

Advances in Biofloc Technology: Emerging Trends and Their Implications for Aquafauna Health and Nutrition

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Abstract

This review comprehensively explores emerging trends in biofloc technology (BFT), focusing on its historical development, evolution, recent advances, and significant effects on aquatic animal nutrition and health. Biofloc systems, characterized by high-density microbial aggregates, have demonstrated substantial benefits, including improved nutritional value, enhanced immune response, and sustainable aquaculture practices. Recent developments emphasize optimizing microbial community management, nutritional quality, and disease mitigation through bioflocs. Comparative analyses with traditional aquaculture systems highlight the nutritional superiority and immunophysiological benefits of BFT.

Keywords: Biofloc Technology (BFT), Aquaculture, Aquatic Organisms, Microbial Aggregates, Nutritional Enhancement, Immune Response and Sustainable Aquaculture.

Introduction

1. Historical Background of Biofloc Technology

Biofloc technology has roots dating back to early wastewater treatment research conducted in the mid-20th century, where microbial flocs were initially recognized for their capability to efficiently remove nutrients and pollutants from wastewater (Mehrim & Refaey, 2023). The foundational concept involved harnessing microorganisms, predominantly bacteria, to assimilate and metabolize excess nutrients, particularly nitrogenous compounds, thus effectively purifying the water. Early studies during the late 1970s and early 1980s began exploring the potential application of microbial flocculants in various environmental management scenarios.

The transition of biofloc from wastewater management into aquaculture occurred notably in the late 1980s when researchers started investigating microbial aggregates' potential for improving water quality and providing nutritional support in fish farming systems (Wang et al., 2022). Initial investigations focused predominantly on closed, minimal water exchange systems, where microbial flocs demonstrated significant potential in ammonia removal through the assimilation of nitrogenous waste.

Significant contributions were made by researchers such as Yoram Avnimelech, who, in the late 1980s

and early 1990s, conducted pioneering studies that laid the groundwork for contemporary biofloc systems (Raza et al., 2024). Avnimelech's research primarily focused on optimizing carbon-to-nitrogen ratios to stimulate heterotrophic bacterial growth, thereby converting inorganic nitrogenous waste into microbial protein. These early works established critical operational principles and laid the foundation for biofloc technology as a sustainable aquaculture practice.

By the late 1990s and early 2000s, biofloc technology was further refined, primarily in shrimp and tilapia culture systems, driven by increasing concerns over water scarcity, environmental pollution, and unsustainable feed practices prevalent in traditional aquaculture (El-Sayed, 2021). Early commercial adoption during this period validated biofloc technology's practical viability, highlighting improvements in production efficiency, water conservation, and environmental sustainability.

2. Evolution of Biofloc Technology

The evolution of biofloc technology can be clearly traced through its progressive improvements in system design, microbial understanding, and nutrient utilization efficiency, contrasting sharply with traditional fish farming practices. Traditional aquaculture, particularly in open pond systems, has long relied on frequent water exchange to manage

waste accumulation, resulting in significant environmental degradation, water use, and susceptibility to pathogen intrusion. Feed inefficiencies and disease outbreaks in traditional systems also led to higher operational costs and antibiotic reliance (Gilchrist et al., 2006 and Manyi-Loh et al., 2018).

In contrast, BFT has evolved from a concept focused on waste bioremediation to a fully integrated, multifunctional aquaculture system. Early systems concentrated solely on water purification through heterotrophic microbial assimilation of nitrogenous waste. However, current BFT practices emphasize maximizing microbial biomass as an in situ protein source, improving feed conversion ratios (FCR), reducing external feed inputs, and minimizing environmental impact (Li & Dai, 2025). Technological advancements have introduced controlled aeration systems, sensors for real-time monitoring of dissolved oxygen and C:N ratio, automated feeding systems, and advanced probiotic integrations, making BFT more precise and manageable. Additionally, the incorporation of IoT-enabled platforms and machine learning algorithms for predictive water quality and microbial dynamics management has begun to emerge, especially in intensive shrimp farming sectors (Ahmed et al., 2024).

Compared to traditional fish farming, BFT offers superior outcomes in terms of biosecurity (due to zero water exchange), sustainability (by recycling nutrients), and animal welfare (by creating stable micro-ecosystems). Furthermore, its compatibility with multiple aquatic species and its integration potential with recirculating aquaculture systems (RAS) and aquaponics reflects its future-forward adaptability.

As BFT continues to evolve, research now focuses on customizing microbial consortia, engineering functional bioflocs for species-specific nutritional requirements, and reducing energy inputs. These advancements position biofloc technology not merely as an alternative but as a leading model for next-generation sustainable aquaculture.

3. Different Types of Biofloc Technology and Their Significance

Over the years, biofloc technology has evolved into several distinct forms based on microbial consortia, carbon sources, and environmental parameters. These systems are generally classified into three main types, each with unique mechanisms and contributions to aquaculture sustainability.

3.1 Heterotrophic Biofloc Systems:

These systems primarily stimulate the growth of heterotrophic bacteria by supplementing organic carbon sources such as molasses, sugarcane bagasse,

or starch (Ray & Lotz, 2014 and Martins et al., 2020). The added carbon elevates the C:N ratio, encouraging bacteria to assimilate toxic nitrogenous waste (mainly ammonia and nitrite) into microbial protein biomass (Avnimelech, 1999 and Panigrahi et al., 2018). This microbial biomass becomes a nutritious live feed for the cultured organisms.

Significance: Heterotrophic systems are highly efficient in nitrogen removal and protein recycling (Lowrey et al., 2016). They are ideal for high-density shrimp or tilapia farming, especially in inland aquaculture where water scarcity is a concern. These systems also reduce dependence on external feed, lowering feed costs while minimizing environmental impact.

3.2 Autotrophic Biofloc Systems:

Autotrophic systems focus on the activity of nitrifying bacteria (e.g., *Nitrosomonas*, *Nitrobacter*) and algae, which convert ammonia to nitrite and nitrate without the need for organic carbon addition (Nag et al., 2022). These systems rely on photosynthesis and naturally occurring microbial communities.

Significance: Autotrophic systems are often more stable in systems with low organic inputs and better suited for species sensitive to high suspended solid concentrations (Machineni, 2019). They offer a more energy-efficient method of maintaining water quality, although the biofloc generated is typically lower in nutritional value than heterotrophic flocs.

3.3 Algae-Based or Photoautotrophic Biofloc Systems:

These systems utilize sunlight to grow microalgae as part of the floc, contributing oxygen and nutritional diversity (de Moraes et al., 2020 and Abakari et al., 2022). Algae contribute essential fatty acids, carotenoids, and vitamins, enhancing the biofloc's nutritional composition (Wei et al., 2016).

Significance: Algae-enriched biofloc systems provide excellent antioxidant and immune-boosting properties to cultured species. These systems are particularly beneficial in polyculture setups and ornamental fish production, where coloration and health status are premium factors. However, light availability and algal bloom control are operational challenges.

3.4 Hybrid and Integrated Systems:

Recent innovations have led to hybrid biofloc systems that combine heterotrophic and autotrophic pathways or integrate biofloc with recirculating aquaculture systems (RAS), aquaponics, or integrated multitrophic aquaculture (IMTA) (Zimmermann et al., 2023).

Significance: These integrated systems offer enhanced nutrient recycling, better control over microbial

dynamics, and tailored environmental conditions. For example, a BFT-RAS hybrid can use biofloc for nitrogen assimilation while RAS handles solid waste and oxygenation efficiently.

Overall, the selection of biofloc system type depends on the target species, production goals, resource availability, and technical expertise. A well-chosen system can significantly boost yield, reduce input costs, and foster more resilient aquaculture operations.

4. Nutritional Parameters and Composition of Biofloc

Bioflocs are composed of a rich consortium of living and dead particulate organic matter, primarily consisting of heterotrophic bacteria, algae, protozoa, fungi, detritus, uneaten feed, and excreted waste products (Emerenciano et al., 2017). These aggregates are bound together by extracellular polymeric substances (EPS), resulting in highly nutritious microbial biomass that serves both as a feed additive and a water treatment agent.

