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Review Paper

Low-Carbon and Environmentally Sustainable Aquaculture in Coastal Ecosystems: A Systematic Literature Review

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Abstract

Low-carbon aquaculture is increasingly recognized as a vital strategy to mitigate climate change, improve resource efficiency, and ensure sustainable food production. This systematic review, following the PRISMA 2020 protocol, analyzed 58 peer-reviewed studies selected from 312 published between 2020-2024, providing a transparent and replicable synthesis of the current evidence. Research is predominantly focused in Asia and Europe, regions where rapid aquaculture growth coincides with emerging climate policies. Key strategies for reducing environmental impacts include Integrated Multi-Trophic Aquaculture (IMTA), cultivation of low-trophic species such as seaweeds and filter feeders, and the restoration of coastal ecosystems, all of which enhance carbon sequestration, nutrient cycling, and ecosystem resilience. The review identifies the most commonly reported sustainability indicators as global warming potential (GWP), energy consumption, land use, nutrient loading, and eutrophication. Despite ongoing technological innovations, global aquaculture remains largely unsustainable with persistently low environmental performance. Barriers to improvement include incomplete carbon accounting, fragmented regulatory frameworks, and limited consumer awareness. Additionally, significant knowledge gaps in greenhouse gas emissions and carbon sequestration constrain robust life cycle assessments. Transitioning to low-carbon aquaculture requires not only technological innovation but also with stronger governance, ecosystem-based management, and integrated policy frameworks to enhance sustainability and climate resilience. This review underscores the urgency of coordinated action across research, industry, and policy sectors to optimize low-carbon strategies, address existing knowledge gaps, and support the development of sustainable aquaculture systems that are both environmentally responsible and economically viable.

Keywords

Low-Carbon Aquaculture, Integrated Multi-Trophic Aquaculture, Coastal Ecosystem Restoration, Sustainability Indicators, Climate Resilience

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1. INTRODUCTION

Aquaculture serves as an important solution to worldwide food security needs while supporting economic development in Asian countries. The sector has emerged as one of the fastest expanding industries within the global food market. The sector produces more than 57 percent of all farmed fish worldwide. The primary function of aquaculture exists to protect worldwide food security needs especially in coastal areas that depend on marine resources for their economic survival (Food and Agriculture Organization of the United Nations, 2024), but faces mounting challenges regarding environmental sustainability. However, its environmental footprint greenhouse gas (GHG) emissions, nutrient loading, and habitat alteration has prompted a shift towards low-carbon, environmentally sustainable approaches (Zhang et al., 2024a). Low-carbon aquaculture combines climate-smart techniques which reduce emissions while maintaining operational efficiency. The study combines current global research and scientific discoveries with ScienceDirect research from 2020 to 2024 to evaluate various strategies and obstacles while identifying new possibilities, which provides data-driven guidance to policymakers and industry stakeholders. The environmental impacts increase because of the excessive dependence on fish-based feed and fossil fuel energy use, combined with inadequate waste management practices.

The increasing public awareness of climate change calls for the immediate development of aquaculture systems that produce low carbon emissions while maintaining productivity. This study aims to reduce environmental damage through the implementation of Recirculating Aquaculture Systems (RAS) (Tchonkouang et al., 2024; Tom et al., 2021), Integrated Multi-Trophic Aquaculture (IMTA) (Bennett et al., 2023; Cutajar et al., 2022), the use of renewable energy (Bashir et al., 2022; Kurniawan et al., 2022) and alternative feeds derived from microalgae and various marine by-products that have significant potential to enhance or support circular aquaculture (Ahmed and Turchini, 2021; Kurniawan et al., 2022). The operationalization of low-carbon aquaculture systems faces significant challenges due to high start-up costs, technological limitations, and existing funding constraints (Ahmed and Turchini, 2021; Saikia, 2024). The purpose of this review is to examine recent developments in low-carbon aquaculture systems, identify key technologies that support this transition, and evaluate the challenges and future opportunities.

