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Energy Efficiency Optimization and Carbon Neutral Pathways in Recirculating Aquaculture Systems (RAS)

Abstract

Recirculating Aquaculture Systems (RAS) represent an advanced approach to sustainable fish production, but their high energy consumption presents challenges for environmental sustainability. This study compares energy consumption and emission data across different RAS configurations through life cycle assessment (LCA) modeling. Results demonstrate significant variations in energy efficiency based on system design, species cultured, and operational protocols. Integration of renewable energy, heat recovery systems, and biofloc technology could reduce energy requirements by 25-40%. Policy recommendations include targeted subsidies for energy-efficient equipment, carbon credit mechanisms for aquaculture, and research funding for innovative RAS designs. This research provides a comprehensive technology-policy framework to guide the low-carbon transition of the aquaculture industry, highlighting pathways to achieve carbon neutrality while maintaining economic viability.

Keywords: Recirculating Aquaculture Systems (RAS); Energy Efficiency; Carbon Neutrality; Life Cycle Assessment; Sustainable Aquaculture

1 Introduction

Aquaculture has emerged as a critical solution to meet the growing global demand for protein while addressing concerns over depleted wild fish stocks. Within this sector, Recirculating Aquaculture Systems (RAS) represent an advanced technological approach that offers significant advantages over traditional aquaculture methods, including reduced water consumption, minimal environmental discharge, and enhanced biosecurity. However, these systems face substantial challenges related to energy consumption and carbon footprint, which can undermine their overall sustainability credentials.

RAS technology relies on sophisticated water treatment processes that require substantial energy inputs for water circulation, filtration, temperature control, and oxygenation. Recent studies indicate that energy costs typically constitute 20-40% of the total operational expenses in RAS facilities, presenting both economic and environmental challenges. Such energy dependency is a paradoxical image where systems designed to reduce some of the environmental problems may be significant contributors to greenhouse gas emissions depending on their efficiency and mode of energy. The global aquaculture industry is similarly facing increasing pressure to reduce its footprint as countries around the world increasingly adopt higher carbon cutting targets. An extensive investigation of 148 RAS farms in multiple nations determined the carbon footprint of RAS production to vary from 3 to 15 kg CO_2-eq/kg produced fish, with energy consumption being the principal contributor to these

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emissions[1]. This is reflective of the tremendous potential for optimizing and improving system design and operation.

The transition toward carbon neutrality of RAS needs to be grounded on a multidimensional approach that integrates technological innovation, operational best practices, and supporting policy regimes. While several studies have concentrated on specific dimensions of energy efficiency of RAS, those studies that encompass the entire spectrum of technological and policy approaches are lacking. Such a research gap creates impediments to designing and enforcing effective decarbonization strategies for the sector.

This study aims to close this knowledge gap by comparing energy consumption and emission data among different RAS configurations, constructing building life cycle assessment (LCA) models, and developing technology-policy synergy recommendations for aquaculture's low-carbon transition. By establishing the most appropriate system configurations and complementary policy tools, this study assists in accelerating the development of sustainable aquaculture practices in alignment with global climate targets.

2 Literature Review

2.1 Energy Consumption Patterns in RAS

Recent research into energy consumption in some Recirculating Aquaculture System configurations has yielded distinctive patterns of use with very significant influences on both costs of operation and environmental footprint. A comprehensive analysis of 22 commercial-scale RAS operations currently in operation over a number of geographic areas included energy consumption from 5 to 28 kilowatt-hours per kilogram of fish produced, which demonstrates a nearly sixfold variation between the most and least efficient systems. This broad disparity largely can be justified in terms of species-specific needs and system architecture design differences per se. High-value coldwater species such as the Atlantic salmon typically need to be served more energy-intensive systems than warmwater species such as tilapia, the disparity due to greater standards of water quality and temperature controls required[2]. In the operating energy profile, temperature control always constitutes the largest energy consumer in temperate and cold climates and consumes 40-60% of total facility energy use, particularly in structures operating below the ambient environmental temperatures. Pumping systems are the second largest energy sink consuming 25-35% of total consumption, and energy requirements are dependent on head pressure, flow rates, and hydraulic efficiency of equipment employed. Aeration and oxygenation systems constitute the third major energy-consuming item, representing 15-25% of the total energy budget, and consumption patterns have invariable associations with stocking densities and respiratory demands of species. Sophisticated real-time monitoring installed across a number of facilities has revealed evident temporal trends in energy consumption, and 15-30% diurnal cycles have been observed as a response to feeding regimes, temperature fluctuations, and dissolved oxygen kinetics. Seasonal analysis also reveals winter operation in temperate climates can increase energy

