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Research Article

BIOFLOC TECHNOLOGY IN SHRIMP AQUACULTURE: RECENT ADVANCES, NUTRITIONAL BENEFITS, HEALTH, ENVIRONMENTAL SUSTAINABILITY AND FUTURE PERSPECTIVE

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ABSTRACT

Biofloc Technology (BFT) has emerged as an innovative and sustainable approach to shrimp aquaculture, offering improved water quality, nutrient recycling, feed efficiency, and environmental sustainability. This review highlights the fundamental principles, applications, nutritional benefits, growth performance, health advantages, economic feasibility, and future prospects of BFT in shrimp farming. The technology primarily relies on manipulating the carbon-to-nitrogen (C:N) ratio to stimulate heterotrophic microbial growth, converting nitrogenous waste into protein-rich microbial biomass that serves as an additional natural food source for cultured shrimp. BFT contributes to improved shrimp growth, survival, feed conversion efficiency, and immune responses while reducing water exchange, feed dependency, and nutrient-rich effluent discharge. Furthermore, microbial communities within bioflocs provide essential nutrients, probiotics, and immunostimulatory compounds that support shrimp health and disease resistance. Despite these advantages, challenges such as high energy consumption, continuous aeration requirements, suspended solid accumulation, and intensive system management remain significant limitations. Future integration of artificial intelligence, Internet of Things-based monitoring, and climate-smart aquaculture practices could enhance operational efficiency and commercial viability. Overall, BFT represents a promising strategy for sustainable, resource-efficient, and environmentally responsible shrimp aquaculture.

Keywords: Aquaculture, Climate change, Water quality, Nutrition, Biofloc Technology.

INTRODUCTION

The fastest-growing sector of the world's food production system is aquaculture, which is essential for providing animal protein to a population that is expected to reach 9 billion people by the middle of the century (Tran et al. 2023). Global seafood production has increased substantially, and aquaculture is now one of the fastest-growing food production sectors. It is projected that the global population will reach nearly 9 billion by 2050, increasing the demand for aquatic food. Although a great bounce, the increase in production between 2016 and 2018 is considered insufficient, and global aquaculture production should double (Vasava *et al.,* 2020). In other words, the aquaculture production target should be achieved to meet the food demand of the world, where 3 billion people today do not have access to healthy food at the required level. Seafood production, an important food sector, is facilitated via fisheries and aquaculture. Interest in aquaculture is increasing (Khanjani and Sharifinia, 2020) because the amount of production via fisheries (considering natural stocks) is insufficient (Boyd *et al*., 2020; Dawood, 2021). Thus, fish must be raised at increasing levels but through sustainable methods (Frankic and Hershner, 2003). Otherwise, environmental and economic problems are likely to arise in the long run (Piedrahita, 2003; Sharifinia *et al*., 2018). The decrease in access to clear water sources

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limits the sustainable increase of aquaculture production. Moreover, existing water quality problems due to climate change, such as sudden temperature changes, algal blooms, and decreases in water flow rates, also endanger the growth of the aquaculture sector. Given the decrease in access to water resources, many alternative methods of sustainable water use in aquaculture are being studied, including the reuse of treated water (Turcios and Papenbrock, 2014). Biofloc is generated by adding organic carbon and high aeration, which reduces toxic dissolved nitrogen in the water, where internal waste treatment processes are emphasized and encouraged (Liu *et al*. 2019). Although it is a potential technology, the data on operational parameters of BFT is still inadequate. Hence, there is an urgent need for more applied research on operational parameters of BFT to optimize the system, such as immunological effects, microbial-associated molecular patterns production, and nutrient recycling (Bossier and Ekasari 2017). Hence, this review has been designed to highlight the application of biofloc systems and urge the development of this system to produce more aquaculture products without any pollution to the environment and with limited natural resources of water and land.