This study systematically reviews recent advancements in low-carbon aquaculture technologies and their integration with sustainability indicators and governance frameworks. It aims to understand how innovations such as RAS, IMTA, and coastal ecosystem restoration can contribute to reducing aquaculture's carbon footprint. Despite the potensial of these technologies, various challenges related to energy demand, cost, and scalability persist, which this study seeks to explore.

2. EXPRIMENTAL SECTION

2.1 Materials

The review focused exclusively on primary research articles from ScienceDirect that studied everything published between 2020 and 2024. It specifically examined coastal aquaculture systems and the application of low-carbon strategies within these systems. Only peer-reviewed original research articles with sufficient methodological details were considered. Articles were included if they investigated low-carbon innovations within coastal aquaculture and provided measurable environmental performance outcomes. Exclusion criteria encompassed non-primary research (e.g., reviews, opinion pieces), studies unrelated to coastal ecosystems (e.g., freshwater or terrestrial ecosystems), and studies with insufficient methodological clarity or duplicate records.

2.2 Methods

This systematic review followed the PRISMA 2020 protocol (Page et al., 2021; Taslim et al., 2025) to ensure methodological transparency, replicability, and systematic reporting. A structured search was conducted using the ScienceDirect database with the keyword "low-carbon aquaculture", applied to titles, abstracts, and keywords to identify studies directly relevant to the topic. The search results were initially filtered according to inclusion and exclusion criteria. Studies were assessed based on relevance to coastal aquaculture systems and the application of low-carbon strategies.

The selection process involved the removal of duplicates, followed by screening of titles and abstracts to identify relevant studies. These studies were selected based on their relevance to low-carbon technologies, coastal aquaculture, and sustainability metrics. Criteria for inclusion and exclusion were clearly defined to ensure objectivity and minimize bias.

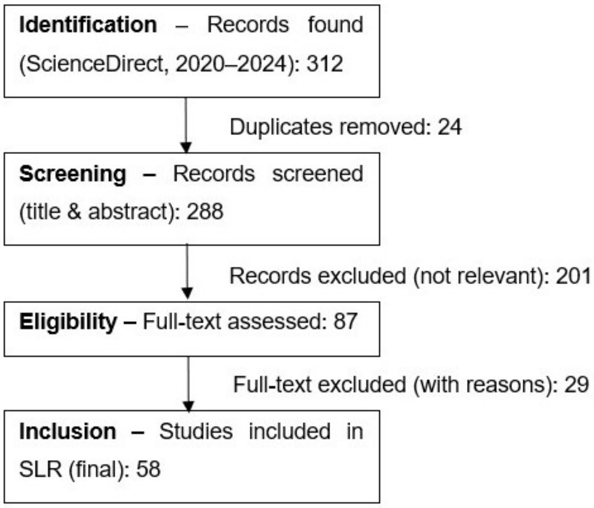

Figure 1. Selection Stage in PRISMA-Style Flow Diagram

3. RESULT AND DISCUSSION

3.1 PRISMA 2020 Review

Of the 312 records identified from ScienceDirect (2020–2024). After removing 24 duplicates, leaving 288 records for title and abstract screening, from which 201 were excluded due to irrelevance. A total of 87 full-text articles were assessed for eligibility, of which 29 were excluded for specific reasons: 12 were not substantially focused on low-carbon aquaculture or life cycle assessment, 11 were unrelated to coastal ecosystems (addressing freshwater or terrestrial contexts), 4 were non-primary research such as opinion pieces or overviews without empirical data, and 2 lacked sufficient methodological details or full access (Table 1). Ultimately, 58 studies were included in the systematic literature review, ensuring a rigorously filtered and contextually relevant evidence base (Figure 1). Information collected included cultured species (e.g., fish, shellfish, seaweed), farming systems (e.g., RAS, IMTA, open systems), geographic distribution, implemented low-carbon strategies (e.g., renewable energy use, carbon offset practices), environmental performance indicators (e.g., carbon footprint, resource use efficiency), and key outcomes (e.g., emission reductions, increased efficiency). This data established an exact and clear framework for documenting the effectiveness of low-carbon aquaculture methods.

