown in bold. Variables with VIF values > 5 were excluded. For marine eutrophication, a reduced model was applied by excluding non-significant and collinear predictors to avoid overfitting and improve model stability.

statistics in Section 3.3, these results represent pooled estimates derived from log-transformed data using random-effects meta-analysis. They should therefore be interpreted as central tendencies across studies rather than direct arithmetic averages.

For CC, the overall mean natural log-transformed value was 5.68, corresponding to approximately 292 kg CO_2-eq t^{-1} after back-transformation. This suggests that, under current system boundaries, bivalve aquaculture generally remains a net source of greenhouse gas emissions rather than a consistent mitigation pathway. However, this interpretation depends on the methodological assumptions and system boundaries applied across studies. Because these estimates are based on absolute reported values rather than relative comparisons to a fixed reference system, they should be interpreted as representing absolute emission levels rather than mitigation effects. However, this outcome should be interpreted cautiously because the number of studies remains limited. Methodological differences are substantial, particularly in functional unit definitions (LW vs. EW), treatment of shell carbon sequestration, and allocation approaches. These methodological differences partly explain the variability observed across species.

Subgroup analysis showed that oysters had the highest mean values (ln = 6.48). Mussels showed lower values, with ln = 5.42 without sequestration and ln = 5.23 with sequestration. Clams showed more variable results, with ln = 6.01 without sequestration and ln = 4.24 with sequestration. Oysters with sequestration showed lower values (ln = 5.21). However, this estimate was based on limited data. The influence of CO_2 sequestration assumptions appeared to vary across species. However, these differences should be interpreted cautiously because methodological approaches differed among studies. Clams showed a substantial reduction when sequestration was included; mussels showed only a slight decrease, and oysters showed a moderate reduction. Overall, sequestration assumptions influence the magnitude of results but do not fundamentally change the overall interpretation of CC. Forest plots illustrate variability across studies and confirm substantial overlap between sequestration scenarios, reflecting high heterogeneity rather than systematic bias (Figure 4). Heterogeneity was high ($I^2 = 90\%$, $\tau^2 = 0.80$). Subgroup differences were statistically significant ($Q = 67.85$, $p < 0.001$), indicating that variability is driven by both methodological differences and species-specific factors.

For eutrophication, the overall mean log-transformed value was −0.91, corresponding to approximately 0.40 kg PO_4^{3-}-eq t^{-1} after back-transformation. Subgroup results showed that mussels had the lowest values, with ln ≈ −1.10 without sequestration and ln ≈ −1.01 with sequestration. Oysters showed moderate values (ln ≈ −0.51), and clams showed the highest variability (ln ≈ −0.19). Differences between sequestration and non-sequestration scenarios were minimal, indicating that eutrophication results are less sensitive to carbon accounting assumptions than CC.

Given the high variability across studies, results are interpreted cautiously, with emphasis on patterns and variability across studies rather than definitive absolute conclusions (Figure 5). Cross-study

