

Review Article

Advances in Bioreactor Technologies for Sustainable Aquaculture Water Treatment

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Abstract

Advances in bioreactor technologies are transforming sustainable aquaculture water treatment by improving pollutant removal and supporting environmental conservation and resource recovery. Recirculating Aquaculture Systems (RAS) represent a leading sustainable approach by integrating physical, chemical, and biological treatment processes to recycle water within the system, minimizing freshwater consumption and effluent discharge. Innovative biological systems integrated with Recirculating Aquaculture Systems (RAS) including Moving Bed Biofilm Reactors, membrane bioreactors, anaerobic digesters, photobioreactors, and biofloc efficiently reduce nitrogen, phosphorus, organic matter, and other pollutants using diverse microbial communities without harmful chemicals. Recent developments feature microalgae cultivation for carbon capture and nutrient recycling, nanotechnology to boost microbial performance, and hybrid treatment methods for enhanced effectiveness. While Moving Bed Biofilm Reactors offer high ammonia and organic removal in compact setups, anaerobic bioreactors provide cost-effective nitrate reduction, and constructed wetlands effectively remove organics and phosphorus with more space needs. These bioreactors technology enhance aquaculture sustainability by reducing pollutant loads, mitigating eutrophication risks, and improving fish health through optimized water quality. Despite operational and cost challenges, these technologies promote water reuse, lower pollutant discharge, and enable circular economy practices like bioenergy production. Future research focuses on tailored, integrated treatments, engineered microbes, and resource-loop closing frameworks to bolster sustainability, regulatory compliance, and economic viability in intensive aquaculture. The aim of this review article is to examine recent innovations and developments in bioreactor technologies applied to aquaculture wastewater treatment.

Keywords

Bioreactor Technologies, Sustainable Aquaculture, Recirculating Aquaculture Systems (RAS), Nutrient Removal, Microbial Treatment, Resource Recovery, Circular Economy

1. Introduction

Sustainable water treatment in aquaculture is important because it minimizes environmental impacts by reducing water usage, preventing pollution, and eliminating the need for harmful chemicals or antibiotics [1]. Recirculating aquaculture systems (RAS), which are land-based closed-loop

systems, recycle water continuously and treat waste to avoid discharges into natural water bodies, thereby protecting ecosystems and conserving water resources [2]. This approach also reduces transportation emissions and carbon footprint by localizing production closer to consumer.

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Aquaculture water pollution challenges include the release of nutrients like nitrogen and phosphorus into the environment, which can cause algal blooms and oxygen depletion. Traditional open-net farming can discharge significant waste, leading to habitat disruption. Wastewater from aquaculture contains suspended solids, organic matter, and nutrients that need efficient removal to maintain water quality and aquatic health [3].

Bioreactor technologies, such as moving bed biofilm reactors (MBBRs) and membrane bioreactors (MBRs), offer advanced biological treatment methods to metabolize ammonia and capture other key pollutants in aquaculture wastewater [4]. These systems use microbial biofilms and other biological processes to transform waste compounds into less harmful substances, improving water quality sustainably [5, 6]. Electrochemical oxidation and hybrid systems combining biological and physical methods are also emerging as innovative solutions to enhance pollutant removal and resource recovery from aquaculture effluents [7, 8].

2. Types of Bioreactor Technologies in Aquaculture Water Treatment

There are several bioreactor technologies used in aquaculture water treatment. The main types include: Anaerobic and Aerobic Bioreactors, Moving Bed Biofilm Reactors (MBBRs), Photobioreactors, Sequencing Batch Reactors (SBRs) and Biofloc Systems as Bioreactor Alternatives [9].

Anaerobic and Aerobic Bioreactors: These systems create environments either without oxygen (anaerobic) or with oxygen (aerobic) to promote microbial processes that break down organic waste and nutrients like nitrogen [10]. Anaerobic bioreactors, such as woodchip denitrifying bioreactors, focus on removing nitrates by converting them to nitrogen gas in oxygen-depleted settings. Aerobic bioreactors facilitate the oxidation of ammonia and organic matter by aerobic microbes [11].