The distribution of citations across the 8 sections of the review (Figure 2). The largest portion comes from the discussion on feed and resource use, reflecting its central role in aquaculture sustainability. Trends and geographic

Table 1. PRISMA 2020 Flow Diagram Summary for ScienceDirect (2020–2024): Low-Carbon Aquaculture

Selection Stage	n
Identification - Records found (ScienceDirect, 2020-2024)	312
Duplicates removed	24
Records after duplicates removed	288
Screening - Records screened (title & abstract)	288
Records excluded (not relevant)	201
Eligibility - Full-text assessed	87
Full-text excluded (with reasons)	29
Inclusion - Studies included in SLR (final)	58
Reason for Full-Text Exclusion	**n**
Not substantially about low-carbon / LCA	12
Not related to coastal ecosystems (e.g., freshwater/terrestrial)	11
Not primary research (opinion/review without data)	4
Inadequate methodological data / full access unavailable	2

focus, as well as aquaculture's environmental challenges, also account for substantial citation shares, underscoring their importance in framing the research landscape. Meanwhile, topics such as low-carbon aquaculture, carbon emissions, energy efficiency, and waste management each contribute smaller but significant portions, highlighting their relevance to specific sustainability dimensions. Overall, the figure indicates a balanced yet weighted emphasis, with resource efficiency and regional dynamics receiving the most citations, while technical and policy aspects complement the broader discussion.

3.2 Trends and Geographic Focus

Research on low-carbon aquaculture has shown steady growth, particularly in Asia (Indonesia, China, Vietnam) and Europe, regions with both high aquaculture production and evolving climate policies (Ahmed and Turchini, 2021). The studies highlight the importance of conserving marine resources, protecting vulnerable species and habitats, and addressing major challenges such as overfishing, habitat degradation, pollution, and climate change (Lotze, 2021). IMTA emerges as an efficient and eco-friendly strategy, recycling by-products to reduce ecosystem pressure while enhancing cultural diversity and economic value (Nissar et al., 2023). The practice of cultivating low-trophic species, including seaweeds and filter feeders provides climate change mitigation benefits through its positive effects on nutrient cycling and carbon storage and marine ecosystem service strength (Riisager-Simonsen et al., 2022). The restoration of degraded coastal ecosystems through the transformation of abandoned aquaculture sites into wetlands demonstrates successful methods for increasing blue carbon sequestration and reducing climate change effects. The study demonstrates that ecosystem-based methods provide an effective solution for environmental impact reduction and sustainable development in aquaculture operations (Chen et al., 2023).

3.3 Carbon Reduction Strategies

3.3.1 Recirculating Aquaculture Systems (RAS)

Low-carbon aquaculture focuses on reducing carbon emissions throughout production, including feed, energy use, and waste management. The adoption of renewable energy sources, such as solar panels and biogas, significantly reduces the overall carbon footprint of farm operations. In modern practices, RAS play a pivotal role by recycling water, thereby conserving freshwater resources, and minimizing effluent discharge. The systems achieve lower environmental impacts because they decline nutrient and pollutant discharge which protects coastal ecosystems more effectively than traditional aquaculture methods do (Liu et al., 2023; Soares et al., 2024). RAS technology suffers from multiple problems, because its operational expenses become excessive due to energy needs, sludge disposal methods, and nutrient treatment systems (Ende et al., 2024; Tom et al., 2021). The water conservation, land efficiency, emission reduction, and production sustainability benefits of RAS make it a valuable system. Addressing its cost and waste management constraints will be crusial for broader global adoption and long-term effectiveness (Tian et al., 2024).