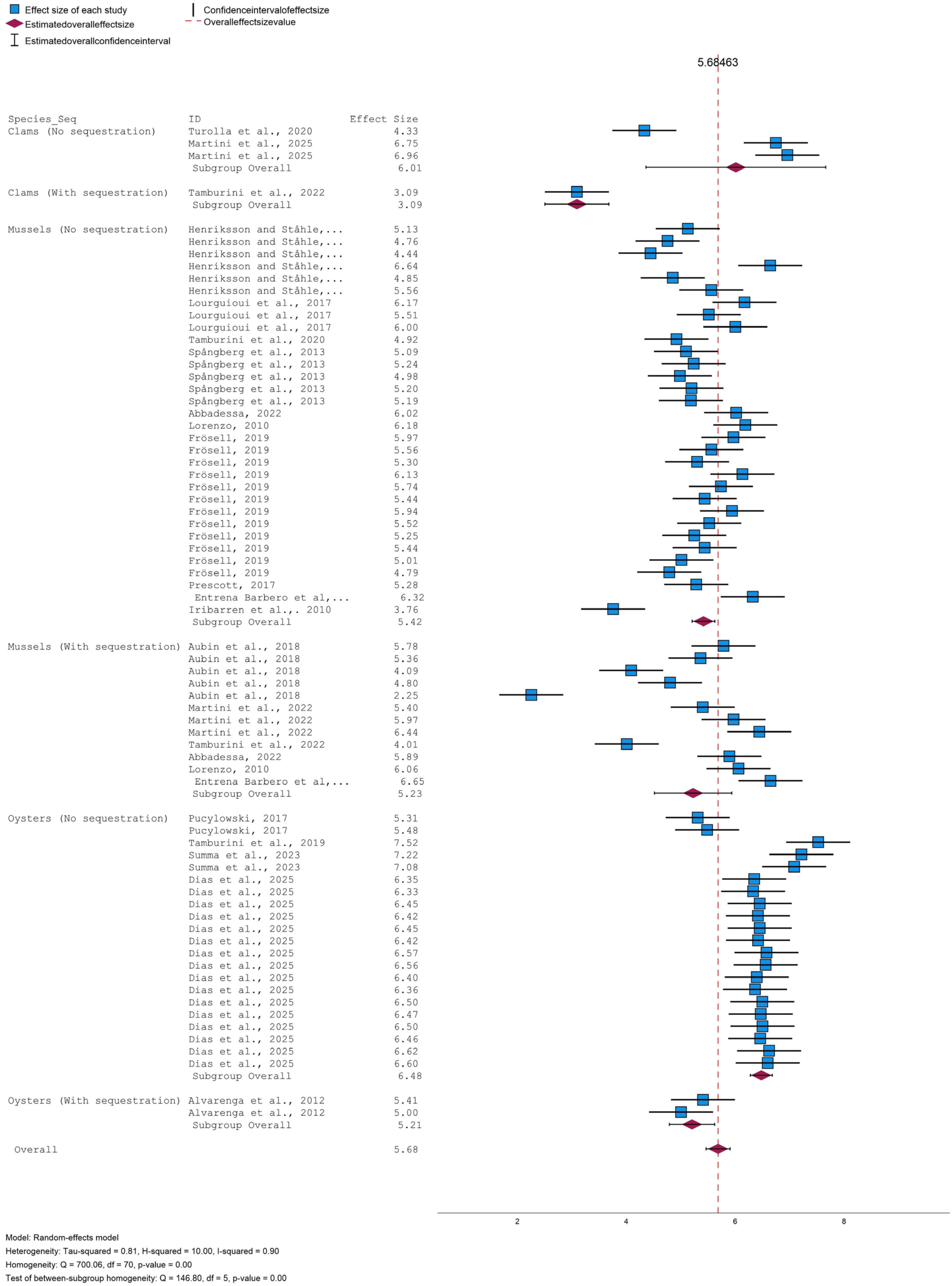

FIGURE 4 | Forest plot of climate change across bivalve aquaculture systems, grouped by species and CO_2 sequestration.

comparisons should therefore be considered exploratory. This is due to substantial differences in methodological assumptions among studies. For CC and eutrophication, heterogeneity was high ($I^2 = 90\%$ and 85%, respectively). This indicates substantial variability reflects real differences in production systems and methodological assumptions rather than random error.

