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The Future of Biofloc Development Techniques for Aquaculture: A Comprehensive Review of Current Scenarios and Potential Improvements

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ABSTRACT

Biofloc technology (BFT) has emerged as a promising solution to address challenges in the expanding field of aquaculture. This review synthesizes recent literature to provide a comprehensive overview of biofloc development techniques, their applications, and avenues for future improvement. BFT offers significant advantages, including enhanced pond health, improved water quality, and reduced operational costs. By cultivating and managing heterotrophic bacteria within the system, BFT minimizes water exchange and facilitates the formation of bioflocs that serve as nutrient-rich food sources for cultured organisms. This review explores the mechanisms underlying biofloc formation, their impact on water quality management, and their role in promoting the growth and health of aquaculture species. However, the implementation of bioflocs in newly established ponds presents challenges, such as limited control over microbial dynamics and the potential presence of bacterial pathogens, which can result in economic losses and jeopardize animal welfare. This review underscores the importance of ongoing innovation and research to optimize biofloc technologies, addressing issues viz. ammonia accumulation and the search for cost-effective feed alternatives. By examining emerging trends and technological advancements, this review underscores the potential of biofloc development techniques to enhance the sustainability and efficiency of aquaculture practices.

INTRODUCTION

Intensive systems with high-density cultures necessitate significant quantities of feed to be introduced into the systems. As a result, water quality deteriorates because of increased concentrations of organic compounds **(Avnimelech, 2007)**. According to **Avnimelech and Ritvo (2003)**, fish only convert 20-30% of their feed into biomass. Approximately, 70-80% of the remaining waste is released into water as unconsumed food and excrement. According to **Stickney (2005)**, the protein in a meal is transformed into ammonia, which acts as the main nitrogenous waste in the protein metabolism of teleosts and aquatic invertebrates. Bacteria aid in the transformation of organic nitrogen present in unconsumed food and feces into ammonia through a process called mineralization **(Gross & Boyd, 2000)**. The utilization of high-protein feed leads to an elevated production of ammonia (NH3) inside the system. Elevated ammonia concentrations in water pose a significant risk to aquatic animals because of its toxicity, which remains even at low levels.

To ensure the safety of aquatic species, ammonia nitrogen levels should not exceed 0.8-2.0mg N/L **(Stickney, 2005)**. Water exchange is the primary method for preserving water quality **(Boyd, 2003)**. Water discharge commonly contains elevated concentrations of fertilizers, particularly nitrogen **(Yoo & Boyd, 2012)**. Several methods have been devised to address the buildup of ammonia in aquaculture, including biofloc technology (BFT), recirculating aquaculture systems (RAS), and periphyton-based aquaculture.

Biofloc technology (BFT) is a highly promising alternative to conventional food production, and has attracted the attention of scientists and aquaculture companies. The system has three primary advantages: (i) it eliminates the need for water exchange, enabling the efficient utilization of limited water resources and preventing the release of nutrient-rich wastewater into the environment; (ii) it reduces the reliance on artificial feed (fishmeal), resulting in lower production expenses while still utilizing cost-effective yet highly nutritious protein sources; and (iii) it promotes the natural development of microbial biomass and improves the growth, efficiency, and immunity of aquatic species raised in the system in addition to purifying the water. Much research has been conducted on the application of this technology in farming methods for producing certain finfish species and crustaceans **(Bossier & Ekasari, 2017; Martins, *et al.*, 2020)**.

Biofloc technology (BFT) is used in aquaculture to control water quality by cultivating and managing heterotrophic bacteria within the culture system while reducing or eliminating the need for water exchange. According to **Jorand *et al.* (1995)**, **Hargreaves (2006)**, **Avnimelech (2007)**, and **De Schryver *et al.* (2008)**, bioflocs are formed during the formation of microbial communities. Bioflocs are composed of a mixture of microorganisms, particles, colloids, organic polymers, cations, and dead cells. Subsequently, these bioflocs can be ingested by cultivated animals to establish a nutrient recycling mechanism inside an aquaculture system. Several studies have demonstrated that biofloc technology (BFT) improves the production efficiency of various aquaculture species, including prawns and tilapia **(Avnimelech, 2007; Kuhn *et al.*, 2008, 2009)**.

Biofloc technology (BFT) allows for the cultivation of marine species such as *P. vannamei* in inland locations without the need for significant water exchange. This minimizes negative effects on local ecology **(Avnimelech, 2015)**. Bacterial populations play a crucial role in biofloc systems **(Cardona *et al.*, 2016)**. Although intense nitrification effectively decreases the accumulation of ammonia and nitrite, microbial control offers superior and more efficient ways to eliminate toxic nitrogen byproducts. The bacterial cells primarily contain proteins. Most microorganisms have a C:N ratio of approximately 4:5. Bacteria require nitrogen from water to synthesize proteins necessary for cell growth and reproduction when provided with organic substrates rich in carbon, such as starch, molasses, and cassava meal. The addition of carbonaceous resources converts harmful inorganic nitrogen into microbial proteins **(Browdy *et al.*, 2012)**.