3.3.2 Integrated Multi-Trophic Aquaculture (IMTA)

Polyculture, particularly through IMTA, combines fed species such as fish with extractive species like seaweed and shellfish to form a symbiotic production system. This approach enhances nutrient recycling while providing carbon sequestration benefits through seaweed biomass. IMTA has been shown to reduce the carbon load from aquaculture facilities by 40–50%, while also lowering nitrogen and phosphorus discharges, thus supporting overall environmental sustainability (Camelo-Guarin et al., 2021; Zoli et al., 2023). The implementation of IMTA has succeeded in establishing itself as an effective method for water management in coastal regions throughout China and Japan and Canada and Chile and Italy and Norway because the system functions effectively

Table 2. The Key Findings Related to Carbon Reduction Potential, Energy Demand, Economic Feasibility, and the Challenges Faced by These Technologies Across Different Regions

Region	Technology	Carbon Reduction Potential	Energy Demand	Economic Feasibility	Key Sustainability Indicators
Asia (e.g., China, Indonesia)	Integrated Multi-Trophic Aquaculture (IMTA)	Moderate (enhanced carbon sequestration through seaweed and shellfish)	Medium–high (requires energy for multiple species)	High (resource use optimization, but capital-intensive)	Carbon footprint, resource use efficiency, nutrient cycling
Europe (e.g., Norway, Spain)	Recirculating Aquaculture Systems (RAS)	High (up to 40% reduction in emissions)	Very high (energy-intensive)	Medium (capital intensive but high output)	GWP, energy consumption, water use, fish health
North America	Integrated Multi-Trophic Aquaculture (IMTA)	High (coastal ecosystem integration enhances sequestration)	Low (natural filtration reduces energy needs)	Medium (economically feasible with proper policies)	Carbon storage, eutrophication reduction, biodiversity enhancement
South America	Mixed (RAS, IMTA)	Low to moderate (limited by technology adoption)	High (energy constraints in rural areas)	Low (limited access to renewable energy and investment)	Carbon emissions, energy consumption, waste treatment efficiency

Note: This table is compiled from various reference sources.

in open-water environments that experience hydrodynamic changes (Riisager-Simonsen et al., 2022). By integrating species from different trophic levels, IMTA optimizes nutrient uptake, utilizes waste as resources, which creates ecosystems that have better biodiversity and critical system strength (Rosa et al., 2020; Sutherland and Armbrecht, 2024). In addition, IMTA provides ecological advantages which protect the environment while generating economic benefits through its capacity to decrease eutrophication and improve habitat services. The implementation of IMTA in aquaculture systems generates higher nutrient recycling rates together with environmental benefits which create a sustainable pathway for the industry when compared to traditional polyculture systems (Biswas et al., 2020; Sánchez-Jerez et al., 2022).

3.3.3 Low-Carbon Feed Innovations

Feed production is major contributors to aquaculture's greenhouse gas emissions. Improving the efficiency of fish feed, a key factor in the environmental impact of the industry, can significantly reduce aquaculture's carbon footprint (Briones-Hidrovo et al., 2023). Incorporating by-products from the plant or animal food industry, such as molasses and plant meals, offers a cost effective sources of carbohydrate for initial growth stages and supports maintain the C:N ratio, contributing to lower carbon emissions (Nisar et al., 2022). Biofloc technology (BFT) enhances waste management and nutrient retention, reducing reliance on artificial diets and contributing to more sustainable aquaculture practices (Flefil et al., 2022; Saidin et al., 2025). Innovations in low-carbon can potentially improve fish growth rates by optimizing feed efficiency. Studies have shown that growth rates, as indicated by thermal growth coefficient (TGC), were high across various treatments, suggesting that low-carbon feeds do not negatively affect growth performance (Krogdahl et al., 2020). However, other factors such as high CO_2 levels can impair digestion and metabolism, leading to reduced growth rates. This indicates that while low-carbon feeds may be beneficial, environmental factors also play a crucial role in fish growth (Das et al., 2023). This highlights that feed efficiency must be considered in tandem with environmental conditions.