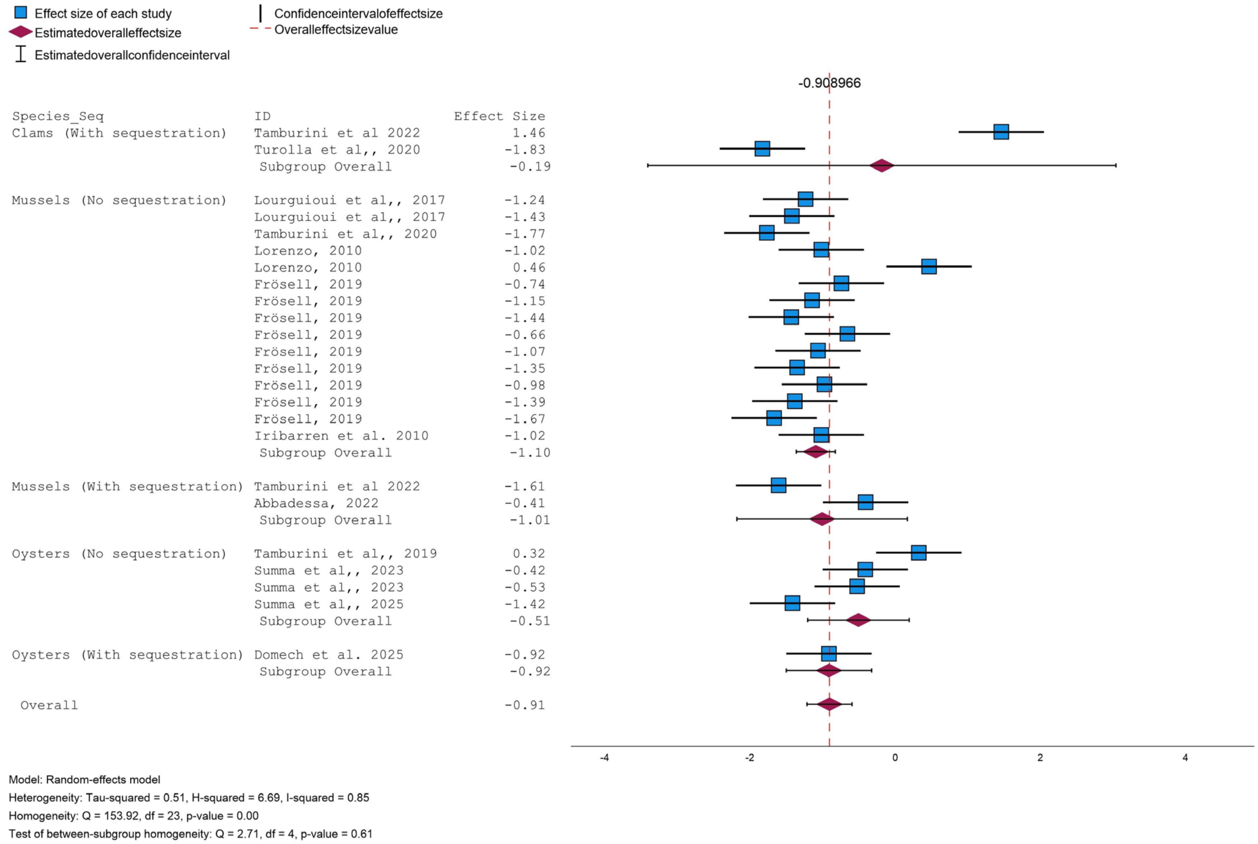

FIGURE 5 | Forest plot of eutrophication across bivalve aquaculture systems, grouped by species and CO_2 sequestration.

4 | Discussion and Practical Implications

This study systematically reviewed and meta-analyzed LCA evidence on bivalve aquaculture to clarify its environmental performance and identify the factors driving variability across systems. By synthesizing 31 case studies, this review provides an up-to-date synthesis of bivalve aquaculture LCAs. It combines systematic review and meta-analysis of the CC impacts, nutrient-related impacts, and energy footprints across mussel, oyster, and clam farming. Overall, the evidence indicates that bivalve aquaculture is characterized by relatively low environmental burdens, with unique contributions through nutrient removal and, under some accounting assumptions, carbon storage in shells.

Comparative LCAs show bivalves generally outperform fed finfish aquaculture systems, particularly intensive species such as salmonids, in several environmental metrics, especially CC and eutrophication [76, 77]. However, these comparisons require careful interpretation. Most bivalve LCAs report results on an LW basis. However, EW is considerably lower (~15%–25%), which influences comparability with other protein sources. Reported advantages in GHG performance are also sensitive to how shell carbon is treated—whether credited to the EW, allocated separately to the shell fraction, or excluded altogether [45].