Moving Bed Biofilm Reactors (MBBRs): MBBRs use plastic carrier media suspended in the reactor to provide surface area for biofilms of bacteria that degrade waste [12]. This design improves treatment efficiency and is well suited for maintaining water quality in recirculating aquaculture systems (RAS) by removing nitrogenous compounds and organic pollutants [3].

Photobioreactors: These capitalize on photosynthetic microorganisms such as algae or cyanobacteria to absorb nutrients like nitrogen and phosphorus while producing oxygen [13]. Photobioreactors can help reduce nutrient loads and improve water quality by harnessing natural biological processes driven by light [14].

Sequencing Batch Reactors (SBRs): SBRs operate in cycles of filling, reacting, settling, and decanting in a single tank [15]. This batch operation allows for flexible control over biological treatment stages such as nitrification and denitri-

fication to address various pollutants in aquaculture wastewater [16].

Biofloc Systems as Bioreactor Alternatives: Biofloc technology promotes the growth of beneficial microbial flocs in aquaculture water, which consume waste nutrients and enhance water quality [17, 18]. It is a cost-effective bioreactor alternative widely used in aquaculture to reduce nitrogenous waste through microbial assimilation and improve feed efficiency [9, 19].

3. Mechanisms and Microbial Processes

Microorganisms involved in aquaculture bioreactor water treatment include a diverse community of bacteria, fungi, algae, and protozoa [20, 21]. Bacteria are central, especially those involved in nitrification, denitrification, and phosphorus removal. For example, genera like *Rhizobacteria* are known denitrifiers and phosphorus removers enriched in biofilm communities, playing vital roles in nitrogen and phosphorus attenuation [22]. Algae contribute through photosynthesis and nutrient uptake, while protozoa and fungi assist in organic matter breakdown and microbial community balance [23].

Biodegradation and biosorption are key mechanisms in these bioreactors. Biodegradation involves microbial metabolism that breaks down organic matter and nutrients into simpler, less harmful forms, such as conversion of ammonia to nitrate (nitrification) and nitrate to nitrogen gas (denitrification) [24, 25]. Biosorption refers to the passive binding and accumulation of pollutants like heavy metals or organic compounds onto microbial biomass or biofilms, aiding pollutant removal [26].

Nutrient removal targets primarily nitrogen and phosphorus, which contribute to eutrophication if discharged untreated [25]. Microbial nitrification and denitrification processes effectively eliminate nitrogen. Phosphorus removal occurs through microbial uptake and precipitation reactions facilitated by bacteria within biofilms [23]. These microbial actions combine to significantly reduce nutrient loads from aquaculture wastewater.

Organic matter degradation is performed by heterotrophic bacteria and fungi that metabolize dissolved and particulate organic compounds, lowering the chemical oxygen demand (COD) and improving water clarity and quality [27]. This degradation sustains the microbial ecosystem and prevents toxic buildup of organic waste in aquaculture systems.

4. Recent Advances and Innovations

Recent advances and innovations in aquaculture water treatment bioreactors emphasize integration with Recirculating Aquaculture Systems (RAS), microalgae-based bioreactors for carbon sequestration and nutrient recovery, the use of nanotechnology and novel materials, and hybrid treatment systems [28, 29].

Integration with RAS enhances water reuse efficiency by combining biological treatment processes in bioreactors that remove nitrogen and organic pollutants, reducing environmental discharge while maintaining water quality in closed-loop aquaculture operations [30]. This approach offers sustainability by minimizing water consumption and nutrient pollution.

Microalgae-based bioreactors represent a cutting-edge innovation where microalgae are cultivated in photobioreactors to capture CO₂ while simultaneously assimilating nitrogen and phosphorus from aquaculture wastewater [31, 32]. Microalgae can fix carbon dioxide much more efficiently than terrestrial plants and produce valuable biomass usable for biofuels, feed, or fertilizers [33]. Closed and open photobioreactor systems offer high biomass productivity, large surface area, and controlled growth environments, making them promising for both carbon sequestration and nutrient recovery [34].

