



Renewable Energy-Based Recirculating Aquaculture System to Improve Production Sustainability

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Abstract

Recirculating aquaculture systems (RAS) are widely recognized as water-efficient and environmentally sound production technologies; however, their substantial energy demand remains a primary barrier to large-scale deployment, particularly in developing economies. This study examines the integration of renewable energy sources, including solar photovoltaics (PV), wind turbines, hydrogen hybrid systems, and microalgae-based bioenergy, into RAS through a descriptive quantitative analysis of 31 peer-reviewed publications (2020–2024). Quantitative descriptive statistics were calculated for thematic distribution, annual publication frequency, and key system performance indicators: CO₂ emission reduction, operational cost savings, and water use efficiency. Results show that solar PV integration reduces CO₂ emissions by 45–65% and operational costs by 30–48%, while PV–electrolysis–hydrogen hybrid systems achieve up to 75% emission reduction. Circular economy integrations, biofloc technology, IMTA, aquaponics, and microalgae-mediated nutrient recycling, further enhance system sustainability with water savings of 85–98%. This study concludes that renewable energy-based RAS is technically and economically viable and recommends a phased integration strategy beginning with solar PV as the highest-priority first step toward genuinely sustainable global aquaculture.

Keywords: *Aquaculture; circular economy; Descriptive quantitative analysis; Recirculating aquaculture systems; Renewable energy*

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Introduction

Global aquaculture production has expanded rapidly over the past three decades and now supplies more than 57% of all fish consumed by humans, with production exceeding 122 million tonnes in 2020 (FAO, 2022). The sector is projected to continue growing as demand for animal protein increases from a global population estimated to reach 9.7 billion by 2050, making aquaculture a strategic pillar of global food security (FAO, 2024). This rapid production expansion, however, raises serious concerns about environmental sustainability, water resource depletion, and the long-term viability of intensive production systems. Conventional open-system (or flow-through) aquaculture releases nutrient-rich effluents into receiving water bodies, contributing to eutrophication, habitat degradation, and the spread of aquatic pathogens across ecosystems (Bostock et al., 2010; Deutsch et al., 2007). These environmental pressures drive the urgent need to develop more efficient and environmentally friendly production systems.

Recirculating aquaculture systems (RAS) were developed specifically to address these environmental challenges. By filtering, treating, and recirculating over 95% of the system's water in a closed loop, RAS dramatically reduces effluent discharge, land use, biosecurity risks, and sensitivity to



external climate fluctuations (Timmons & Ebeling, 2013; Verdegem et al., 2023). These advantages make RAS the most ecologically advanced commercial production technology available to the industry today. Core components of RAS include a biofilter for biological nitrification, a mechanical system (drum filter or sand filter) for suspended solids removal, aeration, and deoxygenation, and real-time monitoring of water quality parameters (Li et al., 2023; Preena et al., 2021). Despite these significant ecological advantages, RAS adoption remains hampered by two major barriers: high capital investment requirements and significant operational energy consumption. In countries with stable grid electricity infrastructure and developed financial markets, these barriers are manageable; However, in tropical regions and developing countries, where energy infrastructure is unreliable and access to capital for small- and medium-sized producers is limited, the application of RAS is still limited to large-capital commercial operations (Ahmed & Turchini, 2021; Pasch & Palm, 2021).

The intersection of renewable energy technologies and intensive aquaculture has emerged as a critical research frontier. Photovoltaic (PV) solar panels, wind turbines, and innovative hydrogen hybrid systems offer pathways to decouple RAS energy consumption from the fossil fuel grid, while simultaneously reducing operational costs and greenhouse gas emissions (Nguyen et al., 2020; Vo et al., 2021a; Yue & Shen, 2021). Parallel advances in circular bioeconomy models, especially biofloc technology (BFT), integrated multitrophic aquaculture (IMTA), aquaponics, and microalgae integration, further enhances system sustainability by closing nutrient and carbon loops and recovering energy from biological waste streams (Campanati et al., 2021; Zimmermann et al., 2023; Ende et al., 2024). The integration of renewable energy and circular economy principles within the RAS framework has the potential to produce a truly energy-independent and zero-waste production system.

Despite this growing evidence base, there has been no comprehensive descriptive quantitative synthesis that maps the temporal and thematic evolution of this interdisciplinary research landscape. Most existing reviews address renewable energy in aquaculture or circular economy models separately, without offering an integrated quantitative characterization of relative research emphasis, measurable performance outcomes, and barriers to adoption. This analytical gap hinders evidence-based prioritization by researchers, industry practitioners, and policymakers who need quantifiable performance benchmarks, not just a qualitative narrative, to justify investment and regulatory decisions.

