Effluent-Free Intensive Fish Farming Advancing Circular Bioeconomy for Sustainable Aquaculture

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Abstract

As global concerns over environmental sustainability and food security intensify, aquaculture is undergoing a transformative shift towards more eco-efficient and resource-conserving practices. This review explores the development and integration of effluent-free intensive fish farming systems grounded in the principles of the circular bioeconomy. Technologies such as Recirculating Aquaculture Systems (RAS), Biofloc Technology (BFT), Biological RAS (Bio-RAS), Partitioned Aquaculture Systems (PAS) and Integrated Multitrophic Aquaculture (IMTA) are examined for their ability to reduce water usage, recycle nutrients and minimize environmental impact. These systems enhance biosecurity, optimize feed conversion and support sustainable fish production through innovative approaches like waste-to-nutrient loops and multi-trophic integration. By fostering closed-loop operations and maximizing resource efficiency, effluent-free intensive aquaculture offers a scalable solution to the growing demand for sustainable seafood while protecting aquatic ecosystems. This paper highlights the potential of circular aquaculture models to redefine modern fish farming and contribute to a more resilient and responsible food production future.

Key words: Bioeconomy, Biosecurity, Photoautotrophic, Hydroponic.

Introduction

The growing global demand for nutritious food and sustainable water use has placed aquaculture at the forefront of innovative food production systems. However, traditional fish farming models often contribute to excessive water consumption, nutrient pollution and ecosystem degradation. To address these challenges, the concept of effluent-free intensive fish farming has emerged, rooted in the principles of the circular bioeconomy. This approach emphasizes resource efficiency, waste minimization and ecological balance by transforming waste into valuable inputs within the production system. A circular economy optimises resource use by reducing waste, conserving energy and promoting sustainability. As the demand for clean water and nutritious food rises, the traditional linear economic model based on extraction, production and disposal is no longer sustainable. Modern societies must transition to circular and life cycle thinking to safeguard finite natural resources. Water, a critical resource, must be managed with strategies emphasising reuse and conservation, integrating circular bioeconomy principles to ensure sustainable use.

Circular Bioeconomy

The circular economy is a production strategy focused on minimizing inputs and waste, closing ecological and economic resource flows and decentralizing production for local consumption. It challenges traditional economic performance metrics and financial roles in shaping natural and social capital. Resource flow analysis falls into two categories: (1) linear, where biological waste is returned to the biosphere and (2) circular, where waste is recycled within the production system. Traditional aquaculture produces excessive nitrogen and phosphorus, harming ecosystems, human health and aquatic life. Rising demand for sustainable aquafarming has led to alternative models with better controls, predictability and waste management. Land-based recirculating aquaculture systems (RAS) treat water and reuse waste as nutrients, representing a major innovation by integrating donor-receiver systems to enhance efficiency.

Recirculation involves water movement through various compartments, tanks, or ponds, where it is partially or fully reused depending on the culture intensity. Extensive and semi-intensive ponds use simpler setups, while intensive systems rely on advanced biofilters, mechanical filters, geo-membranes and other treatments. This technology is widely used in tropical fish farms for biosecurity and is rapidly expanding in marine shrimp, bivalve and seaweed farming, especially in hatcheries and nurseries. Salmon farming also invests in recirculating systems, but at low temperatures, filter microorganisms become less effective, increasing biofilter costs. Low-water-demand systems, whether isolated or recirculating, with intense aeration and a high density of omnivorous tilapia or shrimp, naturally generate bioflocs. In single-compartment setups like ponds or tanks, this is known as Biofloc Technology (BFT). When water is circulated through multiple compartments, it becomes bio-RAS, integrating BFT with Recirculating Aquaculture Systems (RAS).

The primary goal of these systems is to enhance biosecurity in aquaculture, especially in regions where water is scarce or land is expensive. Minimal water exchange helps control diseases while promoting sustainable practices. The recirculation and reuse of water embody the circular economy in aquaculture, enabling near-zero effluent operations. These systems maintain stable water quality by recycling nitrogenous and carbon compounds through bacteria, stimulated by the carbon-to-nitrogen (C:N) ratio in the water.

Recirculatory Aquaculture System

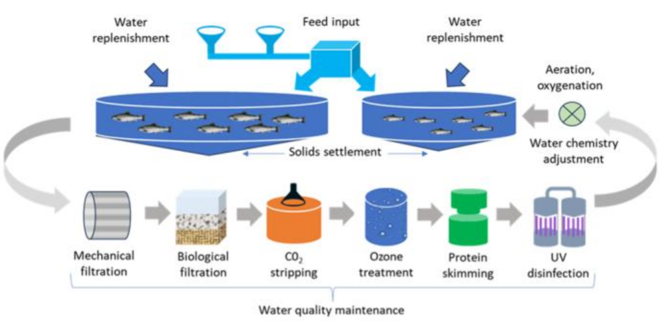

Fig. 1. Schematic design of a typical freshwater RAS (Brown *et al.*, 2024)

Recirculating aquaculture systems (RAS) have evolved over five decades, becoming more accessible as infrastructure costs decline, while fish, labor and feed expenses rise. These systems are widely used in both extensive grow-out setups where water conservation, yield improvement and cost reduction are key and intensive operations, often situated on expensive land near urban markets.