The maintenance of feed quality shows its vital importance because substandard feed formulations lead to decreased growth rates and lower disease defense capabilities and various metabolic health issues (Li et al., 2024). The transition toward low-carbon feeds aligns with broader national and global decarbonization efforts. Scottish-caught pelagic fish have been identified as a low-carbon food source contributing to sustainability targets (Sandison et al., 2021). Since feed production accounts for a substantial share of the environmental impact of marine fish farming, optimizing feed technology is essential to reduce aquaculture's carbon emissions (Bohnes and Laurent, 2021). In summary, low-carbon feed strategies including by-product utilization, biofloc systems, and optimized formulations can enhance fish growth and health while reducing emissions. Nevertheless, their success depends on maintaining high feed quality and managing external factors such as CO_2 levels, ensuring both ecological and economic sustainability.

3.3.4 Renewable Energy in Aquaculture

Renewable energy integration offers aquaculture a promising strategy to reduce its carbon footprint. Sources such as wind and solar power can supply energy for diverse applications, including desalination in freshwater aquaculture and powering Recirculating Aquaculture Systems (RAS) (Zhang et al., 2023). Co-locating aquaculture with offshore renewable energy installations further amplifies sustainability, with wind power showing a greater reduction in carbon footprint compared to photovoltaic systems. Evidence highlights that renewable energy adoption can lead to substantial emission reductions. For example, wind energy has been shown to cut life cycle carbon emissions by up to 93.9%, while photovoltaic electricity achieves reductions of about 87.9% (Frohlich et al., 2023; Yang et al., 2024). Moreover, incorporating renewable energy, improving larval survival, and using sustainable materials can collectively reduce aquaculture-related emissions by 10–30%, making oyster farming a scalable, low-emission protein source (Sun et al., 2025).

Additional innovations include small-scale wave energy devices designed for low-power offshore operations, as well as RAS systems that can directly utilize renewable energy inputs such as wind and wave power to minimize environmental impacts (Ahmed and Turchini, 2021). Aquaculture products powered using renewable energy can also be marketed as more sustainable, potentially increasing consumer appeal and market value (Garavelli et al., 2022). Renewable energy technologies especially wind, solar, and wave power offer aquaculture significant opportunities to reduce greenhouse gas emissions, improve sustainability, and strengthen economic competitiveness. By integrating renewable energy with advanced farming systems like RAS, the industry can advance toward low-carbon production models that align with global climate goals.

3.3.5 Waste Management Technologies

The aquaculture industry produces waste materials that contain high levels of organic substances and nitrogen and phosphorus and organic carbon nutrients which cause eutrophication when waste remains untreated. The Traditional management systems including physicochemical treatments and constructed wetlands for waste treatment require high energy consumption while delivering limited effectiveness according to research by Sun et al. (2020). Modern waste management technologies emphasize recycling and resource recovery. Approaches such as biofloc technology, seaweed co-culture, and anaerobic digestion transform waste into valuable products while minimizing environmental impact. For instance The combination of seaweed and shellfish into farming operations promotes biofiltration because these extractive species take up dissolved nutrients and solid particles which results in cleaner water and extra products that marketable outputs. Anaerobic digestion of aquaculture waste can yield biogas for on-farm energy needs and organic fertilizers for agriculture, promoting a circular production model. Macroalgae and filter-feeding organisms also function as natural biofilters, mitigating pollution by removing inorganic nutrients and particulate waste from the water (Kouhgardi et al., 2023). A practical example is provided a land-based fish farm that plans to build a biogas unit that converts wastewater sludge and fish residues into renewable energy. This project also includes a mobile wastewater treatment system, designed to optimize resource recovery while advancing environmental sustainability (Kiviranta et al., 2020). These insights highlight the value of adopting innovative, low-carbon waste management technologies in aquaculture to enhance sustainability and mitigate environmental impact.