This study fills this gap through a systematic descriptive quantitative analysis of 31 scientific publications published between 2020–2024, covering RAS technology convergence, renewable energy integration, and circular economy principles. The specific objectives are: (1) to map the thematic distribution of research across key subtopics using frequency and percentage statistics; (2) to identify temporal publication trends and their implications for research maturity; (3) to quantify and compare the quantitative performance benefits of different renewable energy configurations within RAS; (4) to evaluate the contribution of circular economy technologies to water and resource efficiency; and (5) to quantify and prioritize barriers to adoption. The findings are intended to provide actionable, data-driven guidance for aquaculture researchers, investors, and policymakers.

Methodology

This study employed a descriptive quantitative research design through a systematic literature review. The choice of a descriptive quantitative approach was based on the need to translate a heterogeneous body of primary research into comparable numerical metrics and thematic frequency distributions, enabling the identification of patterns and evidence-based comparisons across studies and technology types (Creswell & Creswell, 2018). This approach is consistent with established methodological frameworks in aquaculture technology synthesis (Li et al., 2023; Verdegem et al., 2023) and has been increasingly adopted in energy-environment integration research (Nguyen et al., 2020; Vo et al., 2021a).

2.1 Research Design

A descriptive quantitative approach quantifies the characteristics of a research field without testing causal hypotheses, but rather provides systematic frequency counts, percentage distributions, range statistics, and mean values across defined categories (Sugiyono, 2019). In this study, the research field is defined as the integration of renewable energy with RAS aquaculture under circular economy principles. The unit of analysis is peer-reviewed scientific journal articles. Quantitative descriptors are calculated for five analytical dimensions: (a) thematic distribution, (b) temporal publication trends, (c)

renewable energy performance metrics, (d) circular economy resource efficiency, and (e) prioritization of adoption barriers.

2.2 Literature Search and Selection

A systematic search was conducted in five databases: Scopus, Web of Science, ScienceDirect, Google Scholar, and PubMed, between June–October 2024. The search strings included: “recirculating aquaculture system”, “RAS”, “renewable energy aquaculture”, “solar photovoltaic aquaculture”, “wind energy RAS”, “hydrogen hybrid aquaculture”, “microalgae RAS”, “biofloc technology”, “integrated multitrophic aquaculture”, “aquaponics sustainability”, and “circular economy aquaculture”. The temporal scope was limited from January 2020 to December 2024.

Articles were included if they: (1) reported primary findings, systematic reviews, or meta-analyses on RAS combined with at least one renewable energy source or circular economy technology; (2) were published in a Scopus or Web of Science indexed journal; (3) provided quantitative data on one or more performance indicators; and (4) were in English. Articles focusing on open pond aquaculture without a RAS component, conference abstracts without complete data, or duplicate datasets were excluded. The final corpus consisted of 31 articles.

2.3 Data Extraction and Coding

A standardized data extraction form was piloted on five articles before being fully implemented. Variables recorded included: author and year; journal and impact factor quartile; country of study; target aquaculture species; type of renewable energy technology; circular economy integration; and quantitative performance indicators. Primary indicators extracted included: percentage CO₂ emission reduction, operational cost savings, water use efficiency, and water savings relative to flow-through systems. Where studies reported ranges, the arithmetic midpoint was used to calculate the mean. Publications were classified into six thematic categories: (1) RAS & Climate Adaptation; (2) Renewable Energy Integration; (3) Microalgae & Nutrient Recycling; (4) Biofloc & Circular Systems; (5) Biofilters & Infrastructure Design; and (6) Economic Analysis & Feasibility. Barrier data were coded on a two-dimensional impact–frequency scale (1–5), and a priority score was calculated as the product of the two scores, resulting in a composite index (range: 1–25) (Dong et al., 2023).

2.4 Descriptive Quantitative Analysis

Descriptive statistics were calculated using Microsoft Excel v.16.0. For categorical variables, absolute (n) and relative (%) frequencies were tabulated. For continuous variables, minimum, maximum, and arithmetic mean were reported by technology category. Barriers to adoption were ranked by composite priority score (impact × frequency). No meta-analytic pooling of effect sizes was performed due to the heterogeneity of study designs, species, and geographic contexts; instead, comparative tabulation was used to identify consistent patterns. All findings are reported with explicit reference to the original source data to ensure traceability and reproducibility.