Background of Aquaculture and the Need for Innovation

Aquaculture is the ideal source of animal proteins, which could be produced at the lowest cost and very fast. In 2020, global fisheries and aquaculture production became a huge industry with an economic value of $424 billion (FAO, 2022). Aquaculture has become the fastest-growing food production sector, supplying more than half of the world's seafood (FAO, 2022). Among aquaculture species, shrimp farming holds a leading position due to its high export value and consumer demand (Boyd & McNevin, 2015). However, conventional shrimp farming systems rely on large water exchanges, high feed inputs, and chemicals, leading to environmental degradation, disease outbreaks, and rising costs (Avnimelech, 2012). These challenges necessitate sustainable and innovative solutions for intensive shrimp culture. One such innovation is Biofloc Technology (BFT), which addresses the dual concerns of waste management and feed efficiency. Instead of discarding nutrient-rich effluents, BFT recycles them into microbial biomass, thereby reducing pollution and providing natural food for shrimp (De Schryver *et al.,* 2008).

Concept and Principles of Biofloc Technology

The foundation of BFT is the manipulation of the carbon-to-nitrogen (C: N) ratio in aquaculture water. By adding an external carbon source (e.g., molasses, wheat bran), heterotrophic bacteria assimilate ammonia and nitrite, forming microbial aggregates known as biofloc (Avnimelech, 1999). These flocs are rich in protein, lipids, vitamins, and probiotics, making them a valuable feed supplement for shrimp (Khanjani *et al*., 2024). Continuous aeration and mixing are required to suspend the biofloc, ensuring they remain available for grazing by shrimp. This process simultaneously improves water quality, reduces toxic nitrogen levels, and enhances shrimp growth performance (Emerenciano *et al.,* 2017).

Historical Development of Biofloc Systems

The concept of zero-exchange aquaculture with microbial manipulation was first introduced in the early 1990s by Professor Yoram Avnimelech in Israel (Avnimelech, 1999). Since then, countries such as Brazil, Thailand, and India have advanced BFT for commercial shrimp production. Initially tested in tilapia and shrimp, the technology has now expanded to multiple species, including freshwater prawns (*Macrobrachium rosenbergii*), catfish, and ornamental fish (Said *et al.,* 2022). Governments and research institutions increasingly recognize BFT as a green technology because it minimizes water use, reduces environmental impact, and increases productivity (El-Sayed, 2021).

Principles and Mechanisms of Biofloc Technology (BFT)

Biofloc Technology (BFT) is grounded in the principle of recycling nutrients within aquaculture systems by converting waste products into microbial biomass that can be reutilized as a natural food source. Its success relies on a delicate balance of nutrient inputs, microbial community structure, and system management practices such as aeration and mixing. Two critical components underpin the functioning of BFT: carbon-nitrogen (C: N) management and biofloc dynamics, and aeration, mixing, and microbial balance. Understanding these mechanisms is essential for optimizing system performance and ensuring the health and productivity of shrimp and other cultured species. In intensive shrimp farming, uneaten feed and excreta release high amounts of nitrogenous compounds such as ammonia (NH_3), nitrite (NO_2^-), and nitrate (NO_3^-). Ammonia is the most toxic of these, with high concentrations leading to reduced growth, impaired immunity, and even mortality (Avnimelech, 1999). Traditional systems rely on water exchange or biofilters to remove these compounds, but BFT provides a more sustainable approach by recycling them into microbial biomass. The cornerstone of BFT is the regulation of the C: N ratio in the culture medium. By supplementing the system with an organic carbon source (e.g., molasses, wheat bran, tapioca flour), heterotrophic bacteria are stimulated to assimilate dissolved inorganic nitrogen into microbial protein (Avnimelech, 2012; De Schryver *et al*., 2008). A C: N ratio of 12-20:1 is generally considered optimal for maintaining efficient microbial assimilation and stable biofloc formation (Emerenciano *et al*., 2017).

