



HARNESSING BIOFLOC TECHNOLOGY: A SUSTAINABLE PARADIGM FOR MODERN AQUACULTURE – A REVIEW

Panneerselvam Dheeran¹, Kanagaraja Anantharaja^{2*}, Edward Inpent Campal³, Tao Kara³, Manickam Selvaraj^{4,5}, Ulaganathan Arisekar^{6*},
Mohammed A. Assiri^{4,5}, Karuppannan Iswarya⁶

¹Andhra Pradesh Fisheries University, Andhra Pradesh, India

²ICAR – Central Institute of Brackishwater Aquaculture, Tamil Nadu, India

³ICAR – Central Institute of Fisheries Education, Mumbai, India

⁴Department of Chemistry, Faculty of Science, King Khalid University, Abha 61413, Saudi Arabia

⁵Research Centre for Advanced Materials Science (RCAMS), King Khalid University, AlQura'a, Abha, P.O. Box 960, Saudi Arabia

⁶Department of Fish Quality Assurance and Management, Fisheries College and Research Institute, Tamil Nadu Dr. J. Jayalalithaa Fisheries University, Thoothukudi – 628 008, India

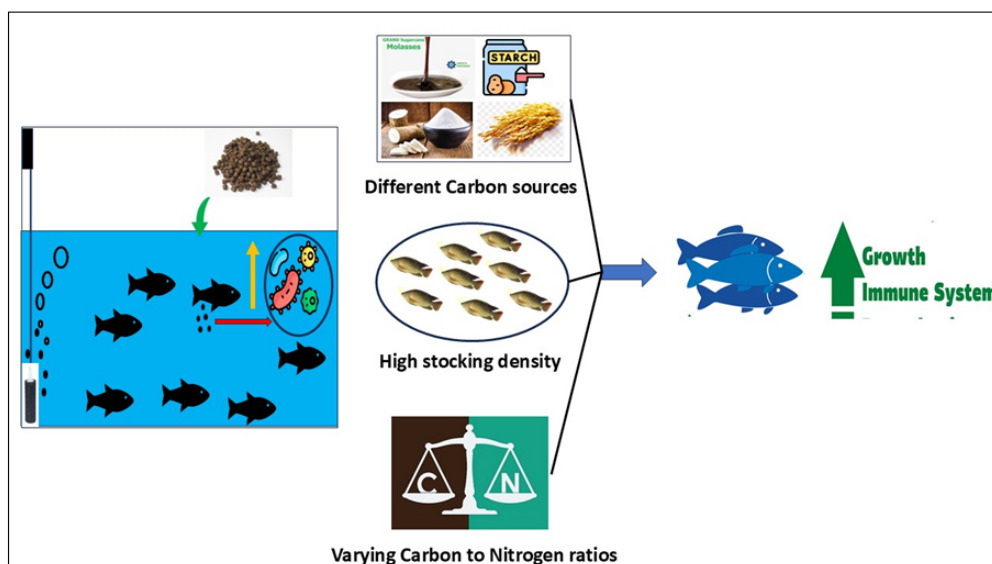
*Corresponding authors: harimfsc2525@gmail.com; anantharaja984@gmail.com

Abstract

Aquaculture has been expanding worldwide due to the emerging global population, which is needed to meet the increasing food demand of mankind. As they emerge rapidly, they create pressure on the environment through intensive resource exploitation and carbon emissions. Therefore, sustainable aquaculture technologies should be explored to resolve this issue. Biofloc technology (BFT) has emerged as a transformative approach to modern aquaculture that addresses critical challenges in productivity, environmental sustainability, and resource efficiency. By leveraging microbial processes, BFT converts nitrogenous waste into protein-rich microbial biomass, thereby enhancing nutrient recycling, water quality, and system productivity. This innovative approach minimizes reliance on conventional feed and water exchange systems, while providing a supplementary food source rich in essential amino acids, lipids, vitamins, and minerals. BFT significantly improves growth performance, feed conversion efficiency, immune responses, and survival rates in intensive aquaculture systems, demonstrating adaptability across diverse aquatic species, such as tilapia, carp, shrimp, and catfish. Despite its numerous advantages, BFT implementation faces several challenges, including the need for precise control of carbon-to-nitrogen (C