Compared with fed finfish systems such as salmonids, bivalves exhibit substantially lower CC impacts and energy demand on a live-weight basis. Salmonids typically emit more than 2500 kg CO_2-eq t^{-1}, require over 50,000 MJ t^{-1} of energy, and contribute around 42.6 kg PO_4^{3-}-eq t^{-1} of eutrophication [40]. When normalized to the EW, using typical yields of ~15%–25% for bivalves [49] and ~57%–73% for salmonids [99, 100], the comparison remains robust. Even under conservative assumptions, bivalves generally showed lower CC and eutrophication impacts than salmonids. Assuming 15% EW for bivalves and 73% EW for salmonids, estimated CC were approximately 2567 versus 3425 kg CO_2-eq t^{-1} EW, respectively. Corresponding eutrophication impacts were approximately 1.72 versus 58 kg PO_4^{3-}-eq t^{-1} EW, respectively. However, energy demand for bivalves on an EW basis was slightly higher than that for salmonids (~71,813 vs. 68,500 MJ t^{-1} EW). Compared with terrestrial livestock, beef production is commonly reported at approximately 60–100 kg CO_2-eq per kg of EW [101, 102]. While pork and poultry are typically around 10–12 kg CO_2-eq per kg of EW, based on full supply-chain assessments. Although these values are not directly comparable due to differences in system boundaries and functional units, the median footprint of bivalves in this review (~2567 kg CO_2-eq t^{-1} EW) indicates a relatively low climate impact among animal protein sources.

However, these advantages are not uniform across species. Clams showed lower CC values, particularly when carbon sequestration was included, although this does not consistently translate into net mitigation. This pattern should be interpreted in light of production systems, as clam aquaculture often relies on hatchery-produced seed, which is associated with higher environmental burdens than wild seed collection. This is mainly due to energy- and material-intensive larval rearing [82, 94]. In contrast, many bivalve systems, including mussels, rely on wild seed collection with lower input requirements. Mussels exhibited a mixed profile, combining relatively low greenhouse gas emissions with more variable eutrophication outcomes, while oysters generally showed moderate climate impacts but higher eutrophication values.

Eutrophication impacts in bivalve systems are primarily linked to indirect sources rather than feed inputs. These include biodeposition, farm maintenance activities, electricity use, and hatchery effluents. These processes contribute to nutrient enrichment and redistribution in surrounding aquatic environments and vary depending on site conditions and production practices [44]. These contrasts suggest that the expansion of bivalve aquaculture may contribute to lowering the climate footprint of food systems relative to more intensive animal protein sources, but this potential depends on both methodological assumptions and effective management of nutrient-related impacts.

A central methodological challenge in bivalve LCAs concerns how biogenic carbon fluxes associated with shell formation are represented. In particular, the extent of these advantages depends strongly on methodological treatment of ecosystem services, particularly carbon sequestration in shells and nutrient removal through filtration. Early LCA studies [42, 74, 95] did not include ecosystem service flows, while a previous study by [93] estimated shell $CaCO_3$ content but excluded biogenic CO_2 fluxes. More recent studies have moved toward more explicit treatment of carbon flows. For example, [43] framed mussel farming as an artificial ecosystem. The study considered shells and wooden poles as potential long-term carbon storage, while excluding flesh carbon because it is released when the bivalves are consumed and metabolized. Further, [45] showed that assumptions about shell fate and biogenic CO_2 release can fundamentally alter results. This raises the question of whether shell sequestration should be allocated to EW, credited to the shell by-products, or treated separately. Other LCA studies (e.g., [79, 80]) further reinforced this divergence—some integrating nutrient removal and biocalcification as credits, while others excluded them entirely.

More broadly, these differences reflect wider methodological inconsistencies across aquaculture LCAs. Our review supports earlier critiques of aquaculture LCA [62, 63, 103] by showing that inconsistencies in functional units, system boundaries, and allocation procedures remain major barriers to comparability. Regression results from our dataset further support this, showing that methodological choices, particularly the impact assessment method (e.g., ReCiPe), play a substantial role in shaping reported environmental impacts. However, some observations originated from the same studies and may therefore not be fully independent, so regression patterns should be interpreted cautiously. A critical and often underappreciated source of variation lies in the definition of system boundaries. Most assessments account for on-farm processes such as fuel use and, to a lesser extent, electricity consumption. However, the inclusion of upstream processes remains inconsistent. These include hatchery seed production and gear manufacturing. Downstream stages, such as transport, processing, depuration, and end-of-life treatment of shell material, are also inconsistently included. Some studies adopt relatively narrow farm-gate system boundaries, whereas others extend to broader cradle-to-market or cradle-to-grave perspectives. This inconsistency contributes substantially to variation in reported impacts. For example, a compilation of blue mussel LCAs found that depuration contributes about 6.6% of emissions where included [104], while other studies identify transport, logistics, and infrastructure as major contributors when system boundaries are expanded. These findings highlight the importance of consistently including all relevant life-cycle stages, as well as adopting more transparent and harmonized methodological choices and clearer, more standardized definitions of system boundaries. Explicit reporting of included life-cycle stages is therefore essential. This is especially important for upstream and downstream processes. Clear reporting would improve comparability across aquaculture LCAs and help align results with emerging sustainability assessment and reporting frameworks.