When the ratio is too low, autotrophic nitrifiers dominate, converting ammonia into nitrite and nitrate. While this removes ammonia, it does not recycle nutrients into edible biomass. Conversely, excessively high C: N ratios may cause oxygen depletion and overproduction of suspended solids, stressing cultured shrimp (Zhang *et al.*, 2016). The resultant nutrient-rich biomass (biofloc) often

serves as alternative feed source for shrimps. The diversity and complex nature of Biofloc comprises bacteria, algae, protozoa, and other microorgan isms which together form an aggregate of organic matter and extracellular polymeric substances (Iber, Benedict Terkula, *et al*.,2025). Different carbon sources influence biofloc characteristics). Simple sugars like molasses provide rapid microbial growth, while complex carbohydrates such as wheat bran support more gradual and stable floc formation (Martínez-Córdova *et al*., 2015). The choice of carbon source also impacts microbial diversity, nutritional composition, and floc palatability for shrimp (Liu *et al*., 2017).

Growth and Survival of Shrimp under Biofloc Technology (BFT)

Growth and survival are the two most critical parameters in shrimp aquaculture, as they determine overall productivity and profitability. Conventional systems often struggle with disease outbreaks, poor water quality, and high feed conversion ratios (FCR), which negatively impact shrimp performance. Biofloc Technology (BFT) has emerged as a sustainable system that enhances shrimp growth and survival by improving water quality, recycling nutrients, and providing microbial flocs as an additional food source (Avnimelech, 2012; Emerenciano *et al*., 2017). One of the most consistent findings across BFT studies is the significant improvement in shrimp survival rates compared to conventional systems. In marine shrimp (*Litopenaeus vannamei*), survival rates of 96-100% have been reported under biofloc conditions, particularly when water quality and biofloc volume are properly managed (Said *et al.,* 2022; Sciendo, 2023). Reduced pathogen load: Heterotrophic microbial communities outcompete pathogenic bacteria such as *Vibrio* spp., lowering the risk of bacterial diseases (Martínez-Córdova *et al*., 2015). Enhanced immune stimulation: Bioflocs contain immunostimulants such as β-glucans, nucleotides, and probiotics that prime the shrimp immune system (Liu *et al*., 2017). Stable water quality: Lower concentrations of ammonia and nitrite reduce toxic stress, improving shrimp resilience (De Schryver *et al*., 2008). Several studies have demonstrated that shrimp cultured in BFT systems achieve higher growth rates compared to conventional pond or clear-water systems. Research published in the *Wiley Online Library* indicates growth improvements of up to 41%, with significantly lower FCR (Islam, 2023; Wiley, 2022). Nutrient-rich microbial protein: Bioflocs are composed of proteins, lipids, vitamins, and minerals that serve as natural feed supplements, reducing dependence on costly formulated diets (Khanjani *et al*., 2024). Continuous feed availability: Shrimp graze on bioflocs throughout the day, improving feed efficiency and reducing feed wastage (Emerenciano *et al.,* 2017). Gut health benefits: Probiotic microbes in bioflocs enhance digestion and nutrient absorption (Martínez-Córdova *et al*., 2015). Stocking density is a crucial factor influencing shrimp performance under BFT. While the technology allows high-density culture, excessively high densities can stress shrimp, reduce dissolved oxygen, and negatively impact both survival and growth (Zhang *et al.*, 2016). Low to medium stocking densities (150-300 shrimp/m²) generally yield better growth and FCR than ultra-high densities (≥500 shrimp/m²) (Manan *et al.,* 2024). At ultra-high densities, shrimp spend more energy on competition and stress adaptation, leading to slower growth despite high survival. A balanced approach-intensification without overstocking-is recommended to optimize productivity and animal welfare. Thus, although BFT can sustain high-density systems, maximum profitability is often achieved at moderate densities where both survival and growth remain optimal.

