A Narrative Review Technological Advances and Sustainability Outcomes of Recirculating Aquaculture Systems

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Abstract
Recirculating aquaculture systems (RAS) have become an innovative and sustainable technology that can overcome the environmental and resource constraints of traditional aquaculture. RAS significantly decreases the amount of freshwater needed, enhances water quality and biosecurity, and allows for high-density fish production by continuously treating and reusing culture water through integrated mechanical, biological, and chemical filtration. The use of advanced biofiltration, automated monitoring systems, the Internet of Things (IoT) sensors, artificial intelligence (AI), and precision aquaculture are some of the recent technological advancements that have further enhanced the performance of the systems, operational efficiency, and environmental sustainability. This narrative review combines the latest information and insights into the principles, key elements, technological developments, sustainability, and challenges of RAS. The review emphasizes the substantial impact of RAS on water conservation, nutrient reductions, fish health, production efficiency, and the potential for incorporating circular economy strategies like aquaponics and nutrient recovery. Yet the potential for widespread adoption is limited by the large capital costs, significant energy demand, complexity of operation, and the need for trained staff. Further studies should focus on energy-efficient system designs, AI-based decision support tools, the use of renewable energy, optimized microbial management, and detailed life cycle assessments for enhancing the environmental and economic sustainability of RAS. Overall, technology and cross-disciplinary cooperation will be essential for expanding the use of RAS and to promoting the sustainable development of aquaculture to satisfy the growing demand for aquatic food globally.

Keywords: Recirculating aquaculture systems, sustainable aquaculture, biofiltration, precision aquaculture, water quality, aquaculture engineering, circular economy

1. Introduction

The growing demand for aquatic food products in recent decades is attributed to population growth, urbanization, improved income, and increased nutrition awareness of aquatic food products. Aquaculture is considered by the Food and Agriculture Organization (FAO) as the fastest-growing food production sector, which is contributing significantly to food security in the world. But traditional aquaculture methods are becoming limited due to limited sources of freshwater, depletion of environmental resources, disease outbreaks, climate change, and depletion of land and water resources. These problems have only made the demand for more sustainable and resource-efficient production systems to achieve future aquaculture expansion even greater (Turlybek et al., 2025, Martins et al., 2010).

One of the most promising technological innovations in modern aquaculture is the Recirculating Aquaculture System (RAS). In contrast to traditional flow-through or pond culture systems, culture water is continually treated and reused in RAS through integrated mechanical, biological, and chemical methods, significantly reducing water use and allowing for optimal culture conditions for fish growth (Timmons and Ebeling, 2013, Badiola et al., 2012). Because production water is recycled, modern RAS can achieve a high recirculation rate of about 90–99%, making them especially well-suited for water-scarce areas and areas with strict environmental regulations (Martins et al., 2010).

In addition to water conservation, there are also several operational benefits of the RAS, such as better biosecurity, lower environmental discharges, better water quality control, year-round production, and closer connections to consumer markets. These traits increase production efficiency, lower transport expenses, and decrease the environmental impact of fish farming (Aubin et al., 2006, Turlybek et al., 2025). Over the last decade, a lot of development has been added to improve RAS performance. The use of new biofiltration technology, automated feeding systems, real-time water quality monitoring, Internet of Things (IoT)-based sensors, artificial intelligence (AI), and precision aquaculture has increased the reliability of the system, production efficiency, and environmental sustainability. At the same time, the adoption of renewable energy, circular economy, and waste recovery technologies has been gaining momentum for further enhancing the sustainability of intensive aquaculture production (Gupta et al., 2024, Badiola et al., 2018)

Despite these developments, there are still some technical and economic constraints that prevent the broad-scale upscaling of RAS. High capital investment costs, energy needed to run the systems, the management of the complex system, and the need for trained staff are still among the significant constraints, especially for small-scale producers and developing countries (Brown et al., 2025). Thus, this narrative review aims to synthesize the existing knowledge about the design and operation of RAS, recent technological advancements, sustainability achievements, challenges faced, and research priorities on the subject. The review aims to give an updated overview of the way in which technological developments are shaping a sustainable production system for the future development of RAS, which is becoming one of the most sustainable production systems.