4.1 Proximate Composition:

The proximate composition of biofloc reflects its rich nutritional value and ecological origin. Its constituents are influenced by various factors including microbial diversity, system age, water quality, aeration, and especially the nature of the carbon source used (Deng et al., 2018).

Crude Protein (25–50% dry weight): The microbial cells (mostly bacteria and microalgae) in the biofloc contribute significantly to its high protein content. This protein is considered highly digestible and comparable to fishmeal in amino acid composition, making it a viable protein supplement or partial replacement in aquafeeds. Studies have shown that biofloc-based diets can reduce dependency on expensive feed protein sources (Rajkumar et al., 2016).

Lipids (1–5% dry weight): Although present in lower quantities compared to protein, biofloc lipids are nutritionally dense. These lipids often contain essential fatty acids like linoleic acid, arachidonic acid (AA), and omega-3 and omega-6 polyunsaturated fatty acids (PUFAs), which play vital roles in the immune function, stress resistance, and growth of aquatic species (Ray et al., 2019).

Carbohydrates (15–25% dry weight): Carbohydrates in biofloc originate from extracellular polysaccharides, microbial cell walls, and detritus. These compounds serve as an energy source and structural component, contributing to the overall energy profile of the feed (Sun et al., 2025).

Vitamins: Bioflocs naturally synthesize and accumulate several essential vitamins, particularly those of the B-complex group (B₁ - thiamine, B₂ - riboflavin, B₆ - pyridoxine, B₁₂ - cobalamin),

vitamin C (ascorbic acid), and vitamin E (tocopherol) (Liu et al., 2024). These vitamins are crucial for metabolic function, immunity, and antioxidative defense mechanisms in fish and shrimp.

Minerals: Bioflocs are rich in macro- and micro-minerals such as calcium, magnesium, potassium, phosphorus, iron, manganese, selenium, and zinc (Mmanda, 2025). These minerals are critical for bone development, osmoregulation, enzyme activation, and immune responses.

Pigments and Bioactive Compounds: Carotenoids like astaxanthin and beta-carotene, derived from microalgae and certain bacteria in biofloc, contribute not only to the coloration of ornamental fish and crustaceans but also offer antioxidant protection and immune modulation (Yusoff et al., 2020).

Extracellular Enzymes and Metabolites: Many bioflocs are enzymatically active, containing amylases, proteases, and lipases that pre-digest food and enhance nutrient absorption (Li et al., 2024). Some microbial metabolites also act as growth promoters and antimicrobial agents.

Overall, the proximate composition of biofloc underscores its potential as a sustainable, functional feed ingredient that supports aquaculture productivity and health outcomes in a cost-effective and environmentally friendly manner.

4.2 Amino Acid and Fatty Acid Profiles :

Bioflocs are a rich source of essential and non-essential amino acids, as well as beneficial fatty acids, making them a promising alternative or supplement to conventional aquafeeds (Barroso et al., 2021).

Amino Acids: Biofloc biomass typically contains high concentrations of essential amino acids such as lysine, methionine, threonine, leucine, isoleucine, arginine, and valine. These amino acids are critical for growth, tissue repair, enzyme synthesis, and overall metabolic regulation in aquatic species. For instance, lysine and methionine are often limiting in plant-based aquafeeds; biofloc supplementation helps bridge this nutritional gap. Non-essential amino acids such as glutamic acid, aspartic acid, and alanine are also abundantly present, contributing to flavor enhancement and gut health.

Protein Quality Index: The amino acid profile of biofloc protein has been shown to compare favorably with fishmeal, particularly in shrimp and tilapia systems (Jatoba et al., 2017). Studies indicate that biofloc-derived protein has a high digestibility coefficient and a well-balanced amino acid composition for aquaculture use. Additionally, the bioavailability of these amino acids is enhanced due to the enzymatic pre-digestion within the biofloc matrix.

Fatty Acids: Although lipids are present in lower concentrations in bioflocs, their quality is notable. Polyunsaturated fatty acids (PUFAs), particularly omega-3 (n-3) and omega-6 (n-6) series, are found in appreciable quantities (Chu, 2017). Key fatty acids include linoleic acid (C18:2 n-6), linolenic acid (C18:3 n-3), and in some algae-enriched systems, eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) (Trevi, 2022). These fatty acids play essential roles in anti-inflammatory processes, cellular membrane integrity, reproductive performance, and stress tolerance.

Sterols and Phospholipids: In addition to fatty acids, biofloc systems may contain sterols and phospholipids that support lipid metabolism, membrane stability, and hormone synthesis in fish and shrimp (Manzoor et al., 2020). The presence of these compounds further enhances the functional value of bioflocs as a dietary component.

Influencing Factors: The specific amino acid and fatty acid composition of bioflocs is influenced by microbial community structure, carbon source type, culture species, and environmental conditions such as pH and temperature (Wei et al., 2020). By modulating these factors, it is possible to tailor the nutritional output of biofloc systems to meet the requirements of target species.

In summary, the amino acid and fatty acid profiles of biofloc biomass reinforce its value as a highly nutritious and sustainable feed resource, capable of supporting optimal growth, metabolic efficiency, and health in aquaculture species.

4.3 Digestibility and Palatability:

Digestibility and palatability are critical factors that determine the effectiveness of biofloc as a feed component in aquaculture (Sgnaulin et al., 2020). The microbial biomass and extracellular enzymes present in bioflocs significantly enhance their digestibility. Multiple studies have demonstrated that the apparent digestibility coefficients (ADC) for crude protein in bioflocs range between 80–90%, comparable to or even exceeding that of traditional fishmeal (Lopes et al., 2024).

The high digestibility is attributed to the fact that many biofloc-associated microbes, including *Bacillus* and *Lactobacillus* spp., produce hydrolytic enzymes such as proteases, lipases, and amylases (Banu et al., 2024). These enzymes assist in breaking down complex organic matter both in the water and in the gut of the fish, thus aiding nutrient absorption and promoting gut health.

Palatability is another advantage of biofloc-based feeds. The natural microbial flavor profile and soft texture of the flocs make them readily accepted by many species, including tilapia, shrimp, and catfish (De Schryver et al., 2008, Monteiro et al., 2018 and Noviana et al., 2024). Additionally, the continuous

availability of biofloc particles suspended in the water column promotes foraging behavior, encouraging frequent feeding and mimicking natural feeding conditions (Nisar et al., 2022).

In experimental trials, species like *Oreochromis niloticus* (Nile tilapia) and *Litopenaeus vannamei* (whiteleg shrimp) have shown a marked preference for diets that include biofloc biomass, leading to increased feed intake, reduced feed wastage, and improved growth performance (El-Sayed, 2021, Silva et al., 2022 and Raza et al., 2024).

Furthermore, bioflocs also contribute to enhanced gut morphology, with histological studies indicating increased intestinal villus length and mucosal surface area in fish fed biofloc-based diets (Asha et al., 2024). These structural improvements translate into better nutrient absorption and growth outcomes (Badrey et al., 2024).

Overall, the high digestibility and palatability of bioflocs support their use as a sustainable, efficient, and species-friendly dietary component, contributing to the success of integrated biofloc-based aquaculture systems.

4.4 Role in Reducing Feed Conversion Ratio (FCR):

Feed Conversion Ratio (FCR) is a key performance metric in aquaculture that determines how efficiently feed is converted into body mass. A lower FCR indicates higher feed efficiency, which is critical for profitability and sustainability in aquaculture operations. Biofloc technology has shown a significant positive influence on reducing FCR in various aquaculture species by enhancing feed utilization through multiple mechanisms (Fry et al., 2018 and Davison et al., 2023).

Mechanism of Action: Biofloc particles, rich in microbial protein, enzymes, and essential nutrients, act as a continuous nutritional supplement in the water column. As fish and shrimp consume these naturally occurring flocs alongside formulated feed, they derive additional nutrients, particularly protein and micronutrients, without requiring additional feed input (NRC-2011). This leads to improved growth and biomass accumulation per unit of feed consumed.

