

Review Article

Biofilm and Microbial Community Dynamics in Aquaculture Bioreactors for Water Quality Control: Current Status and Future Directions

Alebachew Molla* 

Department of Biotechnology, Wolaita Sodo University, Wolaita, Ethiopia

Abstract

A biofilm in aquaculture is a community of microorganisms, including bacteria, algae, fungi, and others, that forms a complex and structured layer attached to surfaces within water systems. Aquaculture bioreactors rely on biofilms as critical microbial consortia that drive water quality improvement through nutrient cycling and organic matter degradation. This review highlights the dynamic succession and diversity within biofilm microbial communities, particularly emphasizing key bacterial groups such as Planctomycetes, Bacteroidetes, nitrifiers, and denitrifiers that mediate ammonia and nitrogen removal. Biofilms form robust structures through sequential attachment, growth, and maturation stages, influenced by physical and chemical parameters. Molecular tools like 16S rRNA gene sequencing have advanced our understanding of biofilm ecology, revealing community shifts responsive to environmental and operational conditions. Biofilms also contribute to pathogen suppression yet pose challenges through antimicrobial resistance, necessitating balanced management to optimize treatment efficiency without biomass overgrowth. Promising future directions include engineering microbial communities and incorporating probiotics to enhance functional biofilms tailored for sustainable aquaculture. This collective knowledge supports improved aquaculture sustainability by ensuring efficient water treatment, fish health, and environmental protection. Continued integration of molecular techniques and biofilm management strategies will enhance bioreactor design and operation for resilient, eco-friendly aquaculture systems. The aim of this review is to assess the role of biofilms and microbial community dynamics in aquaculture bioreactors for effective water quality control and sustainable aquaculture production.

Keywords

Biofilm, Aquaculture Bioreactors, Microbial Community Dynamics, Water Quality Control, Nitrification, Denitrification, Organic Matter Degradation

1. Introduction

Biofilms play a crucial role in aquaculture water treatment by forming attached communities of microorganisms on submerged surfaces that contribute to water quality improvement [1, 2]. These biofilms harbor nitrifying bacteria

that convert toxic ammonia waste into less harmful compounds through nitrification, reducing the need for water exchange and minimizing harmful nitrogen accumulation in culture systems [3, 4]. Additionally, biofilms provide a nutri-

*Corresponding author: alexhm2127@gmail.com (Alebachew Molla)

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tious food source for aquatic species and shelter, thus supporting growth and survival. Their role in trapping suspended solids, breaking down organic matter, and enhancing microbial activity further stabilizes the aquatic environment, making biofilm-based technology a sustainable and cost-effective tool for aquaculture production, especially benefiting resource-limited farmers [5].

Microbial communities within biofilms participate actively in critical biogeochemical cycles such as nitrogen cycling, including aerobic nitrification and anaerobic denitrification, with the presence of both aerobic and anaerobic microenvironments [6-8]. These microbial processes not only improve water quality but also reduce the buildup of pathogenic bacteria by lowering nitrogenous compounds to safe levels [1]. Moreover, biofilm microbial activity enhances the removal of phosphorus and organic matter, thus maintaining a balanced ecosystem conducive to healthy aquaculture practices. Microbial biofilms also contribute enzymes and bioactive compounds that promote immune function and growth in cultured organisms [1, 9].

The integration of biofilm systems into aquaculture aligns closely with sustainable aquaculture practices by minimizing environmental impact, reducing the frequency of water exchange, and recycling nutrients naturally within the system [10]. This promotes efficient resource use, decreases water pollution risk, and supports healthier and higher yields in fish and shellfish production. Biofilm-based technologies thus offer an eco-friendly approach to wastewater treatment and nutrient control in both small-scale and intensive aquaculture, advancing the goals of sustainability in food production [9].

2. Biofilm Formation and Structure

Biofilm formation on bioreactor surfaces in aquatic environments is a highly regulated, multi-stage process critical to water treatment applications in aquaculture [11-13]. Initially, free-floating microbial cells attach reversibly to surfaces through physical interactions aided by bacterial appendages such as pili and flagella. This phase is characterized by weak and reversible binding. As cells transition to irreversible attachment, they produce adhesive substances and surface proteins, establishing strong adherence that enables resistance to physical and chemical shear forces [14]. Subsequently, attached cells proliferate and produce extracellular polymeric substances (EPS), creating a protective matrix that encapsulates cells and forms microcolonies [11, 12]. The biofilm then matures into a complex, three-dimensional structure with differentiated microenvironments, including water channels that facilitate nutrient distribution and waste removal [11, 15]. Cell-to-cell communication through quorum sensing regulates the development and maintenance of this architecture [16]. Finally, biofilms undergo dispersion where cells actively or passively detach, reverting to their planktonic state to colonize new surfaces [17]. The physical and chemical properties of biofilms, such as EPS composition and surface hydropho-

bicity, as well as environmental factors like nutrient availability, temperature, and hydrodynamic forces, critically influence biofilm growth, stability, and functional performance in bioreactors [18, 19]. Understanding these biofilm dynamics is essential for optimizing water quality control and enhancing the sustainability of aquaculture bioreactor systems.

3. Microbial Community Dynamics

Microbial community dynamics within aquaculture bioreactors are central to the efficacy of biofilm-mediated water quality control. These microbial assemblages are typically diverse, comprising bacteria with functional roles in nutrient cycling critical to maintaining system health [20]. Key bacterial groups commonly observed include nitrifying bacteria such as *Nitrosomonas* and *Nitrospira*, responsible for ammonia oxidation and nitrite oxidation, respectively, which are fundamental in biofilm-driven nitrification processes [4, 21, 22]. Denitrifying bacteria, including members of genera such as *Pseudomonas* and *Paracoccus*, are also integral, facilitating the reduction of nitrate to nitrogen gas in anaerobic zones within the biofilm matrix. Other important bacterial taxa involved in organic matter degradation and sulfur cycling, such as *Planctomycetes* and *Saprospiraceae*, contribute to biofilm stability and ecosystem functioning [23, 24].

Temporal changes and microbial succession within bioreactors reflect adaptations to shifting environmental and operational conditions such as nutrient availability, temperature, pH, and hydraulic regimes [25, 26]. Early biofilm stages often see colonization by fast-growing heterotrophs, followed by enrichment of specialized nitrifiers and denitrifiers as biofilm structure matures [12]. Throughout production cycles, microbial community composition shifts can affect water treatment efficiency and biofilm resilience [26].

Environmental factors, including dissolved oxygen levels, organic carbon availability, and water flow patterns, strongly influence microbial population dynamics [27, 28]. Operational parameters such as feed rates, reactor design, and cleaning frequency also shape microbial assemblages by modifying habitat conditions and selective pressures [29]. Understanding these complex microbial interactions and their temporal dynamics is key for optimizing biofilm bioreactor performance and ensuring sustained water quality control in aquaculture systems.

4. Role of Biofilms in Water Quality Control

Biofilms play a pivotal role in controlling water quality in aquaculture systems through multiple mechanisms [30, 31]. Primarily, biofilms contribute to nutrient removal by hosting microbial communities that perform nitrification, converting toxic ammonia to nitrite and nitrate, followed by denitrification, which reduces nitrate to nitrogen gas, effectively re-

moving nitrogen from the system. Additionally, certain biofilm-associated microorganisms facilitate phosphorus removal by assimilating it into biomass or through chemical precipitation processes [9]. Biofilms also play an essential role in the degradation of organic matter, breaking down complex organic compounds into simpler substances that are less harmful to the aquatic environment [3].

The interaction between biofilm microorganisms and aquaculture species is multifaceted. Biofilms provide a beneficial habitat that supports microbial processes vital for maintaining water quality, which in turn creates a healthier environment for cultured species [32]. Additionally, biofilms can serve as a natural source of supplemental nutrition for some aquatic organisms. Importantly, biofilms contribute to controlling harmful microbial populations by outcompeting pathogenic bacteria for space and nutrients and by producing antimicrobial compounds, thereby reducing disease risks in aquaculture operations [33, 34].

However, biofilms can also harbor pathogens protected from disinfectants within their extracellular matrix, necessitating careful biofilm management to balance their positive and negative impacts [35, 36]. Effective biofilm-mediated water treatment in aquaculture relies on understanding these microbial dynamics and optimizing conditions that promote beneficial biofilm functions to sustain clean water and healthy aquatic species [1, 18].

5. Advances in Understanding via Molecular Techniques

Advances in molecular techniques such as 16S rRNA gene sequencing and metagenomics have revolutionized the understanding of microbial communities within aquaculture biofilms [37, 38]. Targeted sequencing of the 16S rRNA gene allows for detailed taxonomic profiling by analyzing hypervariable regions that reveal bacterial diversity and composition in biofilms [39, 40]. This approach distinguishes both culturable and unculturable bacteria, providing insights into the complex microbial consortia involved in nutrient cycling and biofilm functions [39]. Metagenomic analyses complement this by uncovering functional genes related to key bioprocesses such as nitrification, denitrification, and organic matter degradation, offering a functional perspective on microbial community roles [41, 42].

Microbial community profiling through these molecular tools has elucidated succession patterns and shifts in community composition in response to environmental and operational changes, enabling targeted biofilm manipulation [43]. For instance, case studies have demonstrated enhanced water quality outcomes by promoting beneficial bacterial groups involved in ammonia oxidation or denitrification through bioaugmentation or controlled reactor conditions [44, 45]. These molecular insights facilitate precision in designing and managing bioreactors to optimize biofilm performance, re-

duce pathogenic microbes, and improve overall aquaculture system sustainability [20]. In sum, 16S rRNA gene sequencing combined with metagenomics provides a comprehensive framework to decode the microbial ecology of aquaculture biofilms, revealing both taxonomic diversity and functional potential, which is critical for advancing biofilm-based water treatment strategies [46].

6. Challenges and Management

Biofilms in aquaculture systems pose significant challenges due to their inherent resistance to antimicrobial agents, which complicates disease control and water treatment. The extracellular polymeric substance (EPS) matrix of biofilms acts as a physical barrier that restricts antibiotic penetration, while also chemically neutralizing or degrading antimicrobial compounds [47, 48]. This structural protection, combined with altered metabolic states of biofilm cells, leads to increased tolerance and survival against antibiotics [48]. Another critical contributor to resistance is horizontal gene transfer, which occurs at elevated rates within biofilms, facilitating the spread of antibiotic resistance genes among bacterial populations [49]. Studies in aquaculture have reported high prevalence of biofilm-associated resistance genes, such as beta-lactamases, highlighting the potential public health risks posed by biofilm-harbored multidrug-resistant bacteria [50, 51].

Balancing biofilm growth in bioreactors is crucial to maximize treatment efficiency while minimizing negative impacts like clogging, excessive biomass accumulation, or pathogen persistence [52, 53]. Overgrown biofilms can impede mass transfer and reactor hydraulics, reducing system performance. Therefore, controlled biofilm management strategies such as periodic cleaning, hydraulic shear regulation, and selective microbial inoculation are employed [54]. Optimization approaches include modulation of nutrient supply to favor beneficial biofilm communities, use of biofilm inhibitors or dispersants when necessary, and employing materials or coatings on reactor surfaces that support stable but manageable biofilm formation [55].

In sum, addressing biofilm antimicrobial resistance requires integrated strategies combining prevention of excessive biofilm formation with targeted interventions to disrupt resistance mechanisms [48]. Advances in molecular diagnostics and engineered bioreactor designs are enhancing the ability to monitor and control biofilms for sustainable aquaculture water treatment [56].

7. Future Directions

Future directions in enhancing aquaculture bioreactor performance center on engineering microbial communities to optimize biofilm functions and water treatment efficacy. One promising approach is the integration of probiotics with bio-

film management strategies [57]. Probiotics, such as *Bacillus*, *Lactobacillus*, and *Pseudomonas* species, can form beneficial biofilms on surfaces including fish skin and intestinal tracts, creating protective barriers against pathogens while improving water quality through enhanced nutrient cycling and organic matter degradation [58]. These beneficial biofilms produce extracellular polymeric substances with antimicrobial properties and modulate immune responses in cultured species, contributing to disease resistance and overall health [59]. Moreover, probiotics can disrupt harmful biofilms formed by pathogens, limiting their colonization and biofilm development [60].

Advancements in sequencing technologies, including high-throughput 16S rRNA gene sequencing and metagenomics, are providing unprecedented resolution in mapping biofilm microbial ecology in aquaculture systems [61]. These techniques allow detailed profiling of both taxonomic and functional aspects of microbial communities, enabling the identification of key strains and functional genes involved in nutrient removal, pathogen suppression, and biofilm stability [62, 63]. This knowledge supports precision engineering of microbial consortia tailored to specific aquaculture environments and operational conditions [64]. Integration of probiogenomics further accelerates the discovery and application of effective probiotic strains by linking genomic traits to performance in aquaculture contexts [31, 58, 65]. Overall, future innovations will hinge on combining microbial community engineering with molecular insights and probiotic applications to sustainably enhance bioreactor water treatment, disease control, and aquaculture productivity.

8. Conclusion

In conclusion, biofilms and their microbial community dynamics play a crucial role in enhancing water quality control within aquaculture bioreactors. The formation of complex biofilm structures enables efficient nutrient cycling through processes such as nitrification and denitrification, organic matter degradation, and phosphorus removal. Key bacterial groups dynamically shift in response to environmental and operational conditions, maintaining biofilm functionality essential for removing harmful substances and controlling pathogenic populations. Advances in molecular techniques, especially high-throughput 16S rRNA gene sequencing and metagenomics, have provided deeper insights into biofilm ecology, allowing targeted manipulation of microbial consortia to improve bioreactor performance.

These findings underscore the importance of optimizing biofilm growth and microbial interactions to sustain aquaculture productivity while minimizing environmental impacts. Through integrated approaches including probiotic application and engineering of microbial communities, sustainable management of biofilms holds significant promise for advancing water treatment and disease control in aquaculture.

Overall, continued research and technological innovation in biofilm dynamics and microbial ecology are vital for improving sustainability and ensuring healthy, efficient aquaculture systems in the future.

Abbreviations

EPS	Extracellular Polymeric Substance
rRNA	Ribosomal Ribonucleic Acid

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The author declares no conflicts of interest.

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