Functionally, BFT relies on a heterotrophic process that produces edible bioflocs, also known as single-cell proteins (SCP), from uneaten feed, excrement, and extra nutrients. Bacterial mucus loosely binds to the SCP to form visible floating clumps that serve as nutrient-rich foods for prawn or fish cultures. Since each pellet is used twice, both as fresh pellets and SCP, the efficient use of a BFT system leads to a 30% reduction in fish feed costs, thereby increasing aquaculture production and profitability. **(Avnimelech, 2007)**.

The concept of biofloc

Bioflocs are heterogeneous macroaggregates of planktonic materials that are present in aquatic environments. These entities consist of a consortium comprising floc-forming bacteria, filamentous microalgae, diatoms, protozoa, micro- and macro-invertebrates, uneaten feed, and fecal debris **(Avnimelech, 2007)**. The utilization of particulate organic matter and the formation of clusters of bacteria, algae, or protozoa held together in a structure improve waste management, disease control, and water purity in intensive aquaculture systems **(El-Sayed, 2021)**.

The current state of biofloc development techniques have demonstrated a range of novel methods designed to improve the sustainability and efficiency of aquaculture. Biofloc technology (BFT) is a sustainable approach that enhances productivity by transforming harmful substances generated by fish into valuable protein feed. This process effectively reduces the toxicity of nitrogenous compounds in culture systems, thus making it environmentally friendly **(Sharma *et al.*, 2023)**. This technology has been applied to different species, including catfish and prawns, with modifications, such as the use of carbonation and bio-balls to enhance water quality and growth factors **(Pantjara *et al.*, 2010; Deswati *et al.*, 2023)**.

BFT enhances nutrient recycling by upholding a high carbon/nitrogen (C/N) ratio, typically above 15, to stimulate the rapid growth of heterotrophic bacteria. To increase the C/N ratio, additional carbon sources, such as molasses, cassava, hay, sugarcane, starch, wheat bran, and cellulose, were added to the pond water surface, along with constant aeration. Under optimal BFT conditions, a maximum of 0.5 grams of heterotrophic bacterial biomass per gram of carbon substrate can be generated. Farmers can estimate the number of flocs in culture systems using the data that 1g of carbon yields 0.5g of bacteria. The biofloc technique promotes the natural growth of macro-aggregates of organisms that improve self-nitrification in culture water **(Eding *et al.*, 2006)**.

In outdoor BFT systems, algal generation through photosynthesis typically occurs before bioflocking. Algae serve as surfaces for the adherence of bioflocs, which are also referred to as green bioflocs. Indoor bioflocs predominantly comprise microorganisms, and are sometimes referred to as brown bioflocs. Bacterial flocs initiate secondary production by supplying an ample carbon source. This process involves the decomposition of organic waste by bacteria, resulting in the formation of additional bacterial cells (heterotrophic cycles). These conditions are optimal when aeration is adequate **(Crab *et al.*, 2007)**.

Autotrophic and heterotrophic bacteria multiply during this process and draw billions of other cells such as diatoms, fungi, algae, protozoans, and various types of plankton. Traditional aquaculture ponds do not introduce carbon sources or aeration mechanisms, resulting in fewer and less diverse bacterial communities compared with BFT. A minimal number of bacteria did not create significant clusters in the culture system. Traditional pond sediments contain 49% nitrogenous waste, whereas BFT pond sediments contain only 5% (Fig. 1) **(Ogello *et al.*, 2021)**.