Enhanced Nutrient Recycling: Biofloc systems allow for the internal recycling of nitrogenous waste (e.g., ammonia, nitrite), which is converted into microbial protein. This microbial biomass becomes a secondary, highly digestible food source. The dual benefit of water purification and nutrient recovery reduces nutrient losses and improves nutrient retention in cultured species (Khanjani et al., 2023).

Empirical Evidence: Several experimental studies have reported substantial improvements in FCR under biofloc systems:

In *Litopenaeus vannamei* (whiteleg shrimp), FCR improved from 1.8 in conventional systems to 1.2 in BFT systems. In Nile tilapia (*Oreochromis niloticus*), a 15–20% improvement in FCR was observed when biofloc was integrated as a feed supplement (Prates et al., 2023). Polyculture systems with integrated species such as carps and freshwater prawns also showed enhanced feed utilization and lower FCRs due to biofloc supplementation (Hisano et al., 2019 and Dela Cruz et al., 2025).

Species-Specific Variation: The degree of FCR reduction varies with species, developmental stage, water quality conditions, and the quality of biofloc. Carnivorous fish may require higher dietary protein, while omnivorous species derive more substantial benefits from microbial proteins present in bioflocs.

Economic Implications: Reduced FCR directly translates to lower feed costs, which typically account for over 50% of operational expenses in aquaculture. By partially replacing or supplementing traditional feed with biofloc, farmers can reduce overall feed input while maintaining or even enhancing growth rates (Ogella et al., 2021).

In conclusion, the integration of biofloc into aquaculture practices leads to more efficient feed conversion, improved profitability, and a step toward more sustainable and eco-friendly production models.

4.5 Nutritional Modulation through Carbon Sources:

The carbon source added to a biofloc system plays a crucial role in determining the microbial dynamics, floc quality, and nutritional output of the system. Maintaining an optimal Carbon to Nitrogen (C:N) ratio is central to the development and stabilization of the biofloc microbial community. By manipulating the type and dosage of carbon inputs, aquaculturists can influence both the biochemical composition of bioflocs and the overall health and productivity of cultured species (Minaz & Kubilay, 2021).

Importance of C:N Ratio: Maintaining a C:N ratio in the range of 10:1 to 20:1 encourages the growth of heterotrophic bacteria, which assimilate nitrogenous waste (ammonia, nitrites) into microbial protein. This not only detoxifies the water but also results in the formation of nutritionally rich biofloc particles (Panigrahi et al., 2018 and Chavan et al., 2024).

Types of Carbon Sources: Several organic carbon sources have been studied and applied in biofloc systems:

Molasses: A widely used, cost-effective carbon source with high fermentable sugar content, promoting rapid microbial growth (Khanjani & Sharifina, 2022).

Glycerol: A by-product of biodiesel production, it supports consistent microbial proliferation and has been associated with improved floc structure (El-Hawarry et al., 2021).

Starch (corn, cassava): Readily available agricultural by-products that enhance the formation of stable flocs (Abakari et al., 2021).

Wheat bran, rice bran: Solid carbon sources that also contribute to floc formation while introducing some nutritional bulk (Abiri et al., 2022).

Biochar: An emerging carbon additive that provides both microbial substrate and adsorption surface, improving water quality and promoting microbial diversity (Abakari et al., 2020).

Effect on Microbial Composition and Nutrient Content: Different carbon sources stimulate the growth of specific microbial populations:

Simple sugars like molasses encourage rapid bacterial growth, leading to flocs rich in crude protein. More complex carbon sources like bran and starch support diverse microbial consortia, including fungi and protozoa, enriching the floc with additional metabolites and enzymes. Carbon sources also influence floc size, density, and settleability, which impact ingestion and digestion by aquatic animals (Ramsabburayan et al., 2025).

Impact on Cultured Species:

Species such as tilapia and shrimp have shown improved growth and immunity when cultured in systems using organic carbon sources that yield high-quality flocs. Studies indicate that molasses-based flocs enhance protein content, while bran-based systems improve mineral bioavailability and antioxidant enzyme activity in fish (Debbarma et al., 2023).

Economic and Sustainability Considerations:

The selection of carbon sources also affects the economic and environmental sustainability of biofloc systems. Locally available agricultural waste products can significantly reduce input costs. The use of renewable and waste-derived carbon sources aligns with circular economy principles and reduces environmental footprint (Rajendran et al., 2024).

In summary, strategic modulation of carbon sources not only helps maintain optimal water quality but also tailors the nutritional quality of biofloc, thereby enhancing feed efficiency, health, and growth in aquaculture systems.

4.6 Stability and Preservation: One of the critical challenges in the widespread adoption and commercial scaling of biofloc technology is ensuring the stability and preservation of biofloc biomass when it is not immediately consumed by aquatic species or when considered for use as a supplemental dried feed (McCusker et al., 2023).

Fresh Biofloc Stability: In a dynamic BFT system, fresh biofloc biomass is continuously generated. While this biomass remains suspended in the water column, it is highly susceptible to changes in environmental conditions such as pH, dissolved oxygen, and temperature. Fluctuations in these parameters can alter microbial community dynamics, leading to shifts in nutritional value, enzymatic activity, and even potential pathogen proliferation if left unmanaged. Therefore, maintaining consistent aeration, C:N ratio, and microbial equilibrium is crucial for preserving biofloc quality in real-time systems.

Preservation Techniques: To extend the shelf-life of biofloc for offline or supplementary use, several preservation techniques are under investigation and commercial trial:

Drying (Sun-drying, Oven-drying, Spray-drying): These methods reduce moisture content and microbial activity, allowing biofloc to be stored and integrated into formulated feeds. However, high-temperature drying may denature some proteins and destroy heat-sensitive vitamins, requiring careful optimization (Azim and Little, 2008 and Dauda, 2020).

Fermentation: Controlled fermentation using probiotic strains can help preserve biofloc biomass, enhance its probiotic content, and improve palatability. This method also helps suppress spoilage microbes (Kathia et al., 2017).

Freeze-drying (Lyophilization): Though expensive, this method retains the structural integrity and bioactivity of microbial proteins, enzymes, and vitamins, making it suitable for high-value aquaculture applications (Coşkun et al., 2024).

Use of Natural Preservatives: Incorporating antioxidants and natural antimicrobials (e.g., organic acids, essential oils) during storage can reduce spoilage and oxidative degradation (Blasi & Cossignani, 2020).

Shelf-life and Nutritional Retention: Studies have shown that while dried or preserved biofloc retains significant amounts of protein and minerals, the bioavailability and digestibility may decrease depending on the preservation method used. The effectiveness of preservation also varies with floc composition and moisture content at the time of processing (Binalshikh-Abubkr et al., 2021 and Binalshikh-Abubkr et al., 2022).

Challenges in Commercial Preservation:

Maintaining microbial viability post-preservation for probiotic benefits.

Balancing cost-efficiency with nutritional retention. Standardizing drying and storage protocols across different species, climate conditions.

Future Outlook: With growing interest in utilizing biofloc as a formulated feed additive, there is a need

for robust industrial-scale preservation strategies that ensure microbial stability, cost-effectiveness, and minimal nutrient degradation. Further research into encapsulation, enzymatic stabilization, and prebiotic-probiotic enrichment of preserved biofloc is warranted.

In summary, effective preservation and stabilization of biofloc biomass are vital to realizing its full potential beyond live systems, especially for commercial-scale operations and feed formulations.

In summary, bioflocs offer a complete nutritional package that supports growth, improves feed efficiency, and enhances overall aquatic animal health. Their dynamic composition, digestibility, and bioavailability make them a viable and sustainable alternative or supplement to conventional aquafeeds.

5. Importance of Carbon to Nitrogen (C:N) Ratio in Biofloc Systems

The Carbon to Nitrogen (C:N) ratio is a critical determinant in the design and functionality of a successful biofloc system (Xu et al., 2016). It influences the microbial community structure, nitrogen removal efficiency, floc formation, and ultimately, the nutritional composition of the biofloc biomass. Heterotrophic bacteria require carbon to assimilate inorganic nitrogen into biomass; therefore, manipulating the C:N ratio enables control over microbial pathways and nutrient dynamics (Kirchman, 1994 and Soong et al., 2020).