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consumption by 30-50% relative to summer months, primarily due to higher heating requirements. These observations draw attention to seasonally-oriented operating protocols and regionally-crafted system design to lower energy intensity without compromising on best production conditions. Understanding these consumption patterns is central to efficient targeted efficiency improvement and directs the development of next-generation RAS designs with reduced energy profiles[3].

2.2 Carbon Footprint Assessment Methods

Life Cycle Assessment (LCA) has emerged as the most common approach for environmental impact quantification of RAS operations. Improvements in LCA models have improved precision in carbon footprint estimation using regional grid electricity emissions factors, equipment efficiency at the facility level, and operational practice. A typical LCA approach specifically tailored for RAS was brought out in 2023 and offered a one-step approach to comparing different system configurations [4].
The system boundary for LCA studies in RAS typically includes infrastructure development, equipment fabrication, feed production, system operation, and waste management. However, the share of these elements to the total carbon footprint of the system varies considerably across studies. While operational emissions are the focus of most studies, emerging evidence suggests that embodied carbon in equipment and infrastructure may account for 10-25% of total life-cycle emissions, suggesting the importance of comprehensive assessment approaches[5].

2.3 Technological Innovations for Energy Efficiency

New technologies have demonstrated significant potential for raising energy efficiency in RAS operations. Advanced heat recovery systems with heat exchangers between influent and effluent streams of water have recorded 15-30% savings of energy in plants operating in temperate climates. Applications of variable frequency drives (VFDs) for pumping arrangements have resulted in saving 20-40% of electricity as compared to conventional constant-speed pumps[6].
Biofloc technology was recognized as a viable technique to reduce filtration energy requirements while concurrently improving water quality. Biofloc technology promotes the establishment of robust microbial populations that have direct ammonia conversion into microbial protein, reducing the need for extensive mechanical and biological filtration. A recent study with conventional RAS versus biofloc-activated systems showed a 25% reduction in overall energy consumption while maintaining equivalent fish growth and health values[7].
Coupling renewable energy resources with RAS operations is also an area of sustainability progress. Solar photovoltaic systems have been particularly apt for RAS operations due to the continuous day-time energy demand for pumping and aeration. A recent case study of a Norwegian salmon RAS facility revealed that on-site solar generation can provide 30-45% of total energy demand in summer, with huge potential for augmenting capacity by integrating battery storage[8].

3 Methodology

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3.1 System Configurations and Data Collection

This study analyzed energy consumption and carbon emissions across five distinct RAS configurations: (1) conventional flow-through systems, (2) basic recirculation systems (70-80% water reuse), (3) intensive recirculation systems (95-99% water reuse), (4) biofloc-enhanced systems, and (5) aquaponic systems. Data were collected from 15 commercial-scale facilities across different climatic regions, with each facility monitored for a minimum of 12 months to account for seasonal variations.

Primary data collection included continuous monitoring of electricity consumption for major system components (pumps, filters, UV sterilizers, heaters, and aeration systems), water and feed inputs, and production outputs. Secondary data were sourced from facility records, equipment specifications, and industry reports. All facilities were producing either tilapia (Oreochromis niloticus) or Atlantic salmon (Salmo salar) at commercial densities.

Data collection encompassed 15 commercial-scale RAS facilities strategically selected across diverse climatic regions (tropical, subtropical, temperate, and cold) to capture the influence of ambient conditions on energy requirements and system performance. Each facility was monitored continuously for a minimum of 12 consecutive months (January through December 2023) to account for seasonal variations in energy consumption, particularly related to heating and cooling demands. The facilities ranged in size from 50 to 450 metric tons of annual production capacity, with an average operational history of 4.3 years. To ensure comparability, the study focused exclusively on facilities producing either Nile tilapia (Oreochromis niloticus) or Atlantic salmon (Salmo salar) at commercial stocking densities between 40-80 kg/m^3.