Results and Discussion

3.1 Thematic Distribution of Research

A descriptive quantitative analysis of the 31 reviewed publications revealed a broadly distributed research landscape across six main thematic categories. Table 1 presents the frequency and percentage distributions across these categories, along with the temporal range of studies in each cluster.

Table 1. Thematic distribution and frequency of analyzed publications on RAS and renewable energy integration (n=31, 2020–2024)

Research Focus Areas	n	%	Period	Main References
RAS & Climate Adaptation	6	19.4	2020–2023	Ahmed & Turchini (2021); Verdegem et al. (2023); Li et al. (2023)
Renewable Energy Integration	5	16.1	2020–2022	Nguyen et al. (2020); Vo et al. (2021a,b); Yue & Shen (2021)
Microalgae & Nutrient Recycling	5	16.1	2021–2024	Campanati et al. (2021); Ende et al. (2024); Oliveira et al. (2023)
Biofloc & Circular System	6	19.4	2021–2024	Zimmermann et al. (2023); Khanjani et al. (2024); Tom et al. (2021)

Biofilter & Infrastructure Design	5	16.1	2021–2023	Preena et al. (2021); Li et al. (2023); Zhao et al. (2022)
Economic & Feasibility Analysis	4	12.9	2020–2023	Pasch & Palm (2021); Nguyen et al. (2020); Chen & Gao (2023)
TOTAL	31	100.0	2020–2024	,

The two largest thematic clusters, "RAS & Climate Adaptation" and "Biofloc & Circular Systems", each comprised 19.4% of the corpus (n=6), indicating that the scientific community simultaneously prioritizes understanding the environmental risks of conventional aquaculture and developing closed-loop biological solutions. "Renewable Energy Integration" and "Microalgae & Nutrient Recycling" each accounted for 16.1% (n=5), confirming that abiotic and biotic energy pathways receive comparable investigative attention. Economic feasibility studies constituted the smallest cluster (12.9%, n=4), striking given that techno-economic feasibility is a key determinant of technology adoption in commercial operations (Pasch & Palm, 2021). This gap represents the highest priority area for future research investment, in line with Chen & Gao's (2023) observation that feasibility analyses for closed-system technologies in emerging markets remain relatively scarce.

3.2 Temporal Trends in Publication Activity

Table 2 presents the annual frequency distribution and dominant thematic focus of publications during the study period 2020–2024, including supporting contextual studies from a broader reference base.

Table 2. Annual publication frequency, relative proportion, and dominant research themes in the reviewed corpus (n=31)

Year	n	%	Dominant Theme	Main Author
2020	1	3.2	Hybrid energy systems for aquaculture	Nguyen et al. (2020)
2021	8	25.8	RAS ecology; solar energy; wastewater treatment; nutrient recycling	Ahmed, Campanati, Preena, Vo (×2), Yue, Tom, Pasch
2022	3	9.7	Biofilter microbiology; infrastructure; aquaponics	Moschos, Zhao, Okomoda
2023	6	19.4	Circular bioeconomy; industrial aquaculture; bioremediation	Zimmermann, Verdegem, Chen, Li, Oliveira, Dong
2024	2	6.5	Microalgae-RAS integration; BFT progress	Ende, Khanjani
Others/Reviews	11	35.5	Supporting contextual studies	FAO; Timmons; Bostock; Michaud; others
TOTAL	31	100.0	,	,

The data revealed a significant acceleration from 2020 (n=1; 3.2%) to 2021 (n=8; 25.8%), reflecting the catalytic effect of post-COVID-19 policy discourse on food system resilience and blue economy sustainability (FAO, 2022). The year 2021 was characterized by fundamental component-level investigations, RAS ecology, solar energy applicability, and wastewater treatment, which provides empirical building blocks for integrated systems research in the following years. Activity stabilized at three to six papers per year in 2022–2023, with a thematic shift towards integrated circular bioeconomy systems as evidenced by the work of Zimmermann et al. (2023), Verdegem et al. (2023), and Oliveira et al. (2023), evolution that represents the natural maturation of a field of applied research (Ende et al., 2024).

3.3 Descriptive Statistics of Quantitative Performance Indicators

Table 3 presents descriptive quantitative statistics, range and arithmetic mean, for primary resource efficiency indicators across thematic clusters. Resource efficiency metrics integrate water savings, energy reduction, or cost efficiency depending on the primary focus of each study cluster, allowing for cross-thematic comparisons.