3.3.6 Role of Coastal Ecosystems in Sustainable Aquaculture

Dubuc et al. (2024), reported that coastal ecosystems are particularly vulnerable to deteriorating conditions from increasing anthropogenic activities, including aquaculture. Seaweed farms contribute to CO_2 sequestration through photosynthesis, though their potential is constrained by short life cycles and the need for extensive cultivation areas (Visch et al., 2020). In contrast, vegetated coastal ecosystems such as mangroves, saltmarshes, and seagrass meadows function as efficient carbon sinks, sequestering carbon at rates 30–50 times faster than terrestrial forests and storing it for millennial timescales (Merk et al., 2022; Palacios et al., 2021). According to Chen et al. (2023), restoration initiatives will convert abandoned aquaculture sites into wetlands areas enhance blue carbon sequestration while supporting biodiversity and ecosystem resilience.

The concept of coastal blue carbon (CBC) underscores the role of mangroves, saltmarshes, and seagrasses in long-term carbon storage, although their permanence is increasingly threatened by pollution, coastal development, and deforestation (Ruseva et al., 2020). Sustainable aquaculture ponds can also potential as carbon sinks year-round, offering a balance between production and environmental stewardship (Gou et al., 2024; Wang et al., 2024). Moreover, regional drivers such as salinity influence carbon capture dynamics, highlighting the importance of location-specific strategies for example, mussel farming tailored to local conditions can strengthen carbon mitigation outcomes (Vaher et al., 2024). Beyond carbon sequestration, coastal ecosystems provide vital services including filtration, detoxification, and habitat provision. Integrating lower-trophic aquaculture species within these ecosystems can reduce negative impacts and improve overall ecosystem health (Lavaud et al., 2023). As, such, coastal ecosystems are integral to sustainable aquaculture, offering significant carbon sequestration benefits and supporting ecological restoration efforts. The adoption of sustainable practices and effective policies can further strengthen their role in reducing carbon emissions and promoting environmental health.

3.3.7 Carbon Capture in Aquaculture

Carbon capture in aquaculture offers innovative solutions to mitigate these environmental impacts through biological, chemical, and physical approaches. One of the most effec-

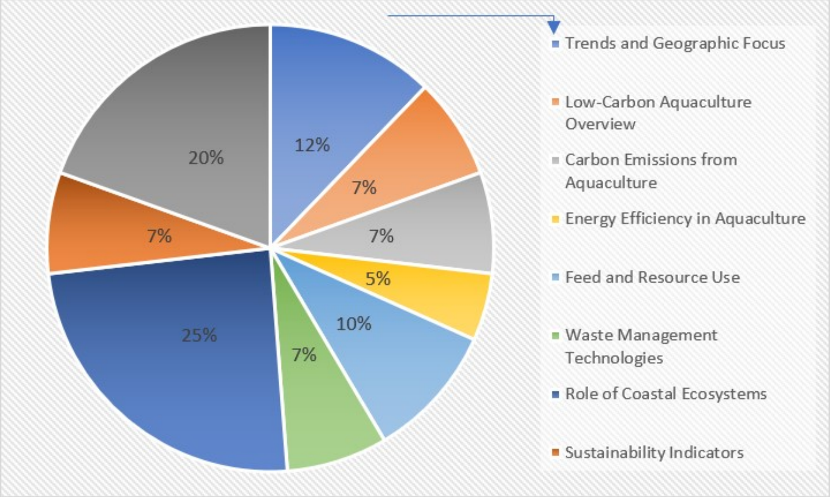

Figure 2. Literature Distribution Across Thematic Sections

tive natural methods is bio-sequestration, in which aquatic organisms such as seaweed and shellfish act as active carbon absorbers (Edwards et al., 2024). Seaweed, for example, can absorb CO_2 up to 20 times more efficiently than terrestrial plants through photosynthesis, while shellfish shells store carbon in the form of stable calcium carbonate ($CaCO_3$). IMTA system leverages the symbiosis between fish, shellfish, and seaweed to absorb nutrients and carbon in an integrated manner, reducing organic waste that could break down into greenhouse gases (Cutajar et al., 2022).

