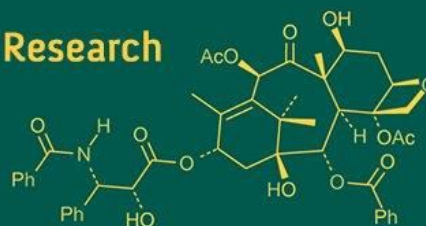


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Carbon footprint in aquaculture and mitigation strategies

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Abstract

Aquaculture has emerged as the fastest-growing food production sector globally and plays a critical role in meeting future protein demand. Alongside its benefits for food and nutritional security, concerns have grown regarding its contribution to climate change through greenhouse gas (GHG) emissions. Although aquaculture generally exhibits a lower carbon footprint than many terrestrial livestock systems, emissions vary widely depending on species, culture system, feed composition, energy use, and management practices. This article synthesizes research published from 2015 onward to examine the sources of carbon emissions in aquaculture and evaluate mitigation strategies capable of reducing its climate impact. Emphasis is placed on life cycle assessment (LCA) studies, species- and system-level comparisons, technological innovations, and policy-relevant interventions. The review highlights that feed production, on-farm energy use, and pond emissions are the primary contributors to aquaculture-related GHGs, while mitigation pathways such as feed reformulation, Integrated multi-trophic aquaculture (IMTA), renewable energy adoption, and expansion of low-trophic farming (bivalves and seaweed) offer substantial opportunities for emission reduction. Strengthening measurement frameworks and supporting farmer-level adoption are essential for transitioning toward climate-resilient and low-carbon aquaculture systems.

Keywords: Aquaculture, carbon footprint, greenhouse gas emissions, life cycle assessment, mitigation strategies, climate change

Introduction

Aquaculture has become an indispensable component of global food systems, supplying more than half of the aquatic food consumed worldwide (FAO, 2020) ^[10]. This sector now accounts for 52% of aquatic animal products consumed worldwide, meeting increasing demands for seafood amidst static or declining wild fish stocks (Jones *et al.*, 2022; Verma *et al.*, 2025) ^[16, 25]. Mariculture, specifically, generates 37.5% of total aquaculture production and nearly all of the world's seaweed harvest (Jones *et al.*, 2022) ^[16].

The global food system accounts for approximately one-quarter of all greenhouse gas (GHG) emissions. Agriculture, a significant component of this system, emits potent greenhouse gases such as methane (CH₄) and nitrous oxide (N₂O), which exacerbate atmospheric warming (Syed salim & Mustapa, 2025) ^[22]. Aquaculture products generally exhibit lower GHG emission footprints compared to terrestrial livestock farming (Jones *et al.*, 2022) ^[16]. For instance, aquaculture species typically showed 63% lower methane emission intensity per unit of animal protein when compared to major protein-producing livestock (Dong *et al.*, 2022; MacLeod *et al.*, 2020) ^[7, 17]. This relative advantage positions aquaculture as a potentially more climate-friendly protein source.

Rapid expansion of aquaculture has been driven by declining capture fisheries, population growth, and increased demand for affordable animal protein (FAO, 2022) ^[9]. While aquaculture is often promoted as an environmentally efficient alternative to terrestrial livestock production, the sector is not climate-neutral (Poore & Nemecek, 2018) ^[20]. The growing scale and intensification of aquaculture operations have raised concerns regarding their contribution to greenhouse gas (GHG) emissions, particularly carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) (MacLeod *et al.*, 2020) ^[17].

Climate change poses a dual challenge for aquaculture. On one hand, aquaculture activities contribute to climate change through emissions arising from feed production, energy use,

land-use change, and farm management (MacLeod *et al.*, 2020; Parker *et al.*, 2018) ^[17, 18]. On the other hand, aquaculture systems are highly vulnerable to climate impacts such as rising temperatures, ocean acidification, extreme weather events, and altered disease dynamics (De León Pérez *et al.*, 2025) ^[15].

Carbon footprint in Aquaculture

The carbon footprint denotes the overall greenhouse gas emissions resulting from an activity, product, or system. This includes carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O), which are identified for their distinct global warming potentials (Verma *et al.*, 2025; Hu *et al.*, 2012) ^[25, 15].