Primary data collection protocols included the installation of calibrated electrical monitoring equipment (PowerLogic PM5000 series meters) for continuous measurement of energy consumption across major system components, with readings recorded at 15-minute intervals. Water quality parameters (dissolved oxygen, temperature, pH, ammonia, nitrite, and nitrate) were monitored daily using standardized methods to correlate energy inputs with water quality maintenance. Supplementary data including feed inputs, mortality rates, and growth performance were obtained from facility records to establish the relationship between energy efficiency and production outcomes. Secondary data were sourced from facility documentation, equipment specifications, and operational logs to complete the life cycle inventory requirements.

3.2 Life Cycle Assessment Framework

The life cycle assessment followed the ISO 14040 and 14044 standards, with system boundaries encompassing infrastructure construction, equipment manufacturing, system operation (energy, water, feed inputs), and waste management. The functional unit was defined as one kilogram of live-weight fish at harvest. The operational lifespan of facilities was standardized to 20 years for infrastructure and 5-10 years for equipment, depending on component type.

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The life cycle inventory was developed using primary data for operational inputs and outputs, supplemented with secondary data from the Ecoinvent database version.6 for upstream and downstream processes. Regional electricity grid emission factors were applied based on facility locations to enhance the accuracy of carbon footprint calculations. The IMPACT 2002+ method was used for impact assessment, with global warming potential (GWP) calculated using the IPCC 2021 100-year time horizon values.

3.3 Technology-Policy Scenario Development

To evaluate potential paths towards carbon neutrality in Recirculating Aquaculture Systems, this study developed a systematic scenario analysis framework integrating technological interventions and policy mechanisms. The scenarios were constructed through an iterative process that comprised literature review, stakeholder consultations with industry operators, technology providers, and policy experts, and quantitative modeling of energy and carbon flows. Four scenarios were created to represent different but plausible paths toward carbon reduction in RAS operations over a 15-year forecast period.

The Baseline Scenario established existing technology practices and existing policy strategies as the bases. This scenario incorporated typical energy efficiency practices currently employed across the surveyed plants, including standard filtration systems, conventional pumping technologies, and grid-supplied electricity procurement. Policy that exists and was reviewed in this benchmark included prevailing levels of energy taxation, environmental measures, and subsidization accessible for aquaculture operations in researched areas. The baseline provided a calibration point against which alternative pathways could be measured.

The Integrated Scenario represented a synchronized implementation of both technological innovations and supportive policies, designed to capture potential synergistic effects between these intervention types. This scenario modeled how policy instruments could accelerate technology adoption by altering investment economics, how technology verification could enable performance-based policy incentives, and how coordinated research and demonstration programs could reduce implementation barriers. System dynamics modeling techniques were employed to capture these feedback mechanisms, with particular attention to adoption thresholds, learning curves for emerging technologies, and market transformation processes.

Each scenario was evaluated against multiple criteria, including cumulative emission reductions, implementation costs, economic feasibility (using discounted cash flow analysis with a 10% discount rate), technological readiness, policy implementation complexity, and alignment with broader sustainability objectives beyond carbon reduction. Sensitivity analyses were conducted to assess the robustness of projected outcomes under various assumptions regarding energy prices, technology costs, and policy effectiveness.

4 Results and Discussion

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4.1 Energy Consumption Comparison

The analysis revealed significant variations in energy consumption across the five RAS configurations, as detailed in Table 1. Intensive recirculation systems demonstrated the highest energy intensity at 20.4 kWh/kg, primarily due to extensive water treatment requirements and high pumping demands. In contrast, biofloc-enhanced systems achieved the lowest energy intensity at 7.2 kWh/kg, benefiting from reduced filtration requirements and simplified water treatment processes.