In biofloc systems, a higher C:N ratio (typically between 12:1 to 20:1) favors heterotrophic bacterial growth, which converts toxic nitrogenous waste such as ammonia and nitrites into microbial proteins. This process not only purifies the water but also enhances the nutritional content of the floc particles, transforming waste into a valuable resource for cultured aquatic organisms (Robles-Porchas et al., 2020).

Different carbon and nitrogen sources play key roles in maintaining and adjusting this balance. Carbon sources can be classified as simple or complex:

Simple Carbon Sources:

Molasses: Molasses is widely used due to its affordability and high sugar content. It rapidly stimulates the growth of heterotrophic bacteria, facilitating quick ammonia assimilation and dense floc formation. It also adds a slight organic load to the system, which can contribute to the nutritional complexity of the floc (Dheeran et al., 2025).

Glycerol: A by-product of biodiesel industries, glycerol is a sugar alcohol that supports sustained microbial growth over time. It has been shown to improve the water quality stability and encourages

the formation of compact, stable flocs (Crab, 2010 and Kumar et al., 2024).

Glucose or Sucrose: These refined sugars provide immediate energy for microbial activity. While effective in small-scale systems, their cost limits large-scale usage. They are best used in research or in scenarios requiring precise microbial responses (Addo et al., 2023).

Complex Carbon Sources:

Rice Bran and Wheat Bran: These are agricultural by-products containing complex carbohydrates, fibers, and micronutrients. They decompose more slowly than simple sugars, thereby supporting a diverse microbial population including bacteria, fungi, and protozoa (Jefferson & Adolphus, 2019 and Su et al., 2022). This diversity improves floc nutritional profile and long-term stability.

Starch (from corn, tapioca, or cassava): Starch is a polysaccharide that decomposes gradually, providing a consistent carbon supply over extended periods. It enhances the structure of the biofloc, making it more digestible for certain species such as tilapia (Tarigan et al., 2025).

Biochar: Though not a traditional carbon source, biochar can serve dual purposes. It acts as a surface for microbial colonization and contributes to the carbon pool indirectly. It also adsorbs harmful compounds, thus improving water quality and enhancing microbial community function.

According to Hancz, 2020, Nitrogen sources, typically introduced through feed or supplementary inputs, vary significantly across different aquaculture species due to differences in nitrogen uptake efficiency, feeding behavior, and growth dynamics:

Biofloc Performance in various fish and non-fish organism culture System

Tilapia (*Oreochromis spp.*): Tilapia systems typically generate moderate nitrogen loads from uneaten feed and feces. Protein-rich feeds serve as the main nitrogen source, and supplementation with organic nitrogen is minimal. However, in high-density BFT systems, nitrogenous wastes can accumulate rapidly, requiring precise C:N adjustments using low-protein feeds or ammonium sulfate (Montanhini Neto & Ostrensky, 2015).

Shrimp (*Litopenaeus vannamei*): Shrimp systems produce high nitrogen loads due to protein-rich diets (Talukdar et al., 2021). Ammonium chloride is often used in experimental systems to simulate high nitrogen environments, ensuring that microbial growth remains heterotrophically dominant. Supplementation with carbohydrate-rich carbon is essential to prevent ammonia toxicity.

Carp (*Cyprinus carpio*, *Ctenopharyngodon idella*): Carps generate variable nitrogen depending on feeding intensity and stocking density (Oprea et

al., 2015). Fish waste and excreta contribute significantly to the nitrogen pool (Fernandez-Jover et al., 2007). Protein content in feed needs careful calibration to avoid over-nitrification. Natural nitrogen from organic detritus and excreta is commonly utilized in extensive or semi-intensive BFT ponds.

Catfish (*Clarias gariepinus*): Known for high feed intake and rapid nitrogen excretion, catfish systems benefit from controlled ammonia inputs for microbial stimulation (Ott et al., 2024). Use of nitrogen amendments such as ammonium chloride is rare; instead, microbial loads are managed through carbon balancing.

Barramundi (*Lates calcarifer*): In marine BFT systems, where nitrogen metabolism is influenced by salinity, nitrogen supplementation is minimal (Abakari et al., 2021). Natural nitrogen from protein digestion and fish excreta is sufficient, requiring effective carbon input management for biofloc stabilization.

Ornamental Fish: Due to lower biomass and feeding rates, nitrogen levels are relatively stable, and excreta serve as the primary nitrogen source (Paul et al., 2020). BFT is mostly used for water quality stabilization rather than protein supplementation in these systems.

Each species requires a tailored nitrogen management strategy to ensure microbial equilibrium, optimal water quality, and nutrient recycling efficiency (Yu et al. 2019). The choice and dosing of nitrogen sources must be adapted based on species-specific metabolic rates, feed types, system design, and operational goals.

The balance between these sources and the system's bioload determines the microbial pathway dominance—whether heterotrophic, autotrophic, or mixotrophic. A heterotrophic pathway is ideal in biofloc systems as it leads to the formation of dense microbial flocs with high protein and enzyme content.

Maintaining a consistent C:N ratio requires regular monitoring of parameters such as Total Ammonia Nitrogen (TAN), Nitrite, and Dissolved Organic Carbon (Luo et al., 2023). Advanced BFT systems are now incorporating real-time sensors, automated dosing systems, and machine learning algorithms to regulate carbon addition and microbial activity dynamically.

Field trials have shown that when the C:N ratio is optimized:

- There is a significant reduction in ammonia and nitrite concentrations.
- The protein content of biofloc biomass increases, enhancing its value as a supplementary feed.

- There is improved fish or shrimp survival, growth performance, and feed conversion efficiency.

In summary, the C:N ratio forms the backbone of biofloc system ecology. Selecting appropriate carbon and nitrogen inputs tailored to species-specific requirements and production goals is key to achieving optimal biofloc performance. Properly managed, the C:N ratio not only drives nutrient recycling and floc development but also promotes a healthier and more productive aquaculture environment.

6. Microbial Communities in Biofloc Systems

Microbial communities are the backbone of biofloc technology, driving critical ecological processes that regulate water quality, nutrient cycling, and nutritional enhancement in aquaculture systems. The biofloc matrix comprises a dynamic and diverse assembly of microorganisms, including bacteria, fungi, algae, protozoa, rotifers, and other metazoans (Abakari et al., 2022, Yun et al., 2022 and Han et al., 2024). These microbial consortia are influenced by numerous factors, such as the C:N ratio, temperature, salinity, dissolved oxygen levels, and the type of carbon and nitrogen sources introduced into the system (Bhatia et al., 2018).

Dominant Bacterial Groups and Their Functional Roles: The most prevalent microbial inhabitants in biofloc systems are bacteria, particularly from the phyla Proteobacteria, Bacteroidetes, Firmicutes, and Actinobacteria (Abakari et al., 2021 & Abakari et al., 2022).

Proteobacteria are involved in nitrogen transformations, including ammonia oxidation and denitrification (Baskaran et al., 2020).

Bacteroidetes specialize in breaking down complex organic matter and polysaccharides, contributing to biofloc stabilization (Rajeev et al., 2024).

Firmicutes, especially *Bacillus* spp., are noted for their probiotic properties and resilience in harsh environments (Elshaghabee et al., 2017).

Actinobacteria contribute to organic matter degradation and antimicrobial compound production (Zothanpuia et al., 2018 and Javed et al., 2021).

Role of Algae, Fungi, and Protozoa: Photosynthetic microalgae, such as *Chlorella* and diatoms, are also commonly present in biofloc systems. They contribute to oxygenation during daylight hours and assimilate inorganic nutrients like nitrate and phosphate, helping balance the system (Fimbres-Acedo et al., 2020). Fungi participate in decomposing recalcitrant organic matter and contribute to the production of extracellular enzymes that enhance nutrient availability (Tunlid et al., 2022). Protozoa and rotifers feed on bacteria and particulate matter, helping regulate microbial

densities and contributing to the trophic complexity of the floc (Walczyńska et al., 2018).