2. Principles and Components of Recirculating Aquaculture Systems

2.1 Basic Working Principle

Recirculating Aquaculture Systems are high-density fish farming systems that seek to reduce water usage as culture water is treated and recycled over and over again. In contrast to the traditional aquaculture system that uses frequent water exchanges to control water quality, the water in a RAS is recirculated through a series of water treatment units to remove suspended solids, metabolised wastes, dissolved organic matter, and harmful microorganisms before being returned to the fish culture tanks (Timmons and Ebeling, 2013).

RAS is based on the fundamental idea of maintaining a closed-loop water recycling system in which only a small fraction of the water is replaced every day to counter evaporation, sludge removal, etc. Commercial RAS have water flow rates of 90% or greater, which significantly decrease the amount of freshwater needed and allow for stable environmental conditions for high-density fish culture (Turlybek et al., 2025).

Maintaining optimal water quality is important for the successful operation of a RAS. Metabolic wastes, especially ammonia, are expelled constantly from the body of the fish (respiration and excretion). Efficient biological filtration is vital to convert the ammonia to less toxic nitrate through nitrification because ammonia is very toxic at relatively low concentrations. At the same time, the concentrations of dissolved oxygen (DO), carbon dioxide (CO_2), pH, alkalinity, temperature, and suspended solids (SS) all need to be monitored and kept within species-specific limits to promote the health and productivity of the fish (Preena et al., 2021, Timmons and Ebeling, 2013)

2.2 Major Components of RAS

A typical recirculating aquaculture system is a collection of several treatment units that are interconnected to achieve a desirable water quality in the intensive fish production phase. Fish grow in culture tanks, which are the main growing places. Several factors are affected by tank design: formation of water circulation, removal of wastes, fish stocking density, fish welfare, etc. Self-cleaning is often achieved in circular tanks by rotating the water flow, which moves the solid wastes towards a sewer or effluent disposal point (Timmons and Ebeling, 2013)

Mechanical filtration removes suspended solids like uneaten feed and fish faeces, which decrease before causing organic loading. Mechanical filtration systems include drum filters and microscreen filters, which are commonly found because they are effective in removing particulate matter without significantly increasing the oxygen requirement in the system.

The main element of RAS is the biological filtration. Biofilters have surfaces for the nitrifying bacteria, which transform the toxic ammonia into nitrite and then nitrate. Moving Bed Biofilm Reactors (MBBRs) are becoming a popular solution in modern wastewater treatment systems to maximize microbial growth and increase nitrification efficiency when production is intensive (Preena et al., 2021).

Other treatment units may include foam fractionators (protein skimmers) to remove dissolved organic compounds, ozonation units to oxidize organic matter and improve water clarity, and ultraviolet (UV) units, which help to remove pathogens while eliminating chemical residues. These various technologies have great potential for enhancing fish health and disease control in closed fish production systems (de Jesus Gregersen et al., 2021).

Adequate oxygenation is essential because intensive stocking densities will quickly deplete the dissolved oxygen. Dissolved oxygen levels are maintained by oxygen cones, low-head oxygenators, and aeration devices, and carbon dioxide is removed at the same time. Pumps facilitate the flow of water across the treatment train, while modern sensor networks allow for real-time monitoring of water quality parameters, such as dissolved oxygen, ammonia, pH, temperature, oxidation-reduction potential, and others, all of which are important to water quality (Gupta et al., 2024).

Table 1 summarizes the principal components of recirculating aquaculture systems and their respective functions in system performance.

Table 1: Major Components of a Recirculating Aquaculture System

Component	Primary Function	Importance	Reference
Culture tanks	Fish production	Growth and welfare	Timmons & Ebeling (2013)
Mechanical filter	Removes suspended solids	Improves water quality	Dolan et al. (2013)
Biofilter	Converts ammonia to nitrate	Prevents ammonia toxicity	Preena et al. (2021)
Foam fractionator	Removes dissolved organic matter	Improves water clarity	Gregersen et al. (2021)
UV sterilizer	Reduces microbial load	Disease prevention	Gregersen et al. (2021)
Oxygenation unit	Maintains dissolved oxygen	Supports fish metabolism	Timmons & Ebeling (2013)
Pumps	Water circulation	Continuous treatment	Martins et al. (2010)
Sensors	Real-time monitoring	Process control and automation	Gupta et al. (2024)

2.3 Water Quality Management

Maintaining good water quality is essential for the successful operation of a RAS, as fish health, feed conversion ratio, and productivity are directly affected by the water quality. Operators can detect deviation promptly in physicochemical parameters and take corrective actions before adverse effects occur by continuously monitoring physicochemical parameters (Martins et al., 2010).