Within this broader methodological context, the treatment of biogenic carbon remains decisive. At the core of this debate is the calcification reaction:

$$Ca^{2+} + 2HCO_3^- \leftrightarrow CaCO_3 + CO_2 + H_2O$$

However, differences in reported CC outcomes are not driven only by the physical fate of shells. They also depend strongly on how seawater carbonate chemistry is represented in LCA studies. Conversely, some assessments focus mainly on $CaCO_3$ formation. When changes in alkalinity and air–sea CO_2 exchange are not explicitly included, shell production may be interpreted as a carbon sink. Under these assumptions, several studies reported net sequestration [43, 57, 77]. This dual interpretation reflects a fundamental methodological divergence. Some studies consider only the stoichiometric calcification reaction, while others incorporate broader carbonate system dynamics, including alkalinity changes and air–sea CO_2 exchange [9].

In this context, the fate of shells plays a secondary role relative to carbonate chemistry processes. If shells are buried, landfilled, or reused in construction, they may contribute to long-term carbon storage; if they dissolve, the stored carbon may be re-released. However, mussels and oysters are typically sold live in shell on an LW basis. Their end-of-life fate therefore lies beyond the farm gate and is rarely specified. This makes assumptions about landfill, composting, or reuse highly uncertain. Moreover, the magnitude of CO_2 release associated with calcification varies with environmental conditions such as temperature, salinity, and background carbonate chemistry, further complicating cross-study comparisons [105].

This methodological sensitivity is illustrated by individual case studies. The study by [76] explicitly accounts for both CO_2 uptake and release during calcification and nevertheless reports net carbon sequestration at the system level, reflecting the balance between shell formation and production-related emissions. Critical perspectives reject shell formation as sequestration entirely, arguing that $CaCO_3$ precipitation increases CO_2 emissions and reduces ocean uptake [10]. These contrasting approaches show that CC outcomes are not determined by shell fate alone. They also depend strongly on how carbonate chemistry and system boundaries are represented. Studies crediting sequestration often report negative or near-neutral CC, while those excluding such credits highlight fuel and electricity as dominant burdens. This mirrors the sensitivity analyses of [43, 45] and highlights a deeper theoretical tension in LCA: whether short-cycle biogenic carbon fluxes should be credited as mitigation. One study framed shellfish farming as a nature-based negative emissions technology. It is estimated that sequestration of up to 6.23 Mt CO_2-eq annually occurs in China. At the global scale, the estimate reached 5.64 Gt CO_2-eq, equivalent to 17% of 2020 emissions. The authors argue that shell carbon and biodeposition could deliver mitigation efficiencies exceeding afforestation [106]. Conversely, Pernet et al. [9] argue that bivalve shells cannot be considered a true atmospheric CO_2 sink, since calcification releases CO_2 to seawater and sequestration credits often rely on flawed carbonate chemistry assumptions. They caution that without direct flux measurements, carbon market applications for bivalves remain scientifically unsupported. A recent ecosystem-focused review by [8] showed that bivalve aquaculture can alter phytoplankton communities toward smaller, carbon-rich taxa. It may also enhance carbon burial through biodeposition, particularly in shallow, low-energy systems. These processes suggest that restricting analysis to farm-level emissions underestimates the broader ecosystem-scale carbon sink potential associated with bivalve aquaculture.