Nanotechnology and novel materials are being developed to enhance bioreactor performance by improving microbial kinetics, pollutant adsorption, and biofilm development [35, 36]. Nanomaterials can increase the surface area and catalytic activity for microbial communities, leading to higher efficiency in organic matter degradation and nutrient removal [36, 37]. These materials also show potential for anti-fouling and durability improvements in bioreactor components.

Hybrid systems combining physical, biological, and physicochemical methods optimize aquaculture wastewater treatment by integrating processes such as membrane filtration, electrochemical oxidation, and biological degradation [38]. These systems can target a broader range of pollutants and achieve higher treatment efficiencies than single-method systems [39]. For example, combining membrane bioreactors with microalgal cultivation or biofloc systems forms cost-effective, sustainable strategies for comprehensive water treatment [40].

5. Performance and Efficiency

In aquaculture water treatment, the removal rates of solids, organic matter, and nutrients vary among bioreactor types based on their design and operational parameters [21]. Woodchip bioreactors, commonly used for denitrification, typically remove nitrate nitrogen (NO₃-N) at rates ranging from about 0.5 to 10 grams of nitrogen per cubic meter of bioreactor volume per day [41]. They tend to achieve nitrogen load reductions of around 40% on average, with some systems reaching up to 80%, depending on hydraulic retention times and temperature conditions [41]. These systems are relatively low-cost, with installation expenses ranging from roughly \$60 to \$75 per cubic meter and cost efficiencies between \$2.83 and \$13.35 per kilogram of nitrogen removed, making them suitable for stable nitrate removal with low energy consumption but requiring periodic maintenance to avoid clogging [42].

Moving Bed Biofilm Reactors (MBBRs) are more efficient in removing total ammonia nitrogen (TAN) and organic contaminants, achieving near-complete ammonia removal (close to 100%) and organic compound removal efficiencies around 76% [43]. MBBRs benefit from a higher surface area for microbial biofilms, leading to enhanced biodegradation rates, with reported ammonia conversion rates as high as 600 grams TAN per cubic meter per day [44]. However, this efficiency comes at the cost of moderate energy inputs required for aeration and mixing, resulting in higher operational expenses compared to passive bioreactors like woodchip systems.

Constructed wetlands offer effective removal of organic matter and phosphorus, often achieving up to 93% reduction in chemical oxygen demand (COD) and around 76% phosphorus removal [45, 46]. Their performance depends on long hydraulic retention times (often exceeding 18 hours) and sufficient land availability, which can be limiting factors in large-scale operations [47]. Wetlands require minimal energy inputs but pose challenges in terms of space and treatment time [47].

Comparatively, MBBRs provide superior treatment efficiency for nitrogen and organic matter removal in compact spaces with controlled process parameters, making them suited for intensive aquaculture setups like recirculating aquaculture systems (RAS) [48]. Anaerobic digesters (such as woodchip bioreactors) excel in cost-effectiveness and low-energy operation, mainly targeting nitrate removal but with lower overall nutrient removal rates and slower kinetics [49]. Wetlands, while energy-efficient and effective for certain pollutants, are less feasible where space and rapid treatment are critical.

6. Environmental and Economic Impacts

Biological treatment technologies for aquaculture wastewater offer significant environmental and economic sustainability benefits compared to conventional chemical methods [3, 50]. Biological processes use natural microbial communities to degrade organic pollutants and transform nutrients like nitrogen and phosphorus into less harmful forms, reducing the risk of toxic chemical residues and secondary pollution often associated with chemical treatment [50]. This promotes healthier aquatic ecosystems and supports regulatory compliance for environmentally responsible aquaculture operations. Additionally, bioreactors enable resource reuse by facilitating water recycling within recirculating aquaculture systems (RAS), thereby minimizing water consumption and effluent discharge [51]. They also support recovery of valuable byproducts, including bioenergy from anaerobic digestion of sludge and nutrient-rich biomass usable as fertilizer or feed additive, contributing to circular economy principles [52].