Beyond natural approaches, technology for converting aquaculture waste into carbon storage materials is also advancing. For example, pond sludge can be processed through pyrolysis into biochar, a form of biochar that can store carbon in the soil for hundreds of years while enhancing soil fertility (Elkhlifi et al., 2023). Other organic waste can be fermented in anaerobic bioreactors to produce biogas, which not only reduces methane emissions but also provides a renewable energy source for aquaculture operations. On the other hand, innovations such as microalgae photobioreactors in RAS enable efficient absorption of dissolved CO_2 from water, while the resulting microalgae can be utilised as high-nutrient feed. Restoration of coastal ecosystems such as mangroves and seagrass beds is also an integral part of carbon capture strategies in aquaculture (Palacios et al., 2021). These ecosystems not only absorb carbon in their biomass but also store it in seabed sediments that can persist for thousands of years. The combination of modern technology and nature-based solutions positions aquaculture as a sector with significant potential to achieve net-zero emissions in the future (Algozeeb et al., 2022). With the right policy support, investment in research, and large-scale adoption, carbon capture in aquaculture will not only reduce environmental footprints but also open new economic opportunities, such as carbon credit trading and high-value derivative products like biofuels and sustainable feed materials.

3.4 Environmental Sustainability Indicators

Aquaculture's environmental sustainability is assessed through various indicators, including Global Warming Potential (GWP), energy consumption, land use, Net Primary Product Use (NPPU), and eutrophication. Despite innovations and management practices, global aquaculture remains largely unsustainable, with significant challenges in resource use and environmental impact. Global aquaculture has a low average sustainability stand at 26 out of 100, indicating poor sustainability practices across most countries (Briones-Hidrovo et al., 2023; Jiang et al., 2022). Energy consumption is one of the most important sustainability metrics, as aquaculture systems often require substantial energy inputs to operate water pumping, aeration, feed production, and transport. Optimizing energy use is essential to reduce operational costs and environmental impact. Likewise, the monitoring and reduction of greenhouse gas emissions including CO_2, CH_4, and N_2O are crucial steps toward achieving low-carbon aquaculture (Jiang et al., 2022). Environmental Sustainability Indicators (ESIs) also provide a framework for evaluating nutrient disposal in aquaculture effluents, which are major contributors to eutrophication. The ESIs track nitrogen and phosphorus discharge to help identify management strategies which will enhance nutrient efficiency and protect the environment (de Godoy et al., 2022). Aquaculture environmental impacts decrease when operators use management approaches that combine resource efficiency with profit generation and environmental sustainability.

3.5 Barriers and Gaps

Significant uncertainties remain in quantifying carbon sequestration and greenhouse gas (GHG) emissions in aquaculture ponds, limiting accurate assessment of their climate impact according to Zhang et al. (2024b). Beyond technical gaps, social and behavioral barriers also hinder advancement of low-carbon aquaculture. Encouraging consumers to adopt low-carbon aquaculture products is challenging, paralleling the slow uptake of organic farming and reduced meat consumption. These products are often perceived as elitist or premium, restricting widespread acceptance (van den Burg et al., 2022). Public perceptions vary across regions and demographics: rural communities may express stronger support with fewer environmental concerns, while urban populations tend to be more critical (Kraly et al., 2022; Schultz et al., 2024). Within communities, opinions are divided: some value aquaculture for its economic contributions, while others remain skeptical of its ecological impacts (Bjørkan and Eilertsen, 2020). Additionally, unplanned and poorly managed aquaculture expansion can further degrade ecosystems, underscoring the need for integrated policies and climate adaptation strategies to safeguard food security and nutrition (Monsalve and Quiroga, 2022).