Until harmonized guidance is developed for bivalves, sustainability claims will remain contested. Such guidance could be developed through frameworks such as the EU's Product Environmental Footprint [107]. Without it, robust comparisons both across bivalve systems and against fed aquaculture or terrestrial livestock will remain limited. Overall, this divergence reflects two fundamentally different accounting approaches. One treats shell formation as a potential carbon sink. The other accounts for CO_2 release and carbonate system dynamics. This limits comparability across studies and introduces substantial uncertainty in evaluating the climate mitigation potential of bivalve aquaculture.

Several lessons emerge from this synthesis. First, functional units should move beyond simple “per kilogram LW” metrics and shift toward protein- or nutrition-based references. This approach has been advocated by [108] and demonstrated in comparative studies by [43] and a more recent study applying nutritional LCA [109]. This shift better reflects the true function of food as a provider of nutrients and avoids systematic bias arising from differences in EW across species. Second, system boundaries should consistently extend beyond the farming stage. They should include post-harvest processing, transport, and shell end-of-life, which together may account for more than half of total burdens in some cases [42, 93]. Third, allocation must be treated transparently and sensitivity-tested. In line with EU PEFCR guidance [110], a hierarchy should be followed: (i) subdivision or system expansion (substitution), (ii) allocation based on underlying physical relationships (e.g., mass); and (iii) allocation based on underlying physical relationships (e.g., economic). Where applicable, cut-off approaches may also be applied depending on system definition, but these can produce different environmental profiles. In bivalve LCAs, allocation typically arises between edible tissue and shell (which contains most of the carbon and may be treated as waste, by-product, or carbon sink) but may also extend to ecosystem service credits such as nutrient removal. Without explicit justification, results remain difficult to interpret. Fourth, ecosystem services should be explicitly modeled. These include nutrient removal and the potential, but contested, carbon storage in shells. Results should be reported both with and without credits to enable fair cross-study comparison. Our synthesis showed that nutrient removal rarely translated into net eutrophication mitigation. Evidence for species-specific exceptions remains limited and uncertain. Therefore, transparent treatment of such services is essential to avoid misrepresentation. Fifth, while less prominent than climate and eutrophication, acidification impacts were moderate but variable across studies, likely linked to energy use and infrastructure, emphasizing the importance of decarbonizing fuel and electricity inputs. Finally, uncertainty and sensitivity analyses were considered where available. These included Monte Carlo simulations based on pedigree matrices [111] to assess parameter uncertainty, as well as scenario testing (e.g., alternative allocation methods or system boundary definitions) to evaluate methodological sensitivity [87]. These should become routine rather than exceptional, ensuring that results reflect both ecological variability and methodological uncertainty.

At the practical level, the synthesis shows that energy and materials remain the true hotspots across production contexts, often outweighing the benefits of ecosystem services. Electricity-intensive depuration, diesel-powered transport, and reliance on non-recyclable plastics consistently emerge as critical impact drivers. Realizing the sustainability potential of bivalve aquaculture requires more than accounting for ecosystem services like nutrient removal or shell carbon storage. It also requires a transformation of operational practices. Key priorities include decarbonizing energy inputs. For example, solar-powered hatcheries and depuration facilities can significantly lower carbon footprints [112, 113]. Hybrid systems combining solar and micro-wind power for farm equipment may provide further reductions. Strategic vessel logistics, including optimized fuel use and energy-efficient handling, further reduce emissions. Addressing material hotspots is equally critical. Emerging alternatives, such as biodegradable gear and natural fiber-based ropes and trays made from cellulose, hemp, and biocomposite polymers, are gaining attention as sustainable substitutes for conventional aquaculture materials. These offer promising replacements for single-use high-density polyethene gear and are supported by reviews of low-trophic aquaculture material sustainability [114, 115]. Furthermore, valorization of shell waste offers climate and ecosystem dividends if rigorously incorporated into life cycle models [116]. Crushed seashells can be used in cementitious materials as sustainable aggregate substitutes, reducing demand for high-emission construction inputs [117]. Shells also serve as substrate for reef restoration, enhancing coastal resilience, biodiversity, sediment capture, and carbon burial [118, 119]. Collectively, these operational innovations not only lower energy and material burdens but also embed bivalve aquaculture within broader transitions toward resource-efficient and resilient food production. They also create a foundation for positioning bivalve aquaculture within broader, multifunctional marine systems.