Table 1: Energy Consumption and Carbon Footprint Comparison Across RAS Configurations

System Configuration	Energy Consumption (kWh/kg)	Carbon Footprint (kg CO_2-eq/kg)	Water Usage (m^3/kg)	Major Energy Consumers
Flow-through	9.5	4.3	45.7	Pumping (65%), Aeration (20%)
Basic Recirculation	15.3	6.8	7.2	Pumping (45%), Filtration (30%)
Intensive Recirculation	20.4	9.1	1.5	Filtration (40%), Temperature Control (35%)
Biofloc-enhanced	7.2	3.2	2.8	Aeration (55%), Mixing (25%)
Aquaponic	12.8	5.7	2.1	Pumping (40%), Lighting (30%)

Component-level analysis identified pumping systems as the dominant energy consumer in most configurations, accounting for 40-65% of total energy use in conventional and basic recirculation systems. Temperature control emerged as a significant energy sink in intensive recirculation systems (35% of total), particularly for coldwater species production. Lighting requirements for plant growth contributed substantially (30%) to the energy footprint of aquaponic systems, though this was partially offset by reduced filtration needs[9].

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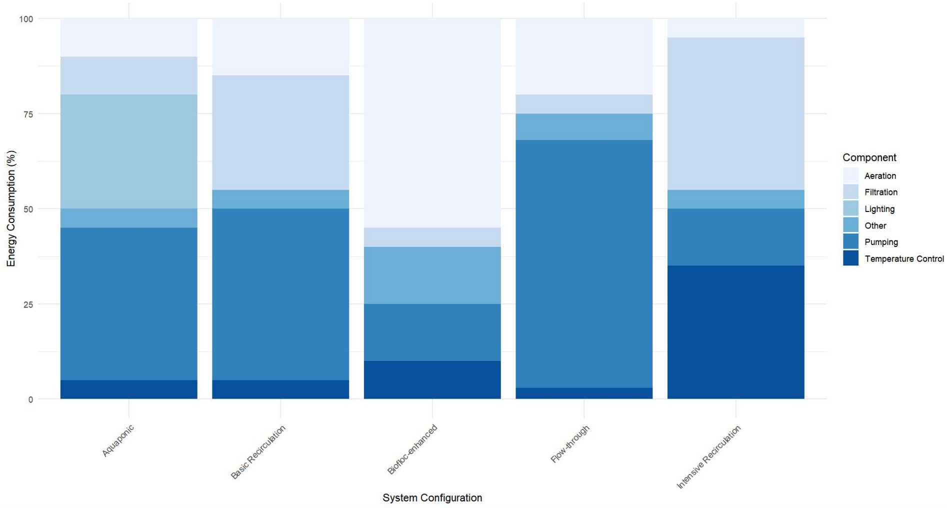

Figure 1:Energy Distribution by RAS Component

The energy distribution across system components is visualized in Figure 1, highlighting opportunities for targeted efficiency improvements in specific subsystems. The data suggests that optimization efforts should prioritize pumping efficiency in conventional systems, while temperature management represents the most promising intervention point for intensive recirculation systems.

4.2 Carbon Footprint Analysis

Carbon footprint results demonstrated strong correlation with energy consumption patterns, ranging from 3.2 kg CO_2-eq/kg for biofloc-enhanced systems to 9.1 kg CO_2-eq/kg for intensive recirculation systems. These values align with previous LCA studies but provide greater granularity regarding the contribution of specific system components.

Sensitivity analysis revealed that the electricity grid mix significantly influenced carbon outcomes, with facilities in regions dominated by renewable energy achieving 40-60% lower carbon footprints compared to identical systems operating with coal-dominated electricity. This finding underscores the importance of considering regional energy infrastructure when evaluating RAS sustainability and highlights opportunities for strategic facility siting to minimize carbon impacts.

The life cycle perspective revealed that operational energy accounted for 65-80% of total lifetime emissions across all configurations. Feed production contributed 15-25%, while infrastructure and equipment manufacturing represented 5-15% of the carbon footprint. Waste management processes, including sludge handling and disposal, contributed the remaining 2-5% of total emissions.