Extensive RAS aim to minimize water use and environmental impact, requiring advanced technology to boost productivity. However, intensive systems demand costly equipment like filters, disinfectants, aerators and emergency backups, alongside high operational expenses such as electricity and maintenance. Despite these challenges, benefits include strategic facility placement, streamlined harvesting and effective disease control. RAS are well-established in hatcheries and nurseries for both freshwater and marine species. While large-scale grow-out production has recently gained commercial success, many earlier operations faced failures before achieving viability.

Biofloc System

Biofloc technology (BFT) is a cost-effective and eco-friendly aquaculture method that enhances water quality by recycling nutrients within the production system. Unlike recirculating aquaculture systems (RAS), which require advanced filtration systems, BFT relies on naturally forming bioflocs in tanks or ponds, reducing operational costs. These bioflocs consist of beneficial bacteria, algae, fungi and organic matter, providing a self-sustaining environment for aquatic species. BFT minimizes the need for water exchange and mechanical filtration, making it particularly suited for species like tilapia and marine shrimp, which thrive in high-solid environments. By utilizing nitrifying bacteria, the system transforms harmful nitrogen compounds into safer forms, while heterotrophic bacteria assimilate ammonium when supplemented with carbohydrates, serving as an additional feed source. This enhances both water stability and feed efficiency, further optimizing production. To maintain its effectiveness, BFT requires continuous aeration, sediment suspension and careful monitoring of water parameters such as dissolved oxygen, pH, alkalinity and the carbon-to-nitrogen (C:N) ratio. The system's flexibility allows it to be integrated with optional settlers, drainage systems and water pumps to optimize solid control and aeration. With its ability to improve sustainability, lower production costs and enhance biosecurity, BFT has gained global recognition as an efficient alternative to intensive RAS setups, enabling high-yield aquaculture with minimal environmental impact.

Biological Recirculatory Aquaculture System

Bio-RAS integrates recirculating aquaculture systems (RAS) with biofloc technology (BFT), combining the strengths of both methods to enhance efficiency and sustainability while reducing costs. This hybrid system leverages water recirculation while allowing bioflocs to form in multiple compartments, improving water quality and minimizing the need for extensive filtration. By merging BFT's ability to recycle nutrients with RAS's controlled environment, bio-RAS optimizes production by reducing feed waste, improving biosecurity and lowering electricity consumption. Bioflocs can develop in specific compartments or throughout the entire circulating water, requiring adaptations in filtration or its exclusion in certain cases. Over the past decade, bio-RAS has been widely implemented in low-cost aquaculture projects, making high-yield production more accessible while maintaining environmental responsibility. This approach promotes sustainable farming, ensuring stable water conditions, efficient nutrient recycling and improved animal welfare, making it an increasingly popular choice in modern aquaculture.

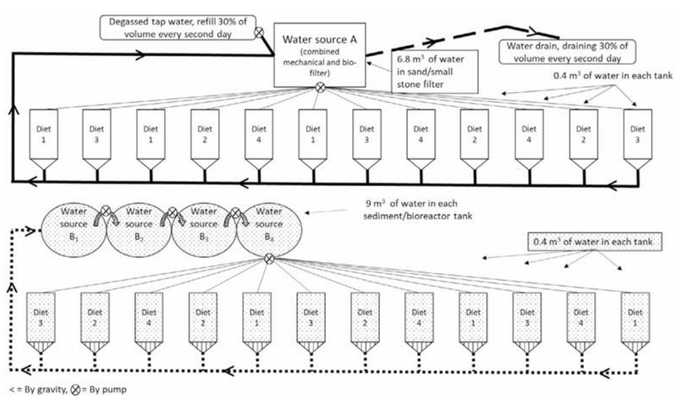

Fig. 2. A simplified diagram of the CW- and bio-RAS systems used by Kiessling and co-workers at AnGiang University in Vietnam (Nguyen *et al.*, 2021).