Beyond standalone production, bivalve farming can be integrated into broader sustainability strategies such as IMTA and multi-use coastal or offshore platforms. In IMTA systems, bivalves recycle waste nutrients from fed species, reducing eutrophication risks while providing food and potential feed ingredients [4, 120, 121]. However, despite decades of research and pilot trials, IMTA has not yet achieved commercial success at scale, reflecting technical, economic, and regulatory barriers. Multi-use platforms further embed aquaculture within marine spatial planning, combining food production with renewable energy or restoration initiatives to enhance biodiversity and sediment capture [29, 122–124]. Bivalve farming may also generate cultural and recreational benefits [125–127]. However, these functions are not directly linked to nutrient cycling processes and therefore do not contribute to eutrophication mitigation. Instead, they represent broader ecosystem and socio-economic benefits operating through indirect pathways, including biodiversity enhancement and spatial co-use [128, 129]. Consequently, only systems explicitly designed for nutrient recovery, such as IMTA, contribute directly to nutrient capture through biomass uptake and harvest [130, 131]. However, the magnitude of this effect is often limited relative to total nutrient emissions, and full nutrient neutrality is rarely achieved in practice, as highlighted by recent system-level assessments [132].

At the global level, however, this review highlights critical geographic blind spots. The predominance of European case studies means current evidence provides partial coverage of production realities in Asia, Africa, and Latin America. These regions dominate global output but differ in farming intensity, energy infrastructure, seed sourcing, and supply chain logistics. Global spatial analyses identify high restorative aquaculture potential across Oceania, parts of Asia, and North America, yet these contexts remain underrepresented in existing LCA datasets [133]. Methodological reviews similarly noted that outside Europe, shellfish LCAs are sparse, especially for non-mussel species and small-scale, low-intensity systems [44, 103]. While this imbalance inevitably constrains the global generalizability of current findings, it does not diminish the value of the synthesis presented here. Instead, it highlights a clear opportunity: regionally diverse LCAs, built on harmonized protocols for carbon and nutrient flux accounting. Such studies would strengthen the evidence base and support a more robust assessment of the role of bivalve aquaculture in low-carbon, resource-efficient food systems.

This study has several limitations that point directly to priorities for future research. Despite harmonizing functional units in this meta-analysis, inconsistent treatment of background processes across studies. This included differences in whether hatchery operations, gear manufacturing, transport, and processing were included, resulting in wide variation in reported outcomes. Additional limitations include databases and language constraints. Although Web of Science, Scopus, and Google Scholar were searched, relevant gray literature, non-English publications, and region-specific reports may not have been captured. Restricting the review to English may have excluded important case studies from major producing countries such as China, Japan, Korea, and Chile, raising the risk of language and publication bias. Although results were standardized to one t LW at the farm gate, this cannot fully harmonize inconsistencies such as the treatment of hatchery operations, gear production, or shell carbon. Converting seed-based results to harvest-level impacts also required yield assumptions that vary across species and production contexts, introducing additional uncertainty.

Statistical analyses introduced further constraints. Regression models were limited by small sample sizes in some categories and potential correlations among predictor variables (e.g., software, allocation, and method choices). In addition, some observations were derived from the same studies and may therefore not be fully independent, which should be considered when interpreting regression patterns. Meta-analysis revealed high heterogeneity across impact categories. I^2 values were approximately 90% for CC and 85% for eutrophication. This indicates substantial between-study variability and limits the generalizability of pooled estimates. Moreover, the use of log-transformed impact values assumes some comparability across LCAs. This assumption may not always be valid because studies differed in system boundaries, allocation approaches, and functional units. Ecosystem services were coded in a binary manner (yes/no for biocalcification), which simplifies reporting but may overlook nuances such as partial credits or temporary storage. Finally, the dataset is time-bound, covering studies published only up to August 2025, and may quickly become outdated as new LCAs, particularly those addressing blue carbon, emerge.