These energy-intensive processes which involve running water pumps, aerators, and other machinery to ensure water quality and movement; producing and transporting feed; and processing and refrigerating aquaculture products (MacLeod *et al.*, 2020) ^[17]. Additionally, emissions are generated from the production and transportation of artificial feed, water quality treatment, water level management, and the processing of aquatic products, which release gases such as carbon dioxide and methane (Tang *et al.*, 2022) ^[23].

Understanding the carbon footprint of aquaculture is crucial for mitigation and enhancing the sector's long-term sustainability and resilience (FAO, 2020) ^[10]. Quantifying these emissions through life cycle assessment (LCA) has revealed substantial variability across species, production systems, and regions, indicating that mitigation strategies must be context-specific rather than uniform (Bohnes *et al.*, 2018; Henriksson *et al.*, 2015) ^[3, 13]. This review synthesizes recent literature to identify major GHG emission sources in aquaculture, compare emissions across species and systems, and highlight effective mitigation strategies (Bohnes *et al.*, 2018; Verma *et al.*, 2025) ^[3, 25].

Over the past decade, a growing body of research has employed life cycle assessment (LCA) to quantify the carbon footprint of aquaculture products and identify emission hotspots (Bohnes *et al.*, 2018) ^[3]. These studies reveal substantial variability across species, production systems, and regions, indicating that mitigation strategies must be context-specific rather than uniform (Henriksson *et al.*, 2015) ^[13]. This article reviews scientific literature published from 2015 onward to (i) identify major sources of GHG emissions in aquaculture, (ii) compare emissions across species and farming systems, and (iii) synthesize mitigation strategies with demonstrated or potential effectiveness.

Major Sources of Greenhouse Gas Emissions in Aquaculture

Feed production

Feed production is consistently identified as the largest contributor to GHG emissions in fed aquaculture systems, often accounting for 50-80% of total life-cycle emissions. Emissions arise from crop cultivation (fertilizer use, soil emissions), land-use change, processing, and transportation of feed ingredients. Fishmeal and fish oil, traditionally derived from wild capture fisheries, contribute significantly due to fuel use in fishing and processing, although their relative impact has declined with reduced inclusion rates in modern feeds.

Plant-based ingredients such as soybean meal and maize introduce emissions linked to land-use change and deforestation in some regions. Consequently, improving feed conversion ratios (FCR) and optimizing ingredient composition are critical levers for reducing the carbon footprint of aquaculture.

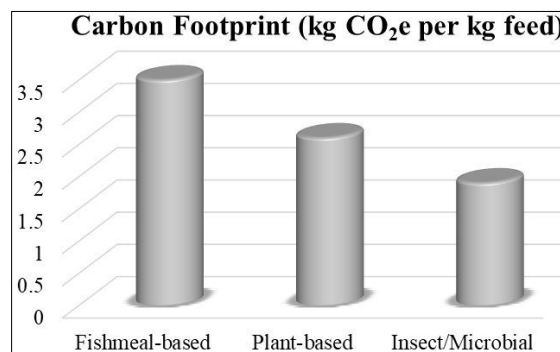


Fig 1: Comparing the carbon footprint of conventional and alternative aquafeed ingredients. Replacing fishmeal and soybean meal with insect meal or microbial proteins can reduce feed-related emissions by 30-50% (Henriksson *et al.*, 2018; Ghamkhar *et al.*, 2021) ^[14, 11]

On-farm energy use

Energy consumption is a major emission source in intensive aquaculture systems, particularly recirculating aquaculture systems (RAS), shrimp farms, and highly aerated ponds. Electricity and fuel are used for water pumping, aeration, temperature control, and feed distribution. The carbon intensity of energy use depends heavily on the local energy mix, with fossil fuel-based grids resulting in higher emissions compared to renewable-powered systems.

Fei Fan *et al.* (2024) ^[8] found that high-energy systems (RAS, intensive tanks, offshore vessels) show footprints where energy use is the main driver; e.g. on one aquaculture vessel, aquaculture pumps alone caused around 51% of life-cycle emissions and approximately 78% of equipment-related emissions.

Pond and sediment emissions

Sediments in aquaculture ponds are primary sites for CH₄ production and important modifiers of N₂O and CO₂ exchange. Earthen ponds used in freshwater and brackish-water aquaculture can emit methane and nitrous oxide due to anaerobic decomposition of organic matter in sediments. In freshwater fish ponds, CH₄ ebullition from sediments dominates total CH₄ flux (median ~80-85% of emissions), far exceeding diffusion through the water column (Vroom *et al.*, 2023) ^[26]. These emissions are influenced by stocking density, feed input, water exchange, and sediment management practices. Although pond emissions may represent a smaller proportion of total emissions compared to feed, they can be significant in extensive and semi-intensive systems.