Ammonia is regarded as the most important water quality parameter, as it is always generated by protein metabolism and can easily be over-accumulated under intensive culture conditions. Biological nitrification is carried out by the bacteria responsible for the oxidation of ammonia and nitrite to nitrate, ensuring water quality is within acceptable limits. Excessive nitrate levels may need to be denitrified, or water changed periodically to maintain optimal culture conditions, although nitrate is much less toxic than ammonia or nitrite (Letelier-Gordo et al., 2020).

Within biofilters, sufficient dissolved oxygen levels should be maintained for the metabolism of fish and the activity of microorganisms. At the same time, high concentrations of CO_2 may negatively influence fish growth, feed consumption, and breathing. In addition, it is crucial to maintain constant pH and alkalinity because, as nitrification occurs, it uses alkalinity, which can cause a gradual decrease in the pH of the system and would negatively impact the biofilter's efficiency if not corrected (Preena et al., 2021).

Recent years have seen significant advances in water quality management technology, including the deployment of sensors and automated monitoring systems, cloud-based platforms, and artificial intelligence tools. They can be used to monitor and measure some important water quality parameters continuously, can help find the failures in the system early, and can give a predictive management strategy that will help improve production efficiency and reduce operational risks (Gupta et al., 2024)

3. Recent Technological Advances in Recirculating Aquaculture Systems

The introduction of new technologies over the last few years has made recirculating aquaculture systems highly automated and data-driven production systems. Advances in new engineering design, biological treatment, digital monitoring, and intelligent management have resulted in improved production efficiency and reduced environmental impacts (Badiola et al., 2012). This has led to RAS being one of the most promising solutions to intensive aquaculture practices.

Moving bed biofilm reactors, better nitrification systems, and integrated denitrification systems have seen significant improvements to biofiltration technology and provide better nitrogen removal while maintaining stable water quality. Improvements in microbial ecology also have led to increased resilience and treatment efficiency in biofilters under intensive production environments (Fernandes et al., 2017).

The automation of the system has become one of the characteristics of the modern RAS. The wireless sensors are constantly measuring dissolved oxygen (DO), water flow, temperature, pH, ammonia, and oxidation-reduction potential (ORP) and transmit the information to a control system that is located in a central place. This is an ongoing process that allows for early detection of abnormalities, reduces the risk of production, and saves labour (Gupta et al., 2024)

AI and machine learning are being adopted in the management of RAS (Mustapha et al., 2021). Water quality predictions, feeding optimization, fish biomass estimation, abnormal fish behaviour detection, and automated control systems can provide aid in decision making. These technologies enhance the efficiency of production and reduce feed losses, energy usage, and environmental pollution. Table 2 summarizes recent technological advances in recirculating aquaculture systems and their applications.

Table 2: Recent Technological Advances in Recirculating Aquaculture Systems (RAS) and Their Applications

Technology	Application in RAS	Key Benefits
Moving Bed Biofilm Reactor (MBBR)	Biological nitrification and ammonia removal	Improved biofiltration efficiency and stable water quality
Automated water quality sensors	Continuous monitoring of pH, dissolved oxygen, ammonia, temperature, and ORP	Real-time system control and early fault detection
Internet of Things (IoT)	Remote monitoring and data acquisition	Enhanced operational efficiency and reduced labour requirements
Artificial Intelligence (AI)	Feeding optimization, biomass estimation, water quality prediction, and disease detection	Improved decision-making and resource efficiency
Ozonation and UV disinfection	Water treatment and pathogen control	Improved biosecurity and reduced disease transmission
Energy-efficient pumps and oxygenation systems	Water circulation and dissolved oxygen management	Lower energy consumption and operational costs
Precision aquaculture technologies	Integrated sensor-based production management	Increased productivity, fish welfare, and sustainability

4. Sustainability Outcomes of Recirculating Aquaculture Systems

The adoption of recirculating aquaculture systems (RAS) is mainly because of their potential to enhance environmental, economic, and social sustainability, along with high fish production output. RAS differ from a traditional pond or flow-through system in that they have lower water usage, less water pollution, increased biosecurity, and allow for intensive fish production while maintaining a high degree of control. The features mentioned above have led RAS to be an important technology for the development of sustainable aquaculture in areas with greater freshwater scarcity, stricter environmental regulations, and even greater climate-related challenges (Turlybek et al., 2025).