For these reasons, the synthesis should not be interpreted as providing a single definitive estimate of bivalve aquaculture's impacts. Rather, its value lies in mapping the range of reported outcomes, highlighting species-level differences, and identifying methodological drivers of divergence. Future research should therefore prioritize standardized system boundaries, transparent accounting of carbon and nutrient fluxes, and broader geographic coverage beyond Europe to better reflect the realities of global aquaculture.

5 | Conclusion

In conclusion, bivalve aquaculture generally carries lower environmental burdens than many animal protein systems. It also provides ecosystem services such as nutrient removal and potential carbon sequestration, though the role of shell carbon storage remains contested. Our meta-analysis indicates that variation in reported outcomes arises from both species-specific differences and methodological choices. These include system boundaries, multifunctionality treatment, and biogenic carbon accounting. Together, these findings highlight the need for harmonized LCA protocols that explicitly account for ecosystem services. Without such standardization, sustainability claims will remain contested and cross-system comparisons unreliable.

A comprehensive environmental assessment also requires consistent inclusion of all life-cycle stages. While most studies account for direct farm-level emissions and energy use, upstream and downstream processes are not consistently represented. These include hatchery inputs, gear production, transport, processing, and shell end-of-life. As a result, total environmental impacts may be systematically underestimated.

Beyond methodology improvement, the role of bivalve aquaculture in climate-smart food systems depends on operational transformation. Key priorities include decarbonizing energy inputs, reducing plastic reliance, optimizing logistics, and valorizing shell by-products through durable pathways. These measures would support circular economy and low-carbon transitions while reducing dependence on contested ecosystem service credits such as shell carbon sequestration or nutrient removal offsets.

Critically, the evidence base remains geographically narrow, with European case studies dominating despite Asia's production dominance and emerging potential in Africa and Latin America. Addressing this imbalance through regionally diverse and standardized assessments is essential for globally robust conclusions and equitable policy frameworks. Given the growing importance of aquaculture within the EU Green Deal, Farm to Fork Strategy, and the UN Food Systems Summit agenda, improving the accounting of carbon and nutrient fluxes in bivalve farming is both a scientific and policy priority. It is also essential for future integration into sustainability certification and carbon accounting schemes. Taken together, these insights position bivalve aquaculture as a promising pathway for more sustainable food systems. However, realizing this potential will depend on methodological clarity, broader geographic representation, and continued operational innovation. Persistent eutrophication burdens must also be addressed alongside climate-related benefits.

Author Contributions

Sujita Pandey: methodology, software, data curation, investigation, validation, formal analysis, visualization, writing – review and editing. **Daniel Taylor:** writing – review and editing, validation, supervision. **Mausam Budhathoki:** conceptualization, methodology, software, data curation, investigation, validation, formal analysis, visualization, project administration, writing – original draft, writing – review and editing. **Marianne Thomsen:** conceptualization, funding acquisition, resources, writing – review and editing, validation, methodology. **Manali Chakraborty:** data curation, investigation, writing – review and editing. **Per Dolmer:** validation, supervision, writing – review and editing. **Stephanie Horn:** conceptualization, data curation, investigation, writing – review and editing. **Richard Newton:** validation, supervision, writing – review and editing.

Funding

This work was supported by the EU Horizon Europe project Offshore Low-trophic Aquaculture in Multi-Use Scenario Realization (OLAMUR, Project ID 101094065); the WIN@Sea project funded by the Velux Foundation (grant no. 00037712) and by the Danish Agricultural and Fisheries Agency under the Grønt Program Fisk og Akvakultur DK [Project No. GPOFA-24-0009], titled Climate Impact of Danish Aquaculture (CLIDA).

Disclosure

The authors declare that no artificial intelligence tools were used in the preparation, analysis, or writing of this manuscript.

Ethics Statement

The authors have nothing to report. This study is a systematic review and meta-analysis based on previously published data; no new animal or human subjects were involved.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All data generated or analyzed in this study are available within the manuscript and its Supporting Information.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Study Information:** Data extraction framework and compiled dataset from life cycle assessment studies of bivalve aquaculture. The Supplementary Appendix contains an Excel spreadsheet summarizing study characteristics, methodological choices, environmental impact results, ecosystem service considerations, and data transparency information extracted from the 31 LCA studies included in the systematic review and meta-analysis.