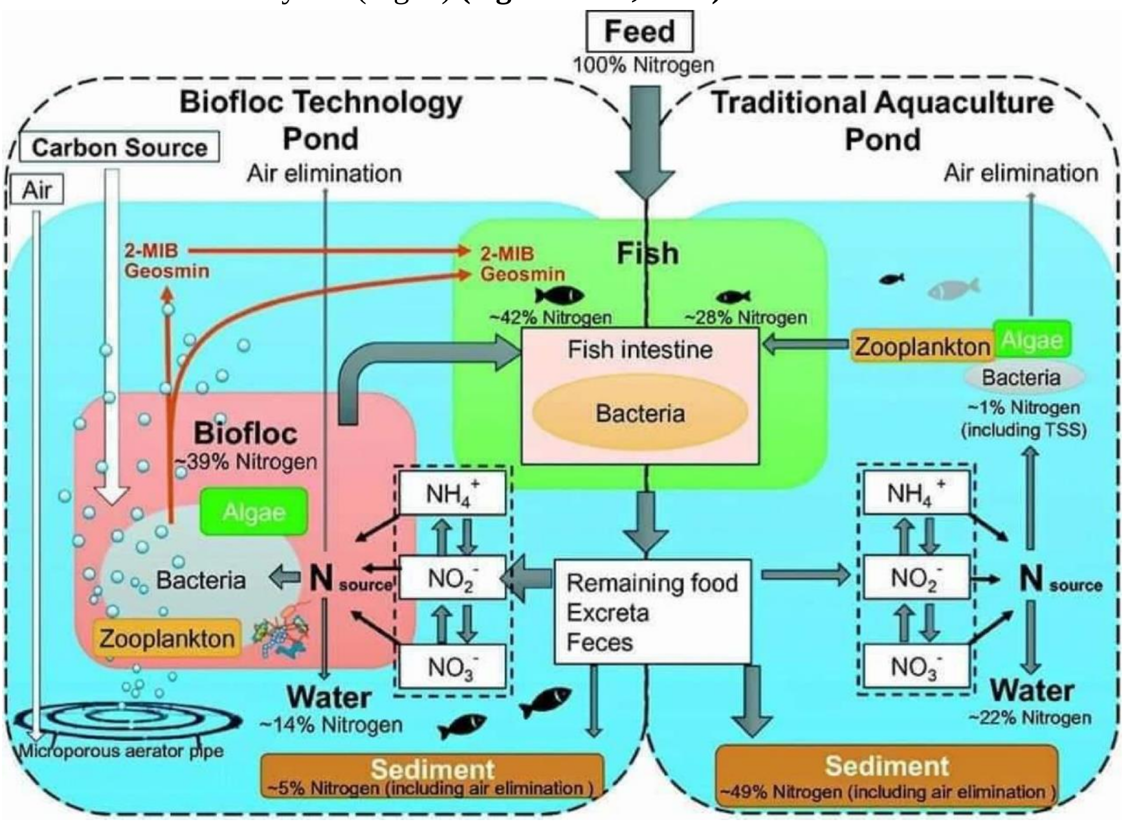

Fig. 1. The role of bacteria in the development of biofloc and the conversion of uneaten feed and toxins feces into edible feed **(Jamal *et al.*, 2020)**

Bio-flocculation mechanism

Microbial cells aggregate to create matrix flocs via intricate flocculation mechanisms regulated by physical, chemical, and biological factors. The primary components of the floc matrix consist of extracellular polymeric structures that create microbial capsules that attach to biofloc components **(Suresh *et al.*, 2018)**. The flocs consist of polysaccharides, proteins, humic chemicals, nucleic acids, and lipids. The majority of these are primarily consisted of slime or capsule layers that were nitrogen-deficient.

Table 1. Comparison of biofloc technology (BFT) with recirculating aquaculture systems (RAS), aquaponics, and traditional pond culture

Aspect	BFT	RAS	Aquaponics	Traditional pond culture	Reference
Water use	Minimal water exchange, high efficiency	Minimal water exchange, high efficiency	Minimal water exchange, high efficiency	Regular water exchange, lower efficiency	**Ebeling & Timmons, 2010; Rakocy, 2012; Boyd & Tucker, 2012; Emerenciano *et al.*, 2013; Goddek *et al.*, 2019)**
Nutrient cycling	In-situ recycling by microorganisms	Biological and mechanical filtration	Nutrients used for plant growth	Limited recycling, relies on external inputs	**(Avnimelech, 2009; Ebeling & Timmons, 2010; Boyd & Tucker, 2012; Goddek *et al.*, 2019)**
Stocking density	High	Very high	Moderate to high	Low to moderate	**(Ebeling & Timmons, 2010; Boyd & Tucker, 2012; Emerenciano *et al.*, 2013; Goddek *et al.*, 2019)**
Disease management	Enhanced resistance due to probiotic effects	Controlled environment, but outbreaks	Balanced system provides some	More susceptible, often requires	**(Rakocy *et al.*, 2006; Ebeling & Timmons, 2010; Crab *et al.*,**

		can be severe	natural resistance	chemicals	**2012; Boyd & Tucker, 2012)**
Energy use	Moderate (mainly for aeration)	High (pumping, filtration)	Moderate to high	Low	**(Ebeling & Timmons, 2010; Boyd & Tucker, 2012; Martínez-Córdova *et al.*, 2015; Goddek *et al.*, 2019)**
Operational complexity	Moderate	High	High	Low	**(Ebeling & Timmons, 2010; Boyd & Tucker, 2012; Emerenciano *et al.*, 2013; Goddek *et al.*, 2019)**
Waste production	Low, mostly converted to microbial biomass	Low, concentrated	Very low, used for plant growth	High	**(Avnimelech, 2009; Ebeling & Timmons, 2010; Boyd & Tucker, 2012; Goddek *et al.*, 2019)**
Sustainability	High	High	Very high	Moderate	**(Ebeling & Timmons, 2010; Boyd & Tucker, 2012; Bossier & Ekasari, 2017; Goddek *et al.*, 2019)**

The existing methods for biofloc synthesis

At present, there are three approaches available for generating bioflocs: natural transition, inoculation, and customized procedures.