4.1 Water Conservation and Resource Efficiency

RAS enjoys a great water-use efficiency as one of its most notable sustainability benefits. Traditional aquaculture facilities often have to exchange their water regularly, which leads to significant amounts of freshwater being used and a strain on local water resources. RAS, on the other hand, continuously treats and recirculates culture water, and only replaces water in the system daily to make up for evaporation, sludge removal, and maintenance of the system. The re-use rate of production water in commercial RAS is in the range of 90% to 99%, where they are well suited for water-limited areas or for urban aquaculture production (Badiola et al., 2012). Water efficiency has a positive effect on the conservation of freshwater resources and is a way of reducing wastewater releases to the environment. Reducing abstraction and discharge also helps to safeguard rivers, lakes, and groundwater and meet increasingly stringent environmental regulations.

4.2 Environmental Sustainability

RAS can reduce common compromises in conventional aquaculture, including water pollution and environmental impact. Water is filtered of suspended solids, dissolved organic matter, and nitrogenous wastes using mechanical, biological, and foam and disinfection systems before it is returned to the system. Nutrient, organic pollution, and eutrophication risks are therefore considerably reduced in closed aquaculture systems compared to open systems (Aubin et al., 2006).

The other significant environmental benefit is enhanced biosecurity. Water treatment and water exchange can be efficient in reducing the introduction and spread of pathogens, parasites, and invasive species in production areas, which are under the control of the farm. This also helps to decrease reliance on antibiotics and chemotherapeutic agents, which further enhances environmental protection and responsible aquaculture operations (Gupta et al., 2024).

Efficiently collecting waste during production, such as sludge and organic residues, can be done more efficiently in an RAS system than in conventional systems. These wastes can then be used in the production of fertilizers, anaerobic digestion, or nutrient recovery, which is in line with the principles of the circular economy and provides a solution to environmental impacts caused by aquaculture waste disposal (Suhr et al., 2013).

4.3 Economic Sustainability

Although RAS requires relatively high initial capital investment, they offer several long-term economic advantages. Through year-round environmental control, the production is not influenced by seasons, which facilitates the production plan and provides a stable market supply. In addition to increased productivity and profitability, higher stocking densities, improved feed conversion ratios, and lower mortality rates and production cycles are other factors that bring increased productivity (Badiola et al., 2018).

Being located in the vicinity of major urban markets can also be a benefit to the economy due to lower transportation costs, reduced post-harvest losses, and fresher products available to consumers. Additionally, the local production enhances the food security and mitigates the adverse environmental effects of long-distance transportation (Davidson et al., 2016).

However, energy efficiency is intrinsically related to economic sustainability. Electricity to pump, aerate, heat, cool, and monitor water is one of the highest operating costs for commercial RAS systems. So, energy efficiency remains an important factor for developing future technologies.

4.4 Food Security and Social Sustainability

RAS contributes to social sustainability by enhancing the dependability and resilience of fish production systems. In controlled production environments, there is a reduction in dependence on climate, and fish are produced year-round. This contributes to improving food security, particularly in the countries that are undergoing rapid urbanization and are facing the challenge of rising demand for quality aquaculture products (Turlybek et al., 2025).

Moreover, RAS provides jobs that demand high technical skills in engineering, water quality management, automation, and aquaculture. The growth of knowledge-based aquaculture industries can hence be expected to stimulate economic development in rural and urban areas as well as to promote innovation in the aquaculture industry.

4.5 Circular Economy Opportunities

The increasing integration of RAS into the circular bioeconomy is a recent development. Recovering nutrients from fish sludge can enhance agricultural applications, and aquaponics integrates fish farming with hydroponic crop farming, where the plants absorb dissolved nutrients produced during fish farming. Solar and geothermal energy are also being used as renewable energy sources to decrease fossil fuel reliance and to lower operational carbon emissions (Suhr et al., 2013). Table 3 summarizes the major sustainability outcomes of recirculating aquaculture systems.