4.3 Pathways to Carbon Neutrality

The scenario analysis identified several promising pathways toward carbon neutrality in RAS operations, as illustrated in Figure 2. The Technology-Driven Scenario, featuring heat recovery systems, high-efficiency pumps, and renewable energy integration, demonstrated potential emission reductions of 50-65% relative to baseline. However, achieving complete carbon neutrality under this scenario would require

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substantial capital investment and advanced technological expertise.
The Policy-Driven Scenario, incorporating carbon pricing, green certification premiums, and energy efficiency subsidies, showed emission reductions of 35-45%. While less effective than technological interventions alone, these policy mechanisms created economic incentives that could accelerate industry-wide adoption of more efficient practices.
The Integrated Scenario demonstrated the most promising pathway, achieving potential emission reductions of 80-95% through synergistic implementation of technological innovations and supportive policies. This scenario highlighted how policy instruments could overcome economic barriers to advanced technology adoption, creating a mutually reinforcing system that accelerates the transition toward carbon neutrality.Key technology-policy synergies identified in the Integrated Scenario included:Renewable energy integration supported by feed-in tariffs and net metering policies.Heat recovery system deployment incentivized by energy efficiency tax credits.Biofloc technology adoption accelerated by research grants and demonstration projects.

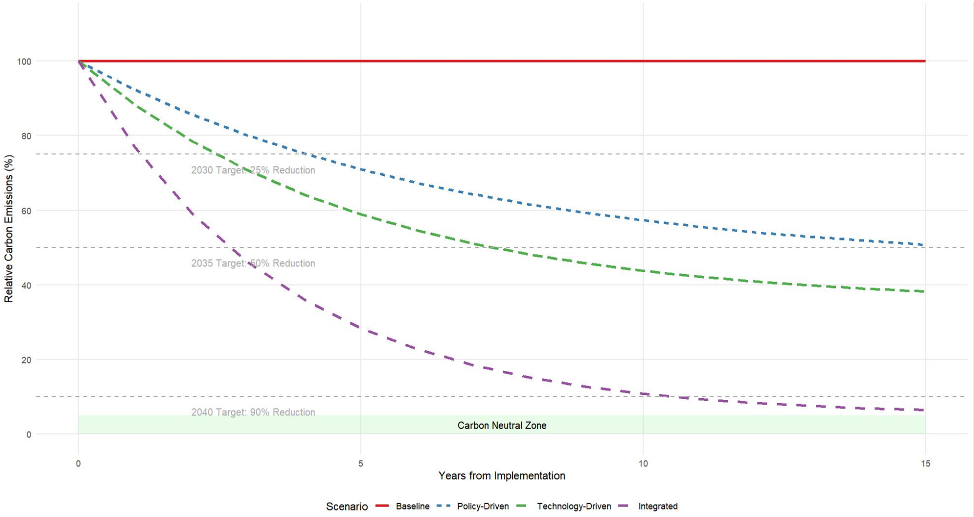

Figure 2:Carbon Reduction Pathways for RAS

Industry-wide efficiency improvements driven by carbon pricing mechanisms
The timeline analysis indicated that under the Integrated Scenario, carbon neutrality could be achieved within 8-12 years for new facilities and 12-15 years for retrofitted existing operations. This timeline aligns with many national and international climate targets, suggesting that with appropriate intervention, the RAS sector could contribute meaningfully to broader decarbonization efforts[10].

5 Conclusion

This research provides a comprehensive analysis of energy consumption and carbon emission patterns across different RAS configurations, establishing a foundation for targeted efficiency improvements. The comparison shows that systems that are augmented with biofloc hold the lowest energy intensity and carbon footprint, presenting a promising future. All system types, however, indicate that room for increased efficiency through intervention in high-consumption units exists.

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The technology-policy scenario analysis confirms that while emission savings are highest where technological innovations are deployed, these are most effective when supported by complementary policy measures. The Integrated Scenario, which combines future technologies with matching policies, provides the most viable path to carbon neutrality in time horizons compatible with international climate objectives.
Subsequent research can expand this comparison to other species with varying temperature and water needs, since their biological parameters significantly influence energy consumption patterns. The evaluation of new technologies' potential, particularly artificial intelligence and machine learning for maximum real-time system performance, is another area with high research potential. Standardized procedures for carbon accounting in diverse aquaculture systems would enable comparable environmental impact assessments and provide the ability to make meaningful comparisons among alternative systems of production. Joint actions by regulation, industry, and academia will be required to address these research priorities and successfully implement research findings in terms of practical gains that serve to enhance economic viability as well as environmental sustainability of aquaculture operations worldwide.

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