Community Dynamics and Biofloc Structure:

The biofloc itself is a three-dimensional aggregate composed of microbial cells, exopolysaccharides (EPS), organic debris, and detritus. It serves both as a natural filter and as a nutrient-rich feed source. Floc structure is stabilized by microbial EPS and is influenced by aeration, shear force, and system design. Over time, microbial succession occurs within the floc. Initial dominance by fast-growing heterotrophs gives way to more specialized organisms such as nitrifiers and denitrifiers, depending on the available nutrients and redox conditions (Li et al., 2025).

Advanced Techniques to Study Microbial Communities: Recent advances in high-throughput sequencing, metagenomics, and transcriptomics have enabled a deeper understanding of microbial diversity and functionality in BFT systems.

16S rRNA gene sequencing is routinely used to identify bacterial populations and monitor shifts over time (Huerta-Rábago et al., 2019).

Metagenomics reveals functional genes involved in nitrogen cycling, organic matter degradation, and biosynthesis of vitamins or antimicrobial peptides (Liu et al., 2024).

Fluorescence in situ hybridization (FISH) and **confocal microscopy** allow for spatial visualization of microbial clusters within flocs (Kniggendorf et al., 2016).

Functional Implications for Aquatic Species: The microbial composition of biofloc has direct consequences on the health and nutrition of cultured species. A balanced microbial ecosystem not only provides supplemental nutrition but also contributes to gut colonization by beneficial microbes, outcompetes potential pathogens, and stimulates host immunity (Padeniya et al., 2022).

Understanding and managing microbial communities in BFT is thus critical for maintaining system stability, optimizing floc quality, and ensuring the health and productivity of farmed aquatic animals.

7. Microbial Communities in Biofloc Systems

Microbial communities are the cornerstone of biofloc technology, orchestrating the ecological, nutritional, and immunological functions that make BFT a sustainable aquaculture strategy. These communities include diverse groups of bacteria, algae, fungi, protozoa, and other microscopic organisms, each contributing uniquely to biofloc formation, nutrient cycling, and pathogen resistance. The interactions among these organisms are influenced by several operational parameters, including C:N ratio, salinity, pH, temperature, and the source of nutrients introduced.

Comparative Functional Roles of Dominant Microbial Groups:

Proteobacteria: This is the most dominant phylum in biofloc systems, particularly the classes Alphaproteobacteria and Gammaproteobacteria. Proteobacteria such as *Nitrosomonas* and *Nitrobacter* are vital for ammonia and nitrite oxidation (nitrification), while others like *Pseudomonas* and *Paracoccus* are known for denitrification. Compared to other groups, Proteobacteria are highly versatile and respond rapidly to nutrient shifts (Schreier et al., 2010).

Bacteroidetes: These bacteria excel in hydrolyzing complex polysaccharides, contributing significantly to the decomposition of organic matter in the floc. *Flavobacterium* and *Cytophaga* species are prevalent. Unlike nitrifiers in Proteobacteria, Bacteroidetes enhance floc texture and stability by producing extracellular polymeric substances (EPS), a key structural element in floc cohesion (McKee et al., 2021).

Firmicutes: Represented mainly by *Bacillus* species, Firmicutes are spore-forming, resilient, and known for probiotic effects. They secrete enzymes like proteases and lipases and produce antimicrobial compounds such as bacteriocins. Compared to Proteobacteria and Bacteroidetes, Firmicutes play a stronger role in disease prevention and gut health improvement in aquatic animals (Todorov et al., 2022).

Actinobacteria: These high-GC Gram-positive bacteria, including genera like *Streptomyces* and *Microbacterium*, are important for degrading complex organics and producing bioactive secondary metabolites. Their role is often complementary to Bacteroidetes but with additional antimicrobial potential (Lang, 2021).

Eukaryotic Microbial Contributors:

Algae: Microalgae like *Chlorella*, *Scenedesmus*, and diatoms are primary producers within the floc. They help assimilate dissolved nutrients such as nitrates and phosphates, particularly in illuminated systems. Unlike bacteria, algae also contribute to oxygen generation through photosynthesis, making them vital for daytime DO stabilization (Rao et al., 2024).

Fungi: Filamentous fungi such as *Aspergillus* and *Penicillium* decompose recalcitrant organics and contribute to enzymatic hydrolysis. While not as dominant as bacteria, their presence adds enzymatic diversity and assists in breaking down non-starch polysaccharides (Ravindran & Jaiswal, 2016).

Protozoa and Rotifers: These micro-grazers control bacterial population dynamics through selective predation. Ciliates (e.g., *Vorticella*) and flagellates enhance nutrient mineralization and reduce the dominance of opportunistic bacteria, thereby supporting a more stable microbial structure (Ravindran et al., 2023).

Table 1. Structural and Functional Comparison of Microorganisms in Biofloc Systems

Microbial Group	Key Functions	Structural Role	Nutritional Contribution	Pathogen Control	Reference
Proteobacteria	Nitrification, Denitrification	Moderate	Low–Moderate	Moderate	Preen et al., 2021
Bacteroidetes	Organic Matter Degradation, EPS Production	High	Moderate	Low	Pan et al., 2023
Firmicutes	Enzyme Production, Probiotic Effects	Moderate	Moderate	High	Stojanov et al., 2020
Actinobacteria	Antimicrobial Production, Degradation	Low	Moderate	High	Barka et al., 2016
Algae	Nutrient Assimilation, Oxygenation	Moderate	High (lipids, pigments)	Indirect	Fuentes et al., 2016
Fungi	Enzyme Production, Organic Degradation	Low	Low–Moderate	Low	Khatoun et al., 2017
Protozoa/ Rotifers	Grazing, Nutrient Mineralization	Indirect	Moderate (as live feed)	High (by suppressing pathogens)	Onianwah et al., 2018

Advanced Molecular Insights: High-throughput molecular tools have allowed aquaculturists to shift from qualitative to functional profiling of microbial communities:

- **Metagenomic sequencing** reveals not only microbial identity but their metabolic potential.
- **Shotgun sequencing** can uncover genes linked to antimicrobial resistance, nitrogen pathways, and vitamin synthesis.

- **Quantitative PCR (qPCR)** enables real-time tracking of key microbial species or functional genes under varying BFT management regimes.

Impacts on Aquatic Animal Health and Performance: Comparative studies reveal that bioflocs dominated by Firmicutes and Actinobacteria are more effective at improving immune responses and growth rates in species like *Litopenaeus vannamei* and *Oreochromis niloticus* than flocs dominated solely by Proteobacteria.

Additionally, algae-rich flocs have higher lipid and antioxidant profiles, which benefit larval stages of fish (Raza et al., 2024).

Thus, designing and managing microbial communities with a strategic balance across taxa can lead to flocs with optimal nutritional and immunological value for aquaculture species.

In conclusion, microbial community dynamics in biofloc systems are multifaceted and vary widely based on system design, input management, and target species. A comparative understanding of each microbial group’s contribution allows for targeted interventions to optimize both floc quality and overall aquaculture performance.

8. Biofloc as a Dietary Stimulant Compared to Traditional Fish Food

Biofloc technology not only serves as a water remediation tool but also as a potent dietary

stimulant for aquaculture species. Unlike conventional feeding practices that rely on formulated feeds, biofloc provides in situ microbial protein, lipids, vitamins, and bioactive compounds. The nutritional contribution of biofloc is not merely supplementary—it actively enhances growth, immunity, and feed utilization efficiency (Ramasubburayan et al., 2025).

Nutritional Composition Comparison : Biofloc particles contain microbial biomass rich in crude protein (25–45%), essential fatty acids, vitamins (B-complex, E), and trace minerals. When compared to traditional pelleted fish feed, which typically contains 25–35% protein and requires external sources of lipids and vitamins, biofloc represents a self-sustaining feed source with ecological and economic benefits.