1. Natural transition approach

Autotrophs are growing with the application of fertilizers, fish/shrimp meal, and other substances. Autotrophs can be converted into heterotrophs by providing them with a carbon source while ensuring that the ratio of carbon to nitrogen remains between 12:1 and 15:1. The speed and duration of biofloc generation are influenced by the salt level and type of carbon used in the system **(Khanjani *et al.*, 2017)**. Higher salinity levels lead to greater biofloc density, and floc quality depends on the carbon source used **(Maica *et al.*, 2012)**. Adding carbonaceous organic matter, such as molasses, to an aquaculture system can enhance water quality and promote faster growth of heterotrophic bacteria without replacing the water, as opposed to using complex carbohydrates such as wheat flour. A color shift from green to brown was noticeable as the flocs accumulated. The drawbacks of this method include its time-consuming nature and the fact that the straightforward conversion from autotrophs to heterotrophs requires several days **(Panigrahi *et al.*, 2019)**.

2. Inoculum approach

This approach entails the introduction of fresh biofloc-based culture water after evaluating the nutrient availability and water quality of the previous crop. To produce bioflocs, the fermented carbon sources (such as rice bran and molasses) are immersed in water and exposed to air for a period of 24- 48 hours. Following the cultivation phase, the biofloc mass was dehydrated and transformed into fine powder. The powder was stored and dissolved in a carbon source to obtain a fermented product. This technique is more efficient than natural transitions since it saves time and allows bioflocs to be produced quickly **(Panigrahi *et al.*, 2019)**.

3. Customization approaches

Probiotics are increasingly used as alternative health management tools in shrimp hatcheries and aquaculture because of their beneficial effects and ability to avoid the drawbacks of antibiotics, such as resistant strains and immune suppression. Probiotics enhance the production performance and immune responses in species such as *P. vannamei* by modulating the immune system. They can be combined into bioflocs to create optimal conditions, providing benefits, such as enzyme production, omega-3 fatty acids, and reduced harmful substances. Probiotics, including lactic acid bacteria (LAB), *Vibrionaceae*, *Pseudomonas*, and *Bacillus* spp., protect various aquatic organisms. Their mechanisms of action include the production of inhibitory compounds, competition for resources and adhesion sites, and enhancement of the immune response. Probiotics also contribute to bioremediation by mineralizing organic matter, enhancing primary productivity, and maintaining a stable pond community through nitrification and denitrification, which helps eliminate excess nitrogen and exclude pathogens **(Panigrahi *et al.*, 2019)** (Table 2).

Table 2. Comparative summarizing the three approaches in biofloc-based aquaculture

Feature	Natural transition approach	Inoculum approach	Customization approaches
Description	The transformation from autotrophs to heterotrophs by adding carbon sources and maintaining a specific C ratio.	Introduction of new biofloc-based culture water and quick biofloc production.	Use of probiotics to enhance production performance and immune responses.
Procedure	Addition of fertilizers, feed, and carbon supply to create autotrophs and transform them into heterotrophs.	Aerate fermented carbon sources with water, dry and process biofloc mass into powder.	Combine probiotics into bioflocs to create optimal conditions.
Efficiency	Time-consuming; straightforward conversion takes several days.	More efficient than natural transitions; saves time and allows quick production of bioflocs.	Enhances production performance and immune responses.
Health Management	Not specified.	Not specified.	Avoids drawbacks of antibiotics; prevents resistant strains and immune suppression.
Immune System Modulation	Not Specified.	Not Specified.	Probiotics modulate the immune system.
Additional Benefits	Enhances water quality and promotes	Rapid production of bioflocs.	Probiotics provide enzyme production,

	faster growth of heterotrophic bacteria.		omega-3 fatty acids, and reduce harmful substances.
Microbial Action	Transformation from autotrophs to heterotrophs.	Generation of bioflocs through fermentation.	Probiotics produce inhibitory compounds, compete for resources and adhesion sites, and enhance immune response.
Bioremediation	Enhances water quality by adding carbonaceous organic matter.	Not mentioned.	Probiotics mineralize organic matter, enhance primary productivity, and maintain a stable pond community through nitrification and denitrification.
Target Organisms	General biofloc systems.	General biofloc systems.	Various aquatic organisms, including shrimp.
Examples of Probiotics	Not applicable.	Not applicable.	Lactic acid bacteria, Vibrionaceae, *Pseudomonas, Bacillus* spp.
Pathogen Exclusion	Not Excluded	Not Excluded.	Probiotics help exclude pathogens.
Resource Efficiency	Enhances resource use without replacing water.	Saves time in biofloc production.	Enhances resource use by competing for resources and improving water quality.
Quality Factors	Biofloc density and quality depend on	Biofloc production is quick and	Probiotics contribute to overall pond health and

	salinity and carbon source.	efficient.	stability.

This table provides a detailed comparison of the three approaches, highlighting their procedures, efficiency, health management benefits, and other factors relevant to BFT-based aquaculture.