Sediments in aquaculture ponds are primary sites for CH₄ production and important modifiers of N₂O and CO₂ exchange. Ebullition, drainage events, and sediment management practices largely determine sediment-driven GHG emissions, so accurate footprints and effective mitigation both require explicit sediment-focused measurement and management (Deng *et al.*, 2024) ^[6].

Processing and transportation

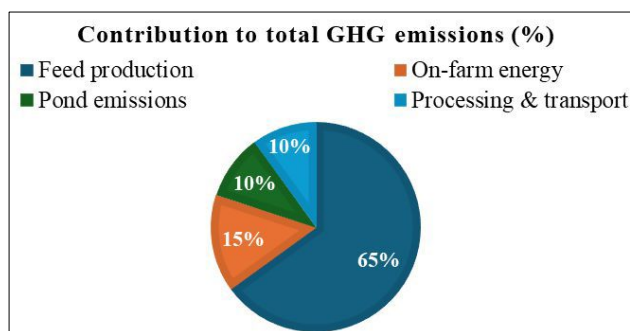


Fig 2: Shows the average contribution of major emission sources in aquaculture systems, compiled from global life cycle assessment studies (Bohnes *et al.*, 2018; MacLeod *et al.*, 2020) [3, 17].

Post-harvest activities, including processing, cold storage, and transportation, contribute additional emissions, particularly for export-oriented aquaculture products transported over long distances. While generally smaller than feed-related emissions, supply-chain emissions can become substantial when air freight or inefficient cold chains are involved.

Carbon Footprint Across Species and Production Systems

Carbon footprints vary widely among aquaculture species and systems. Carnivorous finfish such as salmon typically exhibit moderate to high emissions due to high-protein feeds and energy use, although efficient FCRs can partially offset these impacts. Shrimp farming often shows relatively high emissions per kilogram of product, especially in intensive systems with high energy inputs and feed use.

In contrast, omnivorous species such as tilapia, carp, and catfish generally display lower carbon footprints, particularly in semi-intensive or extensive systems that rely partly on natural productivity. However, poor management and low productivity can increase emissions per unit output. Bivalve molluscs (e.g., mussels, oysters) and seaweeds represent the lowest-carbon forms of aquaculture. These species require no external feed and can provide ecosystem services such as nutrient removal. Seaweed farming has attracted particular interest for its potential role in carbon sequestration, although the permanence and accounting of sequestered carbon remain debated.

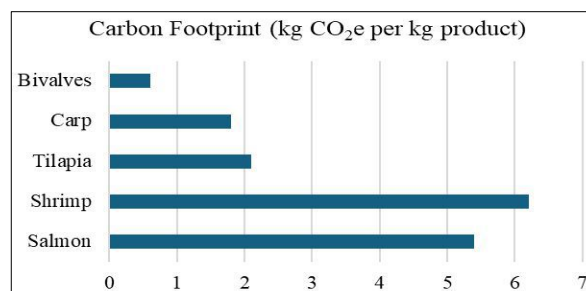


Fig 3: Compares the carbon footprint of selected aquaculture species. Values represent typical ranges reported in LCA studies (Henriksson *et al.*, 2018; MacLeod *et al.*, 2020; FAO, 2020) [14, 17, 10].

Methodological Approaches to Carbon Footprint Assessment

Life cycle assessment (LCA) is the most widely used methodology for quantifying GHG emissions from aquaculture systems (ISO, 2006; MacLeod *et al.*, 2020) [17]. LCAs typically follow ISO 14040 and 14044 standards and assess emissions across multiple stages of production, including feed ingredient production, feed processing, hatchery operations, grow-out farming, harvesting, processing, and transportation (ISO, 2006). Results are commonly expressed as kilograms of CO₂-equivalent (kg CO₂e) per kilogram of live weight or edible product (Bohnes *et al.*, 2018) [3].