Table. 2 Nutritional Composition Comparison in Biofloc Biomass and Traditional Feed

Parameter	Biofloc Biomass	Traditional Feed
Crude Protein (%)	25–45	25–35
Lipid Content (%)	2–10	3–12
Ash Content (%)	15–25	8–12
Fiber (%)	1–3	2–6
Vitamin B12 (µg/kg)	100–250	<50
Digestibility	Moderate–High	High
Palatability	High (species-specific)	High

(Source: Khanjani et al., 2023)

Comparative Performance Metrics: Research studies have demonstrated improved feed conversion ratios (FCR), survival rates, and growth performance in fish and shrimp cultured in BFT systems when compared to traditional aquaculture.

Table. 3 Comparative Performance metrics of Biofloc with respect to different Fish species

Species	System	FCR	Weight Gain (%)	Survival (%)	Reference
<i>Tilapia (Oreochromis niloticus)</i>	BFT	1.3	+25	90–95	Azim & Little (2008); Kuhn et al. (2010); Emerenciano et al. (2012)
<i>Tilapia</i>	Traditional	1.6	–	80–85	Avnimelech (2009)
<i>Shrimp (Litopenaeus vannamei)</i>	BFT	1.2	+20	85–92	Wasielesky et al. (2006); Ekasari et al. (2014)
<i>Shrimp</i>	Traditional	1.5	–	78–84	Krummenauer et al. (2011)
<i>Common Carp (Cyprinus carpio)</i>	BFT	1.4	+18	85–90	Hende et al. (2014); Ghosh et al. (2017)
<i>Common Carp</i>	Traditional	1.7	–	75–80	Ghosh et al. (2017)
<i>Indian Major Carps</i>	BFT	1.3–1.5	+22	87–91	Das et al. (2019); Patil & Kumar (2020)
<i>Indian Major Carps</i>	Traditional	1.6–1.8	–	78–84	Das et al. (2019)
<i>Barramundi (Lates calcarifer)</i>	BFT	1.1–1.3	+24	88–92	Mani et al. (2020); Chakraborty et al. (2021)
<i>Barramundi</i>	Traditional	1.5–1.6	–	80–85	Chakraborty et al. (2021)
<i>Catfish (Clarias gariepinus)</i>	BFT	1.2	+21	89–93	De Jesus et al. (2016); Furtado et al. (2014)
<i>Catfish</i>	Traditional	1.5	–	81–86	De Jesus et al. (2016)
<i>Mullet (Mugil cephalus)</i>	BFT	1.2–1.4	+19	87–91	Khanjani & Sharifnia (2020); Asaduzzaman et al. (2010)
<i>Mullet</i>	Traditional	1.5–1.6	–	78–83	Khanjani & Sharifnia (2020)
<i>Ornamental Fish (e.g., Goldfish)</i>	BFT	1.3	+15	90–94	Ahmad et al. (2022); Nayak et al. (2019)
<i>Ornamental Fish</i>	Traditional	1.6	–	80–86	Nayak et al. (2019)

Mechanism of Dietary Enhancement

Continuous Feeding Access: Biofloc remains suspended in the water column and acts as a constant source of supplemental feed. Fish and shrimp graze on flocs throughout the day, maintaining a more consistent intake of nutrients even when pellet feeding is infrequent or reduced.

This mitigates hunger-induced stress and supports continuous growth (Ogello et al., 2021).

Enzyme Activity Modulation: The consumption of biofloc has been linked to enhanced activity of digestive enzymes such as amylase (for carbohydrate digestion), protease (for protein breakdown), and

lipase (for lipid assimilation). These enhancements lead to better nutrient utilization and more efficient energy conversion from feed (Long et al., 2015).

Gut Microbiome Enhancement: Biofloc introduces beneficial microbial strains (e.g., *Bacillus*, *Lactobacillus*) into the gut of cultured species. These microbes enhance gut flora diversity, aid in nutrient absorption, and competitively exclude pathogens by occupying adhesion sites on the intestinal lining (Qiu et al., 2023 and Ramasubburayan et al., 2025).

Probiotic and Immunostimulatory Properties: Components in biofloc such as β -glucans, peptidoglycans, nucleotides, and polysaccharides act as immunostimulants. These compounds enhance innate immune functions, such as phagocytosis, lysozyme activity, and cytokine expression, contributing to improved disease resistance (Wang et al., 2017 and Ramasubburayan et al., 2025).

Antioxidant Enhancement: Biofloc has been shown to enhance antioxidant capacity in fish tissues by increasing the activity of enzymes like superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx). This reduces oxidative stress and supports better physiological functioning (de Souza et al., 2016 and Yu et al., 2021).

Behavioral Benefits: Fish and shrimp in BFT systems display more natural foraging behaviors, which reduce aggression and promote social stability, particularly in high-density systems (Emerenciano et al., 2022).

Economic and Environmental Advantages:

Reduced Dependency on Fishmeal and Fish Oil: By supplying a substantial portion of dietary protein and essential micronutrients, biofloc lowers the requirement for expensive and ecologically unsustainable fishmeal-based feeds (Gutasi, 2021 and Iheanacho et al., 2025).

Lower Feed Cost per Biomass Produced: BFT systems exhibit superior feed conversion efficiency (FCR), meaning less feed is needed to produce the same biomass, translating into reduced overall feed costs (Ogello et al., 2021).

Enhanced Resource Utilization: Biofloc systems allow for the recycling of nutrients that would otherwise be lost in effluents, thereby improving resource efficiency (Zimmermann et al., 2023).

Decreased Nutrient Loading and Effluent Discharge: As a closed-loop or low-discharge system, BFT minimizes nutrient-rich waste output

into surrounding ecosystems, significantly reducing the risk of eutrophication and water body contamination (Preisner et al., 2021).

Reduced Water Use: Traditional aquaculture systems often require frequent water exchange to manage water quality, whereas BFT operates with minimal exchange, thus conserving freshwater resources (Barga et al., 2023).

Carbon Footprint Reduction: When coupled with renewable energy technologies for aeration and monitoring, BFT can reduce greenhouse gas emissions compared to high-energy recirculating aquaculture systems (RAS) (Fiso, 2025).

Economic Resilience: The reduced reliance on external feed inputs and the adaptability of BFT to diverse geographies and fish species provide resilience against feed price volatility and supply chain disruptions (Heydari, 2024).

In summary, biofloc not only supplements but significantly elevates dietary performance when compared to traditional feed strategies. The multi-nutrient nature, digestibility, and probiotic impact of biofloc create a synergistic advantage for aquatic animal growth and health, particularly in species like tilapia, carp, catfish, and shrimp.

8. Immuno-Physiological Responses of Biofloc versus Traditional Systems

Biofloc technology (BFT) offers a transformative shift in how immune responses and physiological stress are managed in aquaculture. Unlike traditional systems that rely on sterile water and artificial feed, BFT fosters a dynamic microbial ecosystem that not only improves water quality but also acts as a constant source of immunostimulants and health-promoting compounds.

8.1 Enhanced Innate and Adaptive Immunity

Bioflocs are rich in microbial-associated molecular patterns (MAMPs), such as β -glucans, lipoteichoic acids, lipopolysaccharides (LPS), and peptidoglycans. These act as natural immunostimulants, enhancing both innate and adaptive immune responses in fish and crustaceans. Numerous studies report elevated activity of immune enzymes like lysozyme, alkaline phosphatase, and respiratory burst enzymes in fish species cultured in BFT systems (Yu et al., 2020). For example, tilapia cultured in BFT show upregulated expression of immune genes such as *interleukin-1 β* (IL-1 β), *tumor necrosis factor-alpha* (TNF- α), and *interferon gamma* (IFN- γ). These cytokines play key roles in inflammation, phagocytosis, and overall immune readiness. Similarly, shrimp (*L. vannamei*)

exhibit higher hemocyte counts, phenoloxidase activity, and antibacterial peptide production when cultured in BFT (Ebadi & Azlan, 2023).

8.2 Oxidative Stress Management

Biofloc environments have been shown to significantly reduce oxidative stress by increasing the activities of antioxidant enzymes like superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx). These enzymes help neutralize reactive oxygen species (ROS) that typically accumulate under intensive farming conditions (Yu et al., 2021). Reduced oxidative stress translates to better cell integrity, less tissue damage, and enhanced growth.