Table 3. Descriptive statistics (range and mean) of resource efficiency indicators per research theme (n=31)

Research Theme	n	Resource Efficiency Range (%)	Average (%)	Reference
RAS & Climate Adaptation	6	85–98	91.2	Ahmed & Turchini (2021); Li et al. (2023)
Renewable Energy Integration	5	40–75	56.4	Nguyen et al. (2020); Vo et al. (2021a)
Microalgae & Nutrient Recycling	5	55–98	79.6	Ende et al. (2024); Oliveira et al. (2023)
Biofloc & Circular System	6	85–98	92.5	Khanjani et al. (2024); Zimmermann et al. (2023)
Biofilter & Infrastructure Design	5	90–98	94.0	Preena et al. (2021); Zhao et al. (2022)
Economic & Feasibility Analysis	4	30–75	51.3	Pasch & Palm (2021); Nguyen et al. (2020)

The "Biofilter & Infrastructure Design" cluster achieved the highest average efficiency (94.0%), reflecting the fundamental role of biofilter infrastructure in enabling closed-loop water circulation (Preena et al., 2021; Zhao et al., 2022). "RAS & Climate Adaptation" and "Biofloc & Circular Systems" achieved average efficiencies of 91.2% and 92.5%, respectively, confirming consistent performance across geographic contexts and species. The "Renewable Energy Integration" cluster showed the widest range (40–75%) and the lowest average (56.4%), reflecting the technology's site-specific dependence, influenced by differences in solar irradiation, wind speed regimes, electricity prices, and system scale (Nguyen et al., 2020; Vo et al., 2021a). The "Economic & Feasibility Analysis" cluster (51.3%; range 30–75%) also shows high variability, driven by differences in market conditions across study sites (Pasch & Palm, 2021; Chen & Gao, 2023).

3.4 Comparison of Renewable Energy Technology Performance

Table 4 presents a multi-indicator quantitative comparison of five renewable energy configurations applied to RAS, derived from data extracted and synthesized from the reviewed primary literature.

Table 4. Comparison of multi-indicator performance of renewable energy technologies integrated into RAS (values represent reported ranges from primary literature)

Energy Sources	System Type	CO ₂ Reduction (%)	Cost Savings (%)	Water Efficiency (%)	Reference
Solar PV (land-based)	RAS aerator & pump	45–60	30–42	82–90	Vo et al. (2021a)
Floating PV (FPV)	Open Pool & RAS	50–65	35–48	85–95	Vo et al. (2021b)
Wind Turbine	Coastal RAS	40–55	25–38	70–85	Yue & Shen (2021)
PV–Electrolysis–H ₂ Hybrid	Shrimp RACE	68–75	40–52	88–96	Nguyen et al. (2020)
Microalgae–Biogas	Closed loop RAS	55–70	28–45	90–98	Ende et al. (2024)

The PV–electrolysis–hydrogen hybrid system (Nguyen et al., 2020) achieved the highest performance across all three indicators: 68–75% CO₂ reduction, 40–52% cost savings, and 88–96% water efficiency. These advantages stem from a synergistic design in which excess solar electricity produces pure hydrogen and oxygen through electrolysis; hydrogen is used as backup energy, while oxygen is supplied directly to the shrimp tanks for supplemental aeration, eliminating most of the energy costs of mechanical aeration. FPV systems outperform land-based installations on both key metrics because the natural cooling effect of the water surface increases photovoltaic conversion efficiency by approximately 5–15% (Vo et al., 2021b), while eliminating land rental costs and reducing evaporative water losses. Wind turbines exhibit the lowest performance (CO₂ reduction: 40–55%; cost savings: 25–38%) due to intermittency constraints and site specificity requiring greater storage investment (Yue & Shen, 2021). The microalgae–biogas pathway uniquely addresses the challenges of effluent nitrogen and

phosphorus through biological nutrient assimilation.,systemic circular economy benefits that are not captured in simple cost or emissions metrics (Ende et al., 2024; Campanati et al., 2021).

3.5 Circular Economy Technologies: Water Conservation and System Integration

Table 5 presents the quantitative water conservation performance and managerial complexity of six circular economy technologies, as synthesized from the reviewed literature.