Partitioned Aquaculture System

Partitioned aquaculture systems (PAS) were developed in the 1990s in the southern United States for American channel catfish cultivation, using wastewater recirculation to achieve zero effluents. In PAS, fish are densely confined in raceways or smaller ponds, occupying about 5% of the total area, while the remaining 95% is used for water recirculation and reuse. Fish waste circulates through water bodies rich in algae, which absorb nutrients from these residues, mimicking domestic wastewater treatment. By enhancing photosynthesis in isolated ponds, PAS effectively removes nitrogen, phosphorus and other waste, doubling the system's support capacity. This boosts the feeding rate and carrying capacity, making the method highly efficient for fish and shrimp production. Partitioned aquaculture systems (PAS) intensify production in previously extensive ponds and reservoirs dominated by phytoplankton. Depending on the setup, yields can range from 10–50 tons of tilapia per hectare or 10,000 m³ of total volume. Two widely used PAS variations are: (a) In-Pond Raceway Systems (IPRS), where cages, raceways, or containers are placed within a larger water body and (b) Split Ponds (SPs), which separate fish-rearing areas from water treatment zones. These methods enhance efficiency, water management and overall productivity.

In-Pond Raceway Systems (IPRS) and Split Ponds (SPs) are innovative aquaculture systems designed to optimize fish production while improving water quality and sustainability. IPRS confines omnivorous fish at high densities within raceways or cages placed along the periphery of lakes or ponds. The surrounding water body assimilates fish waste, reducing pollution while simplifying feeding, sampling and harvesting. Originally developed for channel catfish farming in the U.S., IPRS has been widely adopted for carp, tilapia and other species across China, India, Brazil, Colombia, Thailand and beyond. SPs, also originating in the U.S., divide fish ponds into two sections using a partition or dike. Water circulates between the sections via high-volume, low-head pumps, with 15–20% of the area dedicated to fish rearing and 80–85% functioning as a recirculating basin. This setup enhances nutrient recycling, improves stocking density and supports more efficient production compared to traditional pond systems. Both IPRS and SPs integrate solar-powered pumps to reduce electricity costs, making them more sustainable and economically viable. By enhancing water management, minimizing environmental impact and increasing production efficiency, these systems have become key strategies in modern aquaculture worldwide. Some partitioned aquaculture systems (PAS) incorporate bio-RAS techniques, utilizing bioflocs for biological water treatment in large-scale fish and shrimp production. At higher densities, bioflocs dominate, requiring increased aeration, water movement and symbiotic supplements like prebiotics and probiotics. These advancements have led to various aquaculture methods, such as aqua mimicry heterotrophic, autotrophic, photo-autotrophic and active suspension systems, blending principles from RAS, BFT and bio-RAS for improved efficiency and sustainability.

Integrated Multitrophic Aquaculture System

Integrated Multitrophic Aquaculture (IMTA) is an advanced, sustainable farming approach that maximizes efficiency by cultivating species from different trophic levels within a shared system. By integrating fed species like tilapia and shrimp with extractive organisms such as mollusks, filter feeders, macroalgae and hydroponic plants, IMTA enhances nutrient recycling, reduces waste and optimizes overall productivity. This system extends beyond aquatic environments, incorporating terrestrial animals and hydroponics to create interconnected loops where waste from one species serves as nutrients for another. The integration of multiple species improves feed utilization, lowers operational costs and enhances environmental sustainability compared to conventional aquaculture. IMTA also strengthens biosecurity by maintaining balanced ecosystems and reducing the risk of disease outbreaks.

Aquaponics, a well-known form of IMTA, links aquaculture with hydroponics, turning fish waste into essential plant nutrients and significantly reducing water and nutrient loss. Additionally, sludge from RAS and bio-RAS can be repurposed as digestible feed for both aquatic and terrestrial species, further improving efficiency and sustainability. By strategically matching species and optimising nutrient flow, IMTA supports eco-friendly aquaculture, promotes biodiversity and offers a more economically viable solution for food production. Its growing adoption worldwide demonstrates its potential to advance sustainable aquaculture practices while meeting the increasing demand for high-yield farming systems.

Conclusion

Effluent-free intensive fish farming models, grounded in the principles of the circular bioeconomy, offer a sustainable path forward for modern aquaculture. By integrating technologies such as Recirculating Aquaculture Systems (RAS), Biofloc Technology (BFT), Biological RAS (Bio-RAS), Partitioned Aquaculture Systems (PAS) and Integrated Multitrophic Aquaculture (IMTA), the aquaculture industry can minimize water use, optimize nutrient recycling and drastically reduce environmental impact. These systems not only improve water quality and biosecurity but also enhance productivity and operational efficiency. Through innovative design and ecological integration, such as combining species across trophic levels and utilizing waste as resources, these models pave the way for high-yield, low-impact fish farming. Embracing these approaches ensures the sustainability and resilience of aquaculture, aligning with global needs for food security, environmental conservation and circular economy implementation.

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