However, deploying bioreactors in aquaculture faces challenges such as the need for careful control of operational parameters (temperature, oxygen levels, pH) to maintain stable microbial communities and treatment efficiency. In-

frastructure and maintenance costs can be high, especially for sophisticated systems like membrane bioreactors and photobioreactors [53]. Land availability may limit the use of wetlands or large-scale photobioreactors at some sites. Furthermore, treatment performance depends on varying influent quality, necessitating customizable designs and skilled management to prevent issues such as clogging or microbial imbalances [54]. Despite these challenges, the environmental advantages, potential for resource recovery, and long-term economic savings position biological bioreactors as key technologies for sustainable aquaculture water treatment [13].

7. Future Perspectives and Research Directions

Future perspectives and research directions in aquaculture wastewater management emphasize the need for site-specific integrated treatment designs. These designs tailor technologies to local environmental conditions, wastewater characteristics, and operational goals, ensuring optimized treatment efficiency and sustainability. Advancing integrated systems that combine biological, physical, and chemical processes can better handle variable influent loads and complex pollutant profiles, enhancing resilience and adaptability [55].

Microbial engineering is a promising frontier, aiming to develop customized microbial consortia with enhanced biodegradation pathways. Through genetic and metabolic engineering, microbes can be tailored to target specific pollutants more efficiently, improve nutrient recovery, and withstand environmental stresses [20, 56]. This approach could significantly boost bioreactor performance, reduce treatment times, and enable recovery of valuable bioproducts.

Circular economy models hold great potential in transforming aquaculture wastewater management by closing resource loops. Instead of viewing wastewater as waste, these models promote recovery and reuse of water, nutrients, and energy [52]. For example, nutrient-rich wastewater can be repurposed as fertilizer or used in integrated multi-trophic aquaculture systems; organic waste can be converted into bioenergy; and microalgae biomass cultivated in photobioreactors can serve as feed or biofuel feedstock [3, 46, 57]. Such circular approaches minimize environmental footprints, reduce dependence on external inputs, and can generate new revenue streams. The transition toward circular economy paradigms aligns aquaculture with sustainable growth targets while addressing global resource challenges.

8. Conclusions

Recent advances in bioreactor technologies have significantly enhanced the sustainability of aquaculture water treatment by providing efficient and eco-friendly solutions for managing wastewater. Key technological developments include the application of Moving Bed Biofilm Reactors

(MBBRs), membrane bioreactors, anaerobic digesters, and integrated hybrid systems that combine biological, physical, and chemical processes. These innovations improve pollutant removal rates particularly for nitrogen, phosphorus, organic matter, and emerging contaminants, while enabling resource recovery such as bioenergy production and nutrient recycling. Microalgae-based bioreactors have emerged as promising tools for carbon sequestration and nutrient uptake, contributing to reduced environmental footprints and circular economy models.

These bioreactor technologies play a crucial role in sustainable aquaculture by maintaining water quality in recirculating systems, minimizing harmful discharges, and reducing freshwater consumption through water recycling. Biological treatment methods avoid the generation of toxic by-products common in chemical treatments, thereby protecting aquatic ecosystems and supporting regulatory compliance. Moreover, integration with resource recovery streams such as bioenergy generation and fertilizer production promote circular bioeconomies that enhance both environmental and economic sustainability of aquaculture operations.

Abbreviations

COD	Chemical Oxygen Demand
MBBRs	Moving Bed Biofilm Reactors
MBRs	Membrane Bioreactors
RAS	Recirculating Aquaculture Systems
SBRs	Sequencing Batch Reactors
SBRs	Sequencing Batch Reactors
TAN	Total Ammonia Nitrogen

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Alebachew Molla is the sole author. The author read and approved the final manuscript.

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