8.3 Gut Immunity and Microbiota Interaction

BFT systems alter the intestinal microbiota by introducing a diverse microbial population that colonizes the gut. This enhances mucosal immunity, primarily through gut-associated lymphoid tissue (GALT) activation (Bemark et al., 2024). The increased microbial diversity fosters competitive exclusion of pathogens, improves nutrient assimilation, and boosts the production of short-chain fatty acids (SCFAs), which serve as signaling molecules for immune regulation (Kim, 2023).

In carp and catfish, gut microbiota under BFT has been linked to elevated secretory IgA levels and mucin production, fortifying the gut barrier (Liu et al., 2024). Probiotic species like *Lactobacillus*, *Bacillus*, and *Pediococcus* are often enriched in the gastrointestinal tract of BFT-reared species, contributing further to health resilience (Khanjani et al., 2024).

8.4 Stress Response and Endocrine Regulation

BFT-grown fish demonstrate lower plasma cortisol and glucose levels during stress events such as handling, high stocking density, or hypoxia. Lower cortisol levels indicate reduced activation of the hypothalamic-pituitary-interrenal (HPI) axis, which in turn stabilizes metabolic and immune functions. Fish in BFT systems also show stable levels of thyroid hormones and growth hormone (GH), essential for sustained performance under intensive conditions (Rosengren et al., 2018 and Yuan et al., 2025).

8.5 Species-Specific Observations

Tilapia: Elevated leukocyte counts, higher phagocytic index, and stronger antibody titers in BFT than in RAS/traditional ponds (Long et al., 2015).

Shrimp: Improved resistance against *Vibrio spp.* and WSSV, with faster recovery and lower mortality in challenge tests (Pang et al., 2019).

Catfish and Carp: Enhanced disease resistance, gut histo-morphological improvements, and fewer skin/gill lesions (Segaran et al., 2023).

Barramundi: Strengthened mucosal immunity and reduced incidence of external parasitic infections (Pattipeiluhu et al., 2024).

Goldfish (*Carassius auratus*): Enhanced coloration, mucosal integrity, and leukocyte proliferation in BFT environments (Huang et al., 2022).

Common Mullet (*Mugil cephalus*): Greater survival rates and antioxidant activity under high-density culture in BFT (Patil et al., 2022).

Indian Major Carps (*Labeo rohita*, *Catla catla*): Improved non-specific immunity (lysozyme, respiratory burst) and reduced parasitic load (Kumar et al., 2021).

African Catfish (*Clarias gariepinus*): Better gill and liver histology, and increased hepatosomatic index when reared in BFT compared to pond-based systems (Hassan et al., 2023).

8.6 Molecular Insights and Future Research

Emerging transcriptomic and proteomic studies are revealing gene-level insights into how biofloc components trigger immune pathways. For instance, heat shock proteins (HSP70), toll-like receptors (TLRs), and antimicrobial peptides (AMPs) are increasingly being studied as biomarkers of BFT-mediated immunity (Kumar et al., 2022).

Ongoing research is focusing on tailoring biofloc composition (via carbon source selection or probiotic enrichment) to enhance species-specific immune benefits. These findings underscore the potential of BFT not just as a farming method, but as a platform for immunological innovation in aquaculture.

9. Biofloc Technology in Aquaculture: Species-Specific Applications and Practical Insights

Biofloc technology (BFT) has been widely adopted in modern aquaculture practices due to its potential to enhance growth, health, and environmental sustainability. The principle of BFT—using microbial communities to convert waste into useful biomass—makes it suitable for a variety of freshwater and marine species. The suitability of BFT depends on the feeding habits, tolerance to suspended solids, and natural grazing behavior of aquatic animals.

9.1 Freshwater Species in BFT

Species	Application in BFT	Key Benefits	Reference
Tilapia (<i>Oreochromis niloticus</i>)	Most widely cultured in BFT	Improved FCR, immunity, and growth under low-protein feeds	Avnimelech (2009); Kuhn et al. (2010)
Common Carp (<i>Cyprinus carpio</i>)	Compatible with BFT under high aeration	Enhanced immunity, better gut morphology	Ghosh et al. (2017)
Rohu (<i>Labeo rohita</i>), Catla (<i>Catla catla</i>)	Indian Major Carps grown under BFT	Increased growth, reduced parasitic load	Das et al. (2019)
African Catfish (<i>Clarias gariepinus</i>)	Tolerates high solids and thrives in BFT	Enhanced liver condition, better survival	Furtado et al. (2014)

9.2 Marine and Brackishwater Species

Species	Application in BFT	Key Benefits	Reference
Whiteleg Shrimp (<i>Litopenaeus vannamei</i>)	Most successful marine species for BFT	Reduced antibiotic use, high density tolerance	Wasielesky et al. (2006); Ekasari et al. (2014)
Tiger Shrimp (<i>Penaeus monodon</i>)	Brackish adaptation of BFT with success	Stable water quality, better resistance to WSSV	Krummenauer et al. (2011)
Barramundi (<i>Lates calcarifer</i>)	Cultured in modified BFT with RAS	Enhanced mucosal immunity and growth	Chakraborty et al. (2021)
Milkfish (<i>Chanos chanos</i>)	Experimental trials in tropical regions	Stable DO, reduced water exchange needed	Ahmad et al. (2022)

9.3 Ornamental and Small-Scale Aquaculture

Species	Biofloc Suitability	Observed Benefits	Reference
Goldfish (<i>Carassius auratus</i>)	Used in BFT for enhanced coloration	Higher survival and immune response	Nayak et al. (2019)
Koi Carp	Suitable for small recirculating BFT tanks	Improved skin shine, reduced fungal infections	Ahmad et al. (2021)

9.4 Comparative Diagram: Biofloc Suitability by Species Type

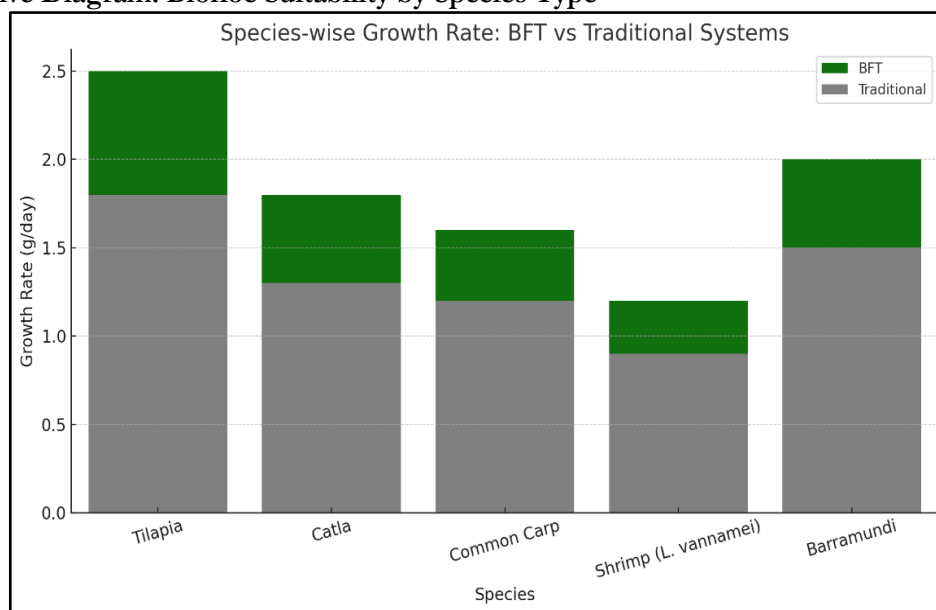


Figure 1. Comparative suitability of biofloc technology across aquatic species

9.5 Challenges in Species-Specific Biofloc Application

Despite the promising outcomes associated with biofloc technology (BFT), its application across fish and shrimp species presents several operational, biological, and economic challenges that need to be addressed to ensure consistent performance and long-term scalability:

1. Feeding Behavior and Species Compatibility: BFT works best with omnivorous and detritivorous species like *Oreochromis niloticus*

(tilapia), *Cyprinus carpio* (common carp), and *Clarias gariepinus* (African catfish), which naturally graze on suspended particles (Shaw et al., 2022). In contrast, carnivorous species such as *Oncorhynchus mykiss* (rainbow trout) and *Salmo salar* (Atlantic salmon) often reject biofloc due to their selective feeding behavior (Kajbaf, 2023). Their growth performance and feed conversion efficiency in BFT systems tend to be lower due to poor biofloc consumption.