Table 3: Sustainability outcomes associated with Recirculating Aquaculture Systems

Sustainability dimension	**Major outcomes**
Environmental	Reduced nutrient discharge, improved biosecurity

Water resources	90–99% water reuse
Economic	Higher productivity, year-round production
Social	Improved food security and employment
Circular economy	Aquaponics, sludge reuse, renewable energy

5. Current Challenges and Limitations

Despite considerable technological progress, there are still some challenges that are preventing the broader adoption of recirculating aquaculture systems. The biggest challenge is the high capital cost of the construction of the systems, the need for special equipment, an automation framework, and water treatment technologies. The start-up costs of these fish farms are significantly higher than those for traditional pond or cage farming, making them less accessible to many small-scale farmers (Badiola et al., 2018)

Running costs are also relatively high due to the need for the continuous circulation of water, oxygenation, heating, cooling, and monitoring, which take up a lot of electrical power. One of the highest costs and environmental impacts in commercial RAS systems is energy use. Reducing energy losses by combining renewable energy sources and optimized engineering design is thus a significant research need.

Another key challenge is the technical complexity. Ongoing water quality, biofilter performance, fish health, and equipment management are necessary for successful RAS operations. If a failure occurs in the system, e.g., pump failure, oxygen depletion, or biofilter instability, fish welfare can deteriorate quickly, and significant financial losses can occur if these failures are not detected early (Turlybek et al., 2025).

Disease management is still difficult despite improved biosecurity. Diseases can quickly become pervasive in closed production systems if pathogens are introduced and established, although diseases do not occur in closed systems due to pathogen introduction from external water sources (Han et al.). Therefore, good biosecurity practices, regular health surveillance, and early detection of disease are still crucial for successful RAS management.

6. Discussion and Synthesis

Recirculating aquaculture systems have grown from specialized intensive production systems to one of the most promising technologies that can support sustainable aquaculture development. RAS can more effectively reduce water usage, enhance environmental management, minimize pollution, and enable fish production throughout the year, which is more consistent with worldwide sustainability goals (Martins et al., 2010).

Innovations in technology have also enhanced the performance of RAS. Recent advancements in biological filtration, automation, AI, and precision aquaculture have greatly enhanced the management of water quality, production efficiency, and reliability of aquaculture operations (Suhr et al., 2013, Van Rijn, 2013). Real-time sensor measurements and predictive decision-support systems can aid in implementing proactive management solutions that help to reduce production risks and increase resource utilization (Summerfelt et al., 2009).

However, sustainability should be evaluated using a holistic perspective that considers environmental, economic, and social dimensions simultaneously. RAS also causes a significant decrease in the use of water and nutrients, and relatively high energy requirements can also affect some of the environmental benefits if electricity is generated from fossil fuels. In this context, future improvements to sustainability should be oriented towards renewable energy integration, life cycle assessment and approaches for the circular economy, which aim at maximizing resource recovery and minimizing environmental impacts (Aubin et al., 2006; Badiola et al., 2018).

7. Research Gaps and Future Directions

Although the technologies are rapidly advancing, there are still several key research gaps. One, there is a need for more improvement in energy efficiency to lower the operational costs and GHGs. Future pumping systems require the use of renewable energy, waste heat recovery, and energy-efficient pumping systems. Secondly, there is minimal usage of artificial intelligence and machine learning in the commercial aquaculture industry. Future research will involve developing predictive algorithms that can be able to optimize the feeding process, detect any outbreak of disease, and predict changes in water quality, among others.

Thirdly, more focus should be placed on the microbial ecology in biofilters. A better understanding of the dynamics of the microbial communities could improve the efficiency of nitrification, the resilience of the system, and disease prevention. Species-specific RAS optimization, scaling up commercial production, life cycle environmental impact, economic viability in various production scenarios, and integration with aquaponics and circular bioeconomy systems should also be explored. Finally, there is a need for international guidelines and policies that would foster sustainability in RAS development through the provision of environmental protection, animal welfare, and food safety.

8. Conclusion

Aquaculture, and more specifically recirculating aquaculture systems (RAS), is one of the most modern and environmentally friendly ways of intensive fish farming that is available today. These represent an attractive option over conventional aquaculture tanks, as they can be water recycling systems, provide enhanced biosecurity, improve production performance, and reduce environmental impacts. Technological innovations such as biofiltration, automation, artificial intelligence and precision aquaculture boost the operational efficiency and sustainability of RAS.

The benefits of these technologies are yet to be sufficient to curb the extensive commercialization of these technologies, due to the high capital investment, usage of energy, and technical complexity. These challenges will be addressed by implementing renewable energy, smart automation, improved microbial control, and circular economy solutions, all aimed at achieving a sustainable future for RAS.

The ongoing interdisciplinary research, technological development, and policy support will be the key drivers in the scaling up of RAS and sustainable aquaculture production to satisfy the rising demand for aquatic food products that have minimum environmental impacts.

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