Table 5. Water conservation performance and managerial complexity of circular economy technologies in aquaculture relative to conventional flow-through systems

Technology	Main Circular Function	Water Savings (%)	Managerial Complexity	Reference
Biofloc (BFT)	Protein recycling; pathogen suppression	85–95	Currently	Khanjani et al. (2024)
RAS (Full Recirculation)	Closed water loop; biosecurity	>95	Tall	Timmons & Ebeling (2013); Ahmed & Turchini (2021)
IMTA	Multi-species nutrient valorization	70–85	Currently	Zimmermann et al. (2023)
Aquaponics	Fish–plant symbiosis; zero effluent	>95	Tall	Okomoda et al. (2022); Love et al. (2015)
Bio-RAS	Biofilm-based nitrification	>95	Tall	Zimmermann et al. (2023)
Microalgae-RAS Loop	O ₂ supply; CO ₂ capture; biomass valorization	90–98	Currently	Ende et al. (2024); Oliveira et al. (2023)

Full RAS, aquaponics, and bio-RAS consistently achieve >95% water savings, confirming these technologies as the gold standard for water-limited aquaculture contexts. Khanjani et al. (2024) demonstrated that BFT achieves 85–95% water savings while converting inorganic nitrogen into high-protein microbial biomass, which reduces commercial feed consumption by 10–25%. This makes it particularly attractive for small-scale producers where feed costs account for 60–70% of total operational expenses. IMTA, while achieving the lowest water savings (70–85%), provides unique ecological functionality through a multitrophic production cascade that processes waste nutrients without external energy input (Zimmermann et al., 2023), making it the most pragmatic entry point into circular economy aquaculture in coastal contexts. The microalgae-RAS loop simultaneously provides biological oxygen supply, CO₂ sequestration, effluent nutrient polishing, and harvestable biomass with a market value of USD 1.5–4.0 per kilogram dry weight.,with evidence from Oliveira et al. (2023) showing the elimination of 92–97% of nitrogen and 85–93% of phosphorus from aquaculture effluents (Ende et al., 2024).

3.6 Barriers to Adoption: Quantitative Priority Analysis

Table 6 presents the results of the descriptive quantitative barrier prioritization analysis, Where Each barrier is scored on a 1–5 impact scale and a 1–5 frequency scale based on the weight of evidence in the reviewed literature, resulting in a composite priority score (range: 1–25).

Table 6. Priority analysis of adoption barriers for renewable energy integrated RAS (composite score impact × frequency)

Obstacle	Impact (1–5)	Frequency (1–5)	Priority Score	Supporting References
High capital investment	5	4	20	Pasch & Palm (2021); Nguyen et al. (2020)
Shortage of skilled operators	4	5	20	Preena et al. (2021); Li et al. (2023)
Energy intermittency risk	4	4	16	Vo et al. (2021a); Nguyen et al. (2020)
Limited access to affordable credit	5	3	15	Pasch & Palm (2021); Chen & Gao (2023)

Regulatory fragmentation	3	4	12	Dong et al. (2023); Verdegem et al. (2023)
High O&M complexity (BFT/IMTA)	3	3	9	Zimmermann et al. (2023); Tom et al. (2021)

High capital investment and a shortage of skilled operators both achieved priority scores of 20, identifying them as the most critical barriers to large-scale adoption. A fully integrated renewable energy RAS system requires USD 150,000–500,000 per ton of annual production capacity, five to ten times greater than the initial investment of conventional pond-based systems (Pasch & Palm, 2021; Nguyen et al., 2020). Thus, concessional financing instruments such as green aquaculture bonds or public-private partnership frameworks are identified as the highest priority policy interventions. Access to affordable credit (score: 15) is particularly relevant in Southeast Asia and Sub-Saharan Africa. Where the majority of small-scale producers do not have access to formal credit at reasonable interest rates (Chen & Gao, 2023; FAO, 2020). Intermittency Energy (score: 16) is a technically addressable barrier through battery storage or hydrogen buffering, but its capital costs exacerbate existing investment challenges. Regulatory fragmentation (score: 12) reflects the absence of a cohesive incentive framework that promotes renewable energy and sustainable aquaculture within a single policy instrument; Verdegem et al. (2023) note that feed-in tariffs and aquaculture licensing are generally administered by separate regulatory bodies with limited coordination, creating compliance costs that hinder adoption.

Conclusion

This study shows that renewable energy-based RAS is technically and economically feasible, with solar PV systems and hydride hydrogen reduces CO₂ emissions by 45–75% and costs by 25–52%. Circular economy technologies achieve water savings of 85–98%. Descriptive quantitative analysis confirms steady research growth (2020–2024), with economic feasibility studies still underrepresented. Capital costs and operator skills shortages are the highest priority barriers (score: 20 each). A solar PV-first, phased integration strategy, supported by concessional financing and technical outreach, represents the most practical path to sustainable global aquaculture.

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