2. Suspended Solids Tolerance: High total suspended solids (TSS) are intrinsic to BFT, but species like *Danio rerio* (zebrafish) or ornamental

goldfish with delicate gill structures exhibit stress, gill clogging, and increased mucus production (Montoya et al., 2024). Species like *Penaeus vannamei* (whiteleg shrimp) and *C. gariepinus* show better tolerance and are thus more suitable (González et al., 2010 and Ye et al., 2023).

3. Dissolved Oxygen Management: Oxygen demand in BFT is significantly higher due to microbial respiration. Oxygen-sensitive species such as *Lates calcarifer* (barramundi) and *Chanos chanos* (milkfish) may experience hypoxic stress under suboptimal aeration (Collins et al., 2013). This necessitates round-the-clock aeration and real-time monitoring.

4. System Complexity and Technical Expertise: Balancing microbial populations and maintaining optimal C:N ratios requires hands-on knowledge. Farmers unfamiliar with microbial dynamics may inadvertently trigger floc collapse, ammonia spikes, or pH crashes. For example, biofloc systems with *Macrobrachium rosenbergii* (giant freshwater prawn) have shown variable results due to inconsistent management practices (Banu & Svedha, 2025).

5. Energy Requirements and Cost: Aeration contributes over 60% of operational energy use in BFT systems. In remote or under-resourced areas, the energy requirement becomes a bottleneck. Although species like *O. niloticus* perform well under low to moderate aeration, intensive systems for *L. vannamei* or *P. monodon* demand continuous, high-capacity aeration (Emerenciano et al., 2022).

6. Biofloc Accumulation and Sludge Management: Without proper floc control, species like *C. carpio* show signs of gill irritation and reduced feeding. Accumulated sludge must be periodically removed and can be recycled as organic fertilizer, but large-scale systems (e.g., shrimp hatcheries) face logistical and economic challenges in handling high volumes of sludge (Iber & Kasan, 2021).

7. Pathogen Risk from Opportunists: Opportunistic bacteria like *Vibrio harveyi* and *Aeromonas hydrophila* can proliferate in BFT if microbial equilibrium is disturbed. Studies in *L. vannamei* culture have shown that poorly managed floc systems can exacerbate disease outbreaks under certain conditions (Said et al., 2022).

8. Species-Specific Nutritional and Behavioral Adjustments: *Tilapia* and *Catla* demonstrate strong enzymatic adaptation to biofloc diets, improving FCR and weight gain (Long et al., 2015). However, *Pangasius hypophthalmus* (striped catfish) shows mixed responses, possibly due to differences in gut morphology and digestive enzyme profiles. Thus, tailoring feed and floc properties to species is essential (Banu et al., 2024).

9. Scaling and Standardization Issues: While BFT is scalable for *L. vannamei* in raceway systems,

larger-bodied species like *C. catla* require more space and uniform aeration, making scale-up difficult (Das & Mandal, 2021). Managing consistency across multiple tanks in large-scale operations demands automation and real-time control systems.

10. Regulatory Framework and Institutional Barriers: In many developing regions, BFT lacks formal recognition, standard operating procedures, or institutional incentives (Wang et al., 2022). This discourages farmers from transitioning from conventional systems, despite the potential gains. Policy-level support is necessary for widespread BFT adoption.

9.6 Summary and Recommendations

BFT is best suited for omnivorous and filter-feeding species that can directly ingest floc particles. It offers immense advantages in terms of water use efficiency, immunity enhancement, and feed cost reduction. However, tailoring biofloc systems (floc density, carbon source, aeration intensity) to species-specific needs is essential for optimal outcomes. Ongoing innovations such as hybrid BFT-RAS systems, species-specific probiotics, and AI-driven water quality regulation are opening new frontiers for aquaculture, reinforcing the relevance of biofloc systems across diversified farming models.

10. Discussion and Conclusion

10.1 Discussion

The integration of biofloc technology into aquaculture marks a transformative advancement in sustainable fish and shrimp farming. This microbial-based system addresses several key challenges in conventional aquaculture, such as disease outbreaks, waste management, water scarcity, and feed costs, by converting waste nutrients into microbial biomass that serves as both a biofilter and a nutritional supplement (Martínez-Córdova et al., 2015).

From a biological standpoint, the continuous presence of microbial flocs fosters a more stable environment that enhances fish physiology. Fish raised in BFT systems display improved stress tolerance, immune stimulation, and gut health due to the microbial communities ingested and surrounding them (Yu et al., 2020). These effects have been validated across multiple species, including tilapia, catfish, carp, and shrimp, as reviewed in this study.

Nutritionally, bioflocs provide a rich mixture of proteins, lipids, carbohydrates, trace minerals, and vitamins, thus supplementing or even partially replacing conventional feed. This can significantly reduce feed conversion ratios (FCR), which directly impacts the economics of aquaculture operations. In species such as *Litopenaeus vannamei*, feed costs constitute more than 50% of production expenses—highlighting the role of bioflocs in cost mitigation.

In some studies, protein input in commercial feeds could be reduced by 20–30% without affecting growth or health when BFT was integrated (Khanjani et al., 2024).

Technologically, BFT aligns well with digitization trends in aquaculture. Sensors and IoT-based systems now allow farmers to monitor key parameters like dissolved oxygen, total suspended solids, and carbon-to-nitrogen (C:N) ratios in real time. This ensures tighter control over microbial balance and prevents system crashes due to overflocculation or oxygen depletion. Moreover, the integration of BFT with other systems—such as Recirculating Aquaculture Systems (RAS), aquaponics, and algae bioreactors—opens avenues for hybrid sustainability models (Flores-Iwasaki et al., 2025).

From an ecological perspective, BFT drastically minimizes water usage and discharge of nutrient-rich effluents, which are known to cause eutrophication in natural water bodies. By adopting a zero-water exchange strategy, BFT reduces the environmental footprint of aquaculture operations. Furthermore, sludge generated from biofloc systems can be reused as organic fertilizer, thereby closing the nutrient loop and supporting the circular economy (Nisar et al., 2022).

However, certain limitations persist. Not all species tolerate high suspended solids. Carnivorous and pelagic fish species often show reduced growth or stress responses in BFT environments. Also, high aeration requirements pose an energy burden, particularly in areas with unreliable power supply. Additionally, managing floc volume and microbial stability still requires skilled intervention, and a lack of standardized operational protocols remains a bottleneck for scalability (Yang et al., 2024).

Social and policy dimensions also influence BFT adoption. While countries like India, Brazil, and Indonesia are taking proactive steps by including BFT in aquaculture training and subsidy schemes, global policy frameworks are still nascent (Jolly et al., 2023). There is a critical need for regulatory standardization and financial incentives to support small- and medium-scale farmers in adopting this technology.

In summary, BFT represents a convergence of biological innovation, sustainability, and aquacultural productivity. Its role in shaping the future of aquaculture is promising, but it must be backed by interdisciplinary collaboration, continuous innovation, and robust field validations across geographies and species.

10.2 Conclusion

Biofloc technology stands at the forefront of modern aquaculture innovation. It addresses many of the core challenges facing the industry:

environmental pollution, high feed costs, disease outbreaks, and limited freshwater availability. Through harnessing the power of beneficial microbial communities, BFT creates a more circular, efficient, and health-promoting aquaculture system.

Its application across a diverse array of species—from tilapia and shrimp to ornamental fish—demonstrates its adaptability and potential for scale. However, the future success of BFT depends on a continued focus on species-specific optimization, cost-effective inputs, and real-time system monitoring.

As we move toward an era of climate-adaptive and resource-conscious aquaculture, biofloc technology offers a compelling model that bridges production efficiency with ecological stewardship. Interdisciplinary research, policy support, and farmer training will be key to unlocking its full potential for a sustainable blue revolution.

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