Despite methodological standardization, considerable variability exists among LCA studies due to differences in system boundaries (cradle-to-farm-gate vs. cradle-to-consumer), allocation methods for co-products, emission factors, and data quality (Henriksson *et al.*, 2012) [12]. For example, the treatment of fishmeal and fish oil co-products or land-use change emissions associated with soybean cultivation can significantly influence reported footprints (Parker *et al.*, 2018) [18]. Additionally, emissions from pond sediments, particularly methane and nitrous oxide, remain poorly quantified and are often excluded or estimated using limited empirical data (Hu *et al.*, 2012) [15].

Recent studies emphasize the need for harmonized LCA frameworks and region-specific emission factors to improve comparability and policy relevance (MacLeod *et al.*, 2020) [17]. Advances in modelling and field measurements are gradually addressing these limitations, but uncertainties remain a persistent challenge in carbon footprint assessment of aquaculture (Bohnes *et al.*, 2018) [3].

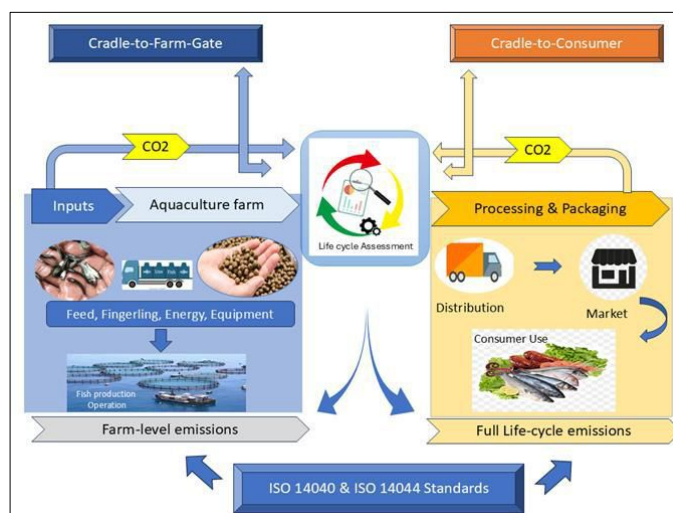


Fig 4. LCA approaches with system boundaries in Aquaculture systems

Table 1: Summary of LCA-Based Carbon Footprint Estimates

System/Species	Carbon Footprint (kg CO ₂ e/kg)	Key Driver	References
Salmon (intensive)	5.0-6.0	High-protein feed, energy use	Henriksson <i>et al.</i> , 2018 ^[14]
Shrimp (intensive)	5.5-7.0	Feed + aeration energy	MacLeod <i>et al.</i> , 2020 ^[17]
Tilapia (semi-intensive)	1.8-2.5	Feed production	FAO, 2020 ^[10]
Carp (extensive)	1.2-2.0	Low external inputs	Bohnes <i>et al.</i> , 2018 ^[3]
Bivalves/Seaweed	<1.0	No feed input	Pessarrodona <i>et al.</i> , 2024 ^[19]
IMTA systems	20-35% reduction	Nutrient recycling	Troell <i>et al.</i> , 2017 ^[24]

Mitigation Strategies for Reducing Carbon Footprint
Feed optimization and alternative ingredients

Improving FCR through better feed formulations, feeding practices, and genetic improvement of cultured species offers the most immediate and cost-effective mitigation potential (MacLeod *et al.*, 2020) ^[17]. Replacing high-impact ingredients with lower-carbon alternatives, including insect meal, microbial single-cell protein, algae-based ingredients, and agricultural by-products, can further reduce emissions (Troell *et al.*, 2014; FAO, 2020) ^[24, 10]. For instance, Tignani, M. V., & Parisi, G. (2025). found that compare to traditional fish meal-based feed (FM-f), PBM-F (Poultry by-product feed), TM-f (*Tenebrio molitor*- mealworm) meal feed and HI-f (*Hermetia illucens*-black soldier fly) meal feed showed 66%, 33% and 29% reduction in CO₂ e emissions in the LCA study for gilt head sea bream (*Sparus aurata*).

Integrated Multi-Trophic Aquaculture (IMTA)

IMTA combines fed species with extractive species such as bivalves and seaweeds to improve nutrient utilization and reduce waste (Troell *et al.*, 2017) ^[24]. By converting dissolved and particulate nutrients into additional biomass, IMTA can lower system-level emissions and enhance overall resource efficiency (Bohnes *et al.*, 2018) ^[3].