Advantages of biofloc technology

Due to the large quantity of food, fish and shrimp ponds have a significant concentration of nutrients. Approximately 50-70% of the feed is present in the water or sediment, leading to a decline in water quality in the cultured pond caused by an imbalance of carbon and nitrogen. Through photosynthesis and nitrification processes, biofloc technology can enhance water quality in fish and prawn ponds by regulating carbon and nitrogen levels **(Crab *et al.*, 2012)**.

Table 3. Advantages and approaches in biofloc technology (BFT)

Advantages	Description	Benefits	References
Eco-friendly culture system	BFT operates with zero drain water after culture, making it an environmentally sustainable option.	Reduces environmental pollution and conserves water resources.	**(Reddy, 2019; Saeedi & Chapara, 2024)**
Reduction of environmental impact	BFT is more capable of reducing environmental impact than other fish farming systems.	Minimizes ecological footprint and enhances sustainability.	**(Reddy, 2019)**
Efficient Use of Land and water	BFT improves the effective use of water and land, maintaining suitable water quality with minimal water usage and exchange.	Enhances resource efficiency and sustainability in aquaculture.	**(Reddy, 2019)**
Production of	Biofloc produced in BFT serves	Provides a cost-	**(Reddy,**

protein-rich biofloc	as supplementary feed for aquatic organisms, enriching their diet.	effective and nutritious feed alternative.	**2019)**
Higher biosecurity	Biofloc technology ensures water cleanliness and enhanced biosecurity by minimizing wastewater contamination and mitigating the danger of disease transmission. Reusing water minimizes the likelihood of introducing exogenous pathogens into the system.	Improves overall health and reduces disease outbreaks in aquaculture.	**(Ray, 2011; Moscoso *et al.*, 2018)**
Enhanced survival and growth rates	BFT enhances fish culture systems' survival rates, growth performance, and feed conversion.	Boosts productivity and efficiency in aquaculture operations.	**(Liu *et al.*, 2014; Bossier & Ekasari, 2017; Reddy, 2019)**
Economic efficiency	Producing inexpensive biofloc as feed decreases the requirement for protein-rich feed, hence enhancing cost-efficiency in production.	Reduces operational costs and enhances economic viability.	**(Reddy, 2019)**
Reduced dependence on wild fisheries	BFT alleviates the strain on catching fisheries, hence reducing the demand for inexpensive food fish and low-quality fish used in the fishmeal business.	Supports sustainable fishery practices and conservation efforts.	**(Reddy, 2019)**
Eco-friendly protein feed production	Converts toxic materials from fish into beneficial protein feed.	Reduces nitrogenous waste, promoting a sustainable aquaculture	**(Sharma *et al.*, 2023)**

		environment.	
Modified systems for the catfish	Introduction of carbonation and bio balls in catfish farming.	Improves water quality and fish growth parameters.	**(Deswati *et al.*, 2023)**
Shrimp farming optimization	Application of BFT in shrimp ponds to enhance overall productivity.	Enhances water quality, reduces disease, and improves feed efficiency.	**(Pantjara *et al.*, 2010)**
Optimal carbohydrate sources	Exploration of an effective carbon source for biofloc in shrimp farming.	Leads to better growth outcomes by optimized nutrient sourcing.	**(Khanjani *et al.*, 2020; Tinh *et al.*, 2021)**
Renewable biosurfactants production	Focus on biosurfactants from renewable sources for BFT.	Encourages eco-friendly and economical production methods.	**(Gunjal, 2022)**
Water quality and environmental control	Implementation of biofloc systems aimed at reducing environmental impact.	Addresses eutrophication and improves water quality through nutrient control.	**(Estim, 2015; Marlida, 2020)**
Best management Practices (BMPs)	Practices used in environmental management to prevent water pollution and other negative environmental impacts.	Pollution control	**(Hairston *et al.*, 1995)**

Drawbacks of biofloc technology

Biofloc systems require high water temperatures to ensure maximum performance of heterotrophic bacteria, resulting in elevated energy expenses. A major disadvantage of biofloc technology is the increased need for aeration and energy to supply sufficient oxygen to many species in the system, including fish, prawns, and bacteria. There is concern about whether cultivated organisms in biofloc systems are acceptable for ingestion, which could affect how well they are received in the market. The requirement for competent personnel to operate biofloc systems is difficult since these systems require specialized knowledge for effective administration and remediation in the event of malfunctions **(Jamal *et al.*, 2020)**. BFT requires higher energy consumption for mixing and aeration. Due to frequent power outages, ensuring a reliable energy supply is a significant challenge in developing countries. Microorganisms require an initial period of approximately two weeks to develop in BFT **(Reddy, 2019; Yu *et al.*, 2023)**.

Although a large bacterial population can be beneficial, the rapid growth of heterotrophic bacteria can lead to excessive turbidity in the system, which may impede the gills of prawns and fish. This is especially true for species that are not well adapted to living in murky waters **(Ogello *et al.*, 2021)**.