Effective governance frameworks are essential. Key regulatory instruments include licensing, environmental standards, biosecurity measures, zoning, and spatial planning. Raja et al. (2024), explains that regular reviews ensure adaptability to evolving technologies and environmental changes. The worldwide industrial expansion needs to adopt sustainable methods because environmental violations will result in trade restrictions that stop international business operations (Pringle et al., 2017). Addressing both technical knowledge gaps and policy-regulatory barriers is essential for accelerating the shift toward low-carbon aquaculture. Integrating renewable energy, improving waste management, and promoting sustainable feed and species selection can significantly reduce environmental impacts.Public perception, governance, and regional contexts must be considered to ensure equitable and effective adoption. By tackling these multidimensional challenges, aquaculture can transition toward sustainable pathways that balance economic growth with ecological integrity.

3.6 Key Findings

The review identified several key technologies aimed at reducing carbon emissions in aquaculture systems. RAS and IMTA are effective systems because they recycle water while decreasing energy usage and improving nutrient distribution. The environmental benefits of these systems were noted in several studies which showed decreases in both global warming potential and eutrophication. The systems achieve emission control yet they still have operational disadvantages. RAS systems need significant energy resources to sustain water movement and oxygen distribution which results in carbon reduction benefits being diminished when energy comes from non-renewable sources (Rasool and Hashmi, 2025; Kousik and Samykano, 2025). IMTA systems provide carbon capture advantages through their seaweed and shellfish components yet they still need to solve their problems with energy requirements and execution across extensive industrial operations (Skifa et al., 2025).

3.7 Comparative Synthesis and Regional Variability

A critical comparison of the studies revealed significant regional variability in performance and adoption of low-carbon technologies. In Asian and European regions which possess advanced aquaculture systems and effective governmental regulations, RAS and IMTA technologies experienced higher adoption rates while achieving better results through carbon reduction and resource efficiency (Badiola et al., 2017). The systems encountered difficulties in South America and Africa because these regions experience slow technological growth while their aquaculture industry continues to grow. The study provides a comparative table which enables researchers to evaluate the performance of different technologies across various regions while showing essential sustainability metrics, including carbon emissions, energy usage, and financial sustainability (Table 2).

3.8 Challenges and Governance Issues

The ongoing governance obstacles continue to exist despite all existing technological advancements. The regional absence of standardized regulations for low-carbon aquaculture technologies creates barriers which prevent their complete adoption. Europe has established complete carbon-reduction targets with financial incentives for renewable energy deployment in aquaculture while Asian countries produce disjointed national and regional policies which restrict technology development. The implementation of IMTA and other technologies depends on multiple stakeholders working together but their collaboration needs effective governance systems to succeed. Norway's dedication to offshore aquaculture and Indonesia's mangrove restoration efforts demonstrates how particular regional contexts create useful governance and policy development insights. The implementation of renewable energy subsidies together with carbon accounting standards and ecosystem restoration support functions as a solution that directs the development of sustainable low-carbon aquaculture systems through specific policy recommendations.

Governance Issues is needed to create an environment conducive to technological innovation, while directing it towards achieving multidimensional sustainability goals. Governance Issues design policies promote technical decarbonization and actively manage socio-environmental trade-offs and maximize synergies, such as how renewable energy can simultaneously improve energy security and create jobs. Institutional capacity to collect data, monitor indicators and inclusively engage stakeholders is a fundamental prerequisite for the success of this integrated framework in guiding a sustainable and equitable transition.

4. CONCLUSIONS

Low-carbon aquaculture technologies such as RAS and IMTA have demonstrated significant potential to reduce the environmental footprint of aquaculture systems, yet their adoption is still limited by challenges such as energy demand, cost, and scalability. This review highlights the need for more comprehensive governance frameworks that can support technology adoption while addressing regional variability. Further research should focus on the trade-offs associated with these technologies, including energy consumption and economic feasibility in diverse aquaculture settings. The establishment of region-specific policy examples together with standardized carbon accounting methods serves as an essential requirement for organizations which want to implement these systems on a worldwide basis. The advancement of low-carbon aquaculture depends on organizations developing new technologies while establishing governance systems and implementing policies that support regional partnerships to create food production systems which can withstand climate change while remaining sustainable.

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