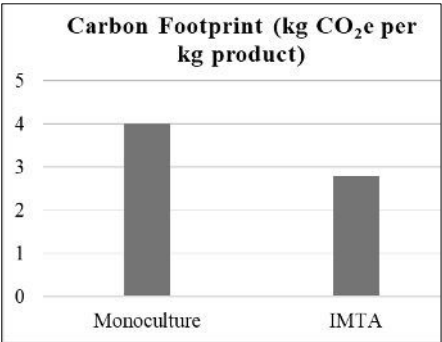


Fig 5: The mitigation potential of Integrated Multi-Trophic Aquaculture (IMTA). LCA studies indicate that integrating extractive species such as bivalves and seaweeds can reduce system-level emissions by approximately 25-35% through improved nutrient utilization (Troell *et al.*, 2017; Bohnes *et al.*, 2018) ^[24, 3].

Expansion of low-trophic aquaculture

Scaling up bivalve and seaweed farming can contribute to climate mitigation by providing low-emission food and potential carbon sequestration benefits (FAO, 2020) ^[10]. Seaweed-derived products such as biochar, bioplastics, and feed additives are being explored for their additional climate benefits.

Energy efficiency and renewable energy

Transitioning to renewable energy sources and improving energy efficiency can significantly reduce emissions from

energy-intensive aquaculture systems. Solar-powered aeration, energy-efficient pumps, and optimized system design are increasingly viable options, particularly in tropical regions (FAO, 2020) ^[10].

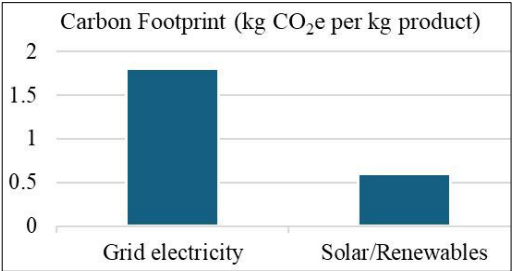


Fig 6: The effect of renewable energy adoption on aquaculture carbon footprints. Transitioning to solar or other renewable sources can reduce energy-related emissions by up to 60-70%, particularly in intensive systems such as RAS and aerated ponds (MacLeod *et al.*, 2020; FAO, 2020) ^[17, 10].

Improved pond and farm management

Management practices that reduce organic matter accumulation, optimize aeration, and enhance water quality can lower methane and nitrous oxide emissions from ponds. These practices often yield productivity and health benefits alongside emission reductions

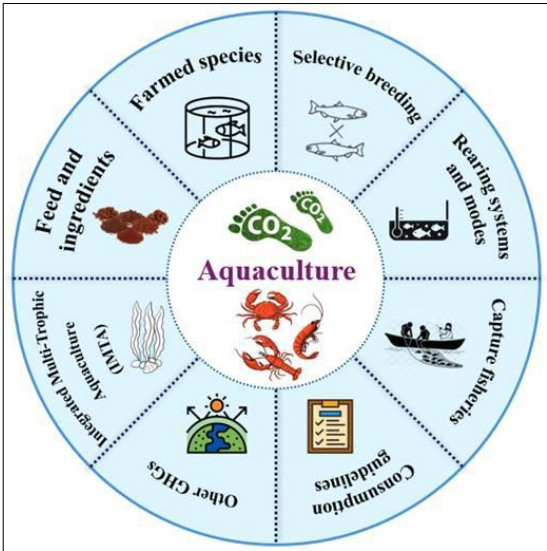


Fig 7: Promising intervention sectors for reducing carbon emissions in aquaculture closely associated with operational activities (on-farm) and strategies (off-farm).

Policy Implications and Research Gaps

Effective mitigation requires supportive policies, including incentives for low-carbon feeds, renewable energy adoption, and certification schemes that recognize climate performance. Major research gaps remain in quantifying pond emissions, standardizing LCA methodologies, and

assessing socioeconomic barriers to adoption of mitigation practices by small-scale farmers.

Conclusion

Aquaculture has the potential to play a significant role in sustainable and climate-resilient food systems. While its carbon footprint is generally lower than that of terrestrial livestock, targeted mitigation strategies are essential to minimize emissions as the sector continues to expand. Feed optimization, low-trophic aquaculture, IMTA, and renewable energy adoption emerge as key pathways toward low-carbon aquaculture. Continued research, harmonized assessment frameworks, and farmer-centered policies will be critical to achieving meaningful emission reductions.

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