The initial phase extended the duration of the production cycle. Alkalinity supplementation is necessary to create favorable conditions for biofloc growth. An imbalance in the microbial community, characterized by a very low bacterial count, can elevate the risk of pollution by the buildup of nitrate compounds. Systems exposed to sunlight may encounter sporadic and seasonal fluctuations in performance, including stoppages in production during intense rainy periods **(Reddy, 2019; Ogello *et al.*, 2021)**. Additional concerns include the potential for the excessive growth of filamentous bioflocs, leading to floc bulking, system instability, and inadequate nitrogen removal **(Ogello *et al.*, 2021)**.

However, there are still significant shortcomings and operational challenges associated with the BFT systems. For instance, variations in microalgae blooms can cause water quality to fluctuate due to the reliance of outdoor systems on the weather. Therefore, when installing outdoor BFT systems, several aspects including site location, light intensity, and season should be considered for sustainable aquaculture production. In addition, close observation of the total suspended solids (TSS) content is necessary. For aquaculture, the ideal TSS concentration is between 500 and 1000mg L^{-1}, above which there is an increase in turbidity, visibility, and FCR, resulting in subpar growth and production (**Jamal *et al.*, 2020; Ogello *et al.*, 2021**).

Although biofloc technology provides advantages in terms of water quality and growth performance, it requires meticulous monitoring and control to avoid problems associated with disease outbreaks or system breakdown.

Table 4. Drawbacks and challenges of biofloc technology in aquaculture

Challenges	Description	Reference
High aeration and water movement Requirement/ Costly aeration equipment	Biofloc systems necessitate substantial aeration and water circulation, resulting in augmented energy demand for mixing and aeration. Expensive equipment is needed to maintain dissolved oxygen levels, adding financial burdens.	**(Reddy, 2019; Yu *et al.*, 2023)**
Reduced response time	The biofloc system's response time can be diminished due to increased respiration rates and the consumption of dissolved oxygen.	**(Reddy, 2019; Jamal *et al.*, 2020)**
Potential pollution from nitrate accumulation	A high microbial population imbalance can increase the risk of pollution from nitrate accumulation, which can potentially pollute the water in biofloc systems.	**(Reddy, 2019; Jamal *et al.*, 2020; Ogello, *et al.*, 2021)**
Challenges in maintaining C/N ratio	Difficulty in achieving and sustaining the ideal carbon-to-nitrogen ratio.	**(Liu *et al.*, 2014; Deng *et al.*, 2018)**
Need for alkalinity supplementation and start-up period	The implementation of biofloc technology necessitates an initial establishment phase. BFT necessitates an initial period of around 2 weeks for the cultivation of microorganisms, which may result in longer production cycles. Continuous alkalinity addition is required to create and sustain favourable circumstances for the growth of biofloc.	**(Reddy, 2019; Ogello, *et al.*, 2021)**
Inconsistent performance and seasonal dependence	The performance of biofloc systems can be inconsistent and may depend on seasonal variations, especially in systems exposed to sunlight.	**(Reddy, 2019)**
Rapid changes in	Nutrient accumulation leads to unstable	**(Yu *et al.*,**

water quality	environments, requiring constant monitoring.	**2023)**
Excessive Turbidity	High bacteria population can cause excessive turbidity, leading to clogging in shrimp and fish gills, especially in species not adapted to turbid waters.	**(Ogello, *et al.*, 2021)**
Frequent maintenance requirements	Biofloc systems often require frequent maintenance, which can be costly and labor-intensive.	**(Reddy, 2019; Jamal *et al.*, 2020)**
Environmental impact concerns	Issues such as nutrient accumulation, eutrophication, and potential pollutant accumulation raise sustainability concerns.	**(Reddy, 2019; Ray & Mohanty, 2020; Rini, 2020; Yu *et al.*, 2023)**
Pathogen risks	Potential for pathogen influence within the system, requiring stringent biosecurity measures.	**(Ray & Mohanty, 2020)**
Seasonal performance variations	Systems exposed to sunlight may experience erratic and seasonal performance, necessitating a halt in output during periods of heavy rainfall.	**(Ogello, *et al.*, 2021)**
Filamentous bioflocs overperformance	Floc accumulation, system instability, and incomplete nitrogen removal may result from the overperformance of filamentous bioflocs.	**(Ogello, *et al.*, 2021)**

Future improvement needs for biofloc technology system

Despite advancements in and benefits of biofloc technology (BFT) in aquaculture, several areas require improvement to enhance its efficiency, sustainability, and overall performance. Below are some key areas for future research:

1. **Energy efficiency**
    - **High aeration and water movement**: The need for significant aeration and water movement increase energy consumption. Developing more energy-efficient aeration systems or integrating renewable energy sources could reduce operational costs and environmental impact.
    - **Reduced response time**: Improving the responsiveness of biofloc systems to changes in dissolved oxygen levels can help maintain optimal conditions and reduce the risk of hypoxia.
2. **Water quality management**
    - **Nitrate accumulation**: It is crucial to manage the accumulation of nitrates and other nutrients. Advanced filtration systems or denitrifying bacteria can help maintain stable water quality.
    - **Consistent C/N ratio**: Achieving and sustaining the ideal carbon-to-nitrogen (C/N) ratio is challenging. Automated monitoring and dosing systems can help maintain a correct balance.
3. **Operational efficiency**
    - **Start-up period and alkalinity supplementation**: Reducing the start-up period for microbial development and optimizing alkalinity supplementation can streamline production cycles. A specific inoculum should be used for fast start-up.
    - **Frequent maintenance**: Simplifying maintenance procedures and developing more robust biofloc systems can reduce labor and operational costs.
4. **System stability and performance**
    - **Seasonal and inconsistent performance**: Addressing the seasonal dependence of outdoor systems, such as installing protective covers or integrating climate control technologies, can improve the stability and performance.
    - **Excessive turbidity**: Managing a large population of heterotrophic bacteria is essential to prevent excessive turbidity and gill clogging in aquatic species. This could involve optimizing the composition and density of bioflocs.
5. **Pathogen control and biosecurity**
    - **Pathogen risks**: Enhancing biosecurity measures to prevent pathogen outbreaks in biofloc systems is crucial. Instead of using pond water, it would be better to use a specific controlled inoculum. This includes regular health monitoring and use of probiotics to boost the immune system of cultured species.
    - **Filamentous bioflocs overperformance**: To maintain system stability and ensure proper nitrogen removal, it is imperative to prevent the excessive growth of

filamentous bioflocs. Regular monitoring and control measures can help maintain system balance.

6. **Environmental impact and sustainability**
   - **Nutrient accumulation and eutrophication**: Implementing best management practices (BMPs) to control nutrient levels and prevent eutrophication can enhance the sustainability of BFT.
   - **Renewable biosurfactants**: Focusing on producing biosurfactants from renewable sources can reduce environmental impacts and promote eco-friendly practices.
7. **Economic and market acceptance**
   - **Cost reduction**: Developing cost-effective biofloc production and maintenance methods can make BFT more economically viable for farmers.
   - **Market acceptance**: It is crucial to ensure that the organisms cultivated in biofloc systems are acceptable for consumption and meet market standards. This includes addressing consumer concerns regarding the safety and quality of the biofloc products.

DISCUSSION

The comparison of BFT, RAS, and aquaponics demonstrates superior water use efficiency with minimal exchange, in contrast to traditional pond culture which requires regular water exchange **(Avnimelech, 2009)**. Nutrient cycling is optimized in BFT and aquaponics through *in-situ* recycling and plant growth utilization, respectively, whereas traditional pond culture relies on external inputs **(Avnimelech, 2009; Ebeling & Timmons, 2010; Boyd & Tucker, 2012; Goddek *et al.*, 2019)**. High stocking densities are achievable with BFT and RAS, while traditional systems are more limited. Disease management benefits are evident in BFT due to probiotic effects and in aquaponics through balanced ecosystems. Energy use is moderate in BFT but high in RAS due to intensive pumping and filtration needs **(Ebeling & Timmons, 2010; Boyd & Tucker, 2012; Emerenciano *et al.*, 2013; Goddek *et al.*, 2019)**. BFT and aquaponics produce minimal waste by converting it into biomass or plant nutrients, promoting sustainability **(Avnimelech, 2009; Ebeling & Timmons, 2010; Boyd & Tucker, 2012; Goddek *et al.*, 2019)**. Overall, BFT and aquaponics offer high sustainability, aligning with modern environmental and resource efficiency goals, while traditional pond culture lags in these aspects.

Extensive analysis of the benefits and challenges of biofloc technology (BFT) in aquaculture. The numerous advantages of BFT have attracted considerable attention, as it is a sustainable and economically feasible choice for aquaculture. However, this poses several obstacles that must be addressed to enhance its implementation and efficiency.

One of the main benefits of BFT is its environmentally friendly nature. BFT effectively minimizes environmental damage and preserve water resources by operating without any discharge of water following the culture process **(Reddy, 2019)**. This renders it a viable and enduring substitute for conventional fish-farming techniques. In addition, BFT has a greater capacity to decrease environmental effects by minimizing the ecological footprint, thereby improving sustainability **(Reddy, 2019)**.

BFT enhances the efficient utilization of land and water resources by preserving an optimal water quality while minimizing usage and exchange. This improves resource efficiency in aquaculture **(Reddy, 2019)**. Producing protein-rich bioflocs serves as an additional food source for aquatic species and offers a cost-efficient and nourishing alternative **(Reddy, 2019)**. Furthermore, this method enhances biosecurity by diminishing wastewater contamination and decreasing the likelihood of disease transmission, thereby enhancing the general health of aquaculture systems **(Arias-Moscoso *et al.*, 2018)**.