Nutritional Benefits and Feed Efficiency in Shrimp Culture under Biofloc Technology (BFT)

Feed is the largest operational cost in shrimp aquaculture, often accounting for 50-70% of total production expenses (Avnimelech, 2012). Therefore, strategies that reduce feed dependence while maintaining growth performance are essential for sustainable and profitable aquaculture. Biofloc Technology (BFT) plays a central role in this regard, as it not only maintains water quality but also provides nutritional benefits through microbial biomass that shrimp can directly consume. The biofloc matrix-comprising bacteria, algae, protozoa, detritus, and extracellular polymers-is highly nutritious, rich in proteins, essential fatty acids, vitamins, and minerals (Khanjani *et al*., 2024). Shrimp grazing on bioflocs benefit from an alternative protein source, reducing reliance on costly formulated diets. This section explores the nutritional composition, substitution potential, and feed efficiency improvements of biofloc technology across shrimp and other aquaculture species. Bioflocs provide a naturally balanced diet with essential macronutrients and bioactive compounds. Protein content: 20-40% of dry weight (Wasielesky *et al.,* 2013).Lipid content: 1-5%, with beneficial PUFA (polyunsaturated fatty acids) such as DHA and EPA (Ju *et al*., 2008).Carbohydrates: 15-25%, serving as an additional energy source (Emerenciano *et al.,* 2017).Vitamins and minerals: High in B-vitamins, carotenoids, and trace minerals such as zinc and selenium (Crab *et al.,* 2012).Immunostimulants: Bioactive molecules (β-glucans, nucleotides, peptidoglycans) enhance shrimp immunity (Martínez-Córdova *et al*., 2015). Up to 30% replacement of dietary protein with dried biofloc meal showed no negative impact on growth or survival (Kumar *et al.,* 2017). Higher levels (>40%) may reduce palatability and growth due to imbalanced amino acid profiles. Wiley Online Library reports growth improvements when biofloc meal replaced 25-30% fishmeal in shrimp diets (Wiley, 2022). Biofloc is a heterogeneous aggregate of suspended particles associated with extracellular polymeric substances and a variety of microorganisms. Microbes such as bacteria, fungi, invertebrates and detritus are composed of it. It is live feed rich in protein formed as a result of the conversion of unused feed and excreta in a culture system to a natural food on exposure to sunlight. In a loose matrix of mucus that is secreted by bacteria and linked by filamentous microorganisms or electrostatic attraction, each Biofloc is held together. Large floc can be seen with the naked eye, but most of them are microscopic. The size of the flock varies from 50-200 microns. Biofloc is found to have good

nutritional value. The dry protein weight varies from 20-50 percent to 0.5-15 percent of fat. It is a good source of vitamins, minerals, and phosphorus, in particular.

Health and Immunity in Shrimp Aquaculture under Biofloc Technology (BFT)

Aquaculture intensification, particularly shrimp culture, has been threatened by recurring disease outbreaks, high feed costs, and water quality deterioration. Biofloc Technology (BFT) has emerged as a sustainable approach that integrates microbial-based water treatment with an in-situ nutritional resource for cultured species. Beyond environmental and feed advantages, BFT has gained substantial recognition for its role in enhancing shrimp health and immunity. Shrimp lack adaptive immunity and rely exclusively on innate immune responses, including enzymatic defenses, hemocyte activity, and oxidative bursts. BFT has been shown to upregulate several of these responses: Phenoloxidase (PO) Activity.

PO plays a central role in the prophenoloxidase cascade, responsible for melanization and pathogen encapsulation. Shrimp cultured under biofloc conditions consistently show higher PO activity compared with clear-water systems. A controlled study reported that *Litopenaeus vannamei* reared in BFT exhibited significantly higher PO activity even under pathogen challenge, suggesting that biofloc microbes act as immune-priming agents (Crab *et al.,* 2012; Emerenciano *et al*., 2017). Respiratory Burst (RB)RB is associated with the generation of reactive oxygen species (ROS), essential for microbial killing. Shrimp in BFT systems display increased RB activity, reflecting elevated phagocytic and microbicidal capacity (Xu & Pan, 2014). This suggests that the constant exposure to microbial antigens in bioflocs acts like a low-level vaccination, stimulating defense readiness. High metabolic activity and ROS production necessitate antioxidant defenses. Biofloc supplementation in diets has been reported to elevate superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx) activities (Kim *et al*., 2017). These enhancements reduce oxidative stress, leading to greater resilience against environmental fluctuations and pathogenic insults. Lysozyme degrades bacterial cell walls and is a key nonspecific defense enzyme. Shrimp exposed to bioflocs or fed diets enriched with biofloc meal show elevated serum lysozyme levels (Dauda *et al*., 2018). Hemocyte proliferation (total hemocyte count, THC) is also positively influenced under BFT, reinforcing systemic immune defenses. Enhanced immunity translates into practical benefits: survival rates in BFT-reared shrimp under bacterial (*Vibrio harveyi*, *V. parahaemolyticus*) or viral challenges (IMNV, WSSV) are significantly higher than in conventional systems (Wei *et al.,* 2016; Guo *et al*., 2023). Cumulative survival in marine shrimp under biofloc systems has been reported in the range of 96-100%, far surpassing survival in conventional ponds.

Environmental & Operational Insights of Biofloc Technology in Shrimp Culture

Biofloc Technology (BFT) is widely recognized as a sustainable aquaculture practice because it reduces dependence on water exchange and external feed, while simultaneously improving biosecurity. In shrimp farming, environmental and operational management play a crucial role in ensuring that the microbial community remains balanced, waste products are assimilated, and resource efficiency is maximized. Unlike conventional systems that rely heavily on water replacement to dilute metabolites, BFT operates on the principle of microbial nutrient recycling, creating an environmentally friendly culture medium (Avnimelech, 2015; Crab *et al.,* 2012). One of the core environmental benefits of BFT is its capacity to operate with little or no water exchange. This aspect minimizes the introduction of pathogens from external water sources and reduces the release of nutrient-rich effluents into surrounding ecosystems. In traditional shrimp ponds, 10-20% daily water exchange is common, which risks spreading diseases such as White Spot Syndrome Virus (WSSV). By contrast, biofloc systems recycle nitrogenous waste and maintain water quality internally (The Hindu, 2022). Shrimp aquaculture has historically been criticized for its environmental footprint, particularly the discharge of nitrogen and phosphorus into rivers and coastal waters. BFT addresses this by transforming toxic metabolites into microbial biomass. The microbial community assimilates ammonia, nitrite, and dissolved organic matter into biofloc, which is subsequently consumed by shrimp. Studies have shown that total ammonia nitrogen (TAN) levels are significantly reduced under proper C: N management (Ekasari *et al*., 2014). Compared to conventional pond discharge, BFT reduces chemical oxygen demand (COD) and eutrophication risk (Emerenciano *et al.,* 2017).

Commercial and Economic Review of Biofloc Technology in Shrimp Culture

The adoption of Biofloc Technology (BFT) in shrimp aquaculture has been driven not only by environmental sustainability but also by its economic attractiveness. BFT reduces feed dependency, enhances production efficiency, and minimizes water use, thus aligning with cost-effective farming practices. However, commercial viability depends on setup costs, operational expenditures, yield performance, and market conditions. Economic feasibility studies from India, Brazil, and Southeast Asia have demonstrated that biofloc-based shrimp farming can be highly profitable when properly managed, although challenges such as high aeration costs, energy dependency, and labor requirements remain limiting factors (Fish Vigyan, 2021; PubMed, 2020).

Current Challenges & Limitations, and Future Directions & Research in Biofloc Technology (BFT)

Biofloc Technology (BFT) has matured from a promising concept to a mainstream option for intensive shrimp culture, delivering strong performance on survival, growth,

and feed efficiency while reducing water use and discharges. Yet, commercial deployment faces operational, energy, human-resource, environmental, regulatory, and scale constraints. The biofloc system was developed to improve the environmental control over the aquatic animal production. In aquaculture, the strong influential factors are feed cost (60% of total cost), and the most limiting factor is the water and land availability. High stocking density and rearing of aquatic animals require a wastewater aquaculture. Addressing these frictions requires targeted R&D, standardization, and smarter, lower-energy operating envelopes. Below, we synthesize the key bottlenecks and outline a forward-looking research agenda. Continuous aeration and mixing are the lifeblood of BFT; they maintain DO (>5 mg/L), suspend flocs, and drive heterotrophic assimilation. But this makes BFT energy-intensive (often 30-40% of OPEX) and vulnerable to power interruptions that can rapidly precipitate oxygen crashes, TAN spikes, and mortality (El-Sayed, 2021; Samocha *et al.,* 2017). In regions with unstable grids, power failures are a principal risk and compel investment in redundant blowers, gensets, or oxygen cones, which raise CAPEX and emissions (Global Seafood Alliance, 2020s briefings). Excess TSS and volatile suspended solids increase respiration costs, stress shrimp gills, and reduce grazing efficiency; unmanaged floc can drift beyond the ~200-400 mg/L TSS operating window or 10-15 mL L^{-1} Imhoff volume recommended for many shrimp stages (Emerenciano *et al*., 2017; Xu & Pan, 2014).

Advantages of Biofloc technology

Environmental sustainability has become a major objective of modern aquaculture. The importance of protecting the environment and eliminating potential wastes at their sources is acknowledged by all food production methods. For example, new and environmentally friendly systems are encouraged in the aquaculture sector. Since the acceptance of BFT as a sustainable production method in aquaculture, studies have generally focused on rearing water quality. In intensive aquaculture with zero water discharge, a high nutrient input encourages dense microorganism communities (Minaz and Kubilay, 2021). The environmentally friendly system of culture. It decreases the environmental impact. Improves the effectiveness of land and water usage. Limited exchange of water or zero. Higher productivity (increased rate of survival, development, and conversion of feed). Greater Biosecurity. Reduces and cost of cost-effective water pollution. Reduces the pressure on fishing catches.

Disadvantages of biofloc technology

The BFT, due to its working principles, focuses on the welfare of the heterotrophic bacterial community in the environment to keep the water quality within the optimum ranges for fish or shellfish being cultivated. Therefore, BFT strongly influences harvest yield by providing suitable water quality over the culture period (Crab *et al*., 2012). The water temperature required for the bacterial community within BFT limits the species available for the system. The BFT systems work more efficiently at higher water temperatures and are mostly studied in tropical regions. Therefore, cold-water fish species or fish farms functioning in northern countries may have difficulty with the application of BFT systems. In other words, to keep up with the development of aquaculture trends, it is necessary to focus on alternative species in terms of suitability for the BFT. In this context, BFT systems can make it possible to support sustainable farming in many countries and for others to turn to alternative farming types. To provide the living environment of heterotrophic bacteria in the BFT system, the appropriate C/N ratio is provided by adding carbon to the culture water. This causes an abrupt drop in the dissolved oxygen concentration in the water (Gaona *et al*., 2016). Therefore, the system requires a constant mixing and aeration of culture water, resulting in energy costs that could be higher than expected. In addition, the system needs continuous monitoring of fish health and welfare, as bioflocs can increase the levels of suspended solids in the water, leaving fish and shrimp susceptible to environmental stress.

CONCLUSION

Biofloc Technology (BFT) is a sustainable and efficient approach to shrimp aquaculture that improves water quality, feed utilization, shrimp health, and productivity while reducing water use and environmental pollution. Despite challenges such as high energy demand and intensive management, future advances in Artificial Intelligence (AI), IoT-based real-time monitoring, and climate-smart farming practices will enhance the efficiency and profitability of BFT. Continued research and technological innovation will support its wider adoption and contribute to the United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 14 (Life Below Water). Overall, BFT represents a promising strategy for sustainable, climate-resilient, and economically viable shrimp aquaculture.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest

ETHICS APPROVAL

Not applicable

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AI TOOL DECLARATION

The authors declare that no AI and related tools are used to write the scientific content of this manuscript.

DATA AVAILABILITY

Data will be available on request

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