Another notable benefit of BFT is its capacity to enhance survival rate, growth performance, and feed conversion in fish culture systems. This increases the productivity and efficiency **(Reddy, 2019)**. Producing biofloc that is inexpensive decreases the requirement for costly feed high in protein, thereby enhancing the cost-effectiveness and economic feasibility of production **(Reddy, 2019)**. In addition, BFT diminishes reliance on untamed fisheries, promoting sustainable fishing methods and conservation initiatives by reducing the demand for inexpensive and low-quality fish used to produce fishmeal **(Reddy, 2019)**.

Various studies have emphasized the particular uses of BFT, such as transforming harmful substances found in fish into advantageous protein feed. This process helps decrease nitrogenous waste and fosters sustainable aquaculture **(Sharma *et al.*, 2022)**. **Deswati *et al.* (2023)** found that implementing carbonation and bio-balls in catfish farming systems enhances water quality and improves fish growth metrics. Implementing biofloc technology (BFT) in prawn ponds boosts the output by enhancing water quality, minimizing disease, and improving feed efficiency **(Pantjara *et al.*, 2010)**. According to **Khanjani *et al.* (2020)** and **Tinh *et al.* (2021)**, using high-quality carbohydrate sources such as corn starch, maize starch and molasses can improve growth outcomes by optimizing nutrient availability. Renewable biosurfactants derived from biofloc systems promote the use of environmentally friendly and cost-effective production methods **(Gunjal, 2022)**. Additionally, initiatives to control water quality and the environment can help mitigate eutrophication and enhance water quality by regulating nutrient levels **(Estim, 2015)**. In addition, closed aquaculture systems provide enhanced biosecurity by minimizing the risk of introducing exogenous infections into the system **(Ray & Mohanty, 2020)**.

Although BFT offers many advantages, it also poses certain obstacles that can hinder efficient production. An important concern is the requirement for extensive aeration and water circulation, which results in elevated energy demand for mixing and aeration. Ensuring a consistent energy supply can be particularly difficult in underdeveloped nations as they frequently experience power outages **(Reddy, 2019)**.

An additional constraint is the initial period necessary for the growth of microorganisms, which can extend the duration of production cycles and postpone the commencement of production **(Reddy, 2019)**. To promote the growth of bioflocs, it is necessary to provide suitable conditions including alkalinity. However, this increases the complexity and cost of operations **(Reddy, 2019)**. Elevated microbial population imbalances can increase the likelihood of nitrate buildup, thus requiring ongoing monitoring and management **(Reddy, 2019)**.

Systems exposed to sunlight may experience irregular and seasonal performance, necessitating halting of production during periods of high rainfall **(Reddy, 2019)**. The excessive growth of filamentous bioflocs can result in floc bulking, system instability, and inadequate nitrogen removal, leading to operational inefficiencies and environmental problems **(Reddy, 2019)**.

Another disadvantage is the rapid fluctuations in water quality caused by the build-up of nutrients, which necessitate continuous monitoring and control **(Yu *et al.*, 2023)**. The requirement for expensive aeration equipment to sustain adequate dissolved oxygen levels imposes financial challenges, resulting in higher upfront and continuous operational expenditures **(Yu *et al.*, 2023)**. Attaining and maintaining an optimal carbon-to-nitrogen ratio may be difficult and can affect the effectiveness of biofloc systems **(Ray & Mohanty, 2020)**. The system also poses possible pathogens hazards, requiring strict biosecurity control **(Ray & Mohanty, 2020)**. Additionally, environmental concerns such as nutrient enrichment, eutrophication, and pollution accumulation give rise to considerations regarding sustainability **(Jamal *et al.*, 2020)**.

To summarize, although biofloc technology presents notable benefits for the promotion of sustainable aquaculture, it is imperative to tackle its obstacles to achieve successful deployment and optimization. By overcoming these constraints, BFT has the potential to become a more efficient and extensively adopted aquaculture approach.

CONCLUSION

Biofloc technology (BFT) provides notable benefits for sustainable aquaculture, such as environmentally friendly practices, greater utilization of resources, and improved protection against biological threats. It enhances productivity and economic efficiency and minimizes reliance on wild fisheries. It enhances characteristics, such as biomass density and disease resistance. Biofloc technology (BFT), recirculating aquaculture systems (RAS), and aquaponics surpass traditional pond culture in water efficiency, nutrient cycling, and sustainability. Despite higher energy demands and complexity, they offer superior disease management and eco-friendliness, making them promising alternatives for sustainable aquaculture development. Nevertheless, it is crucial to address obstacles, such as substantial energy demands, preservation of microbial equilibrium, and possible ecological consequences. It is essential to address these constraints to optimize the application of BFT and to ensure its widespread adoption in aquaculture. Using a specific inoculum could contribute to controlling pond systems, and by addressing these obstacles, BFT could have a crucial impact on sustainable and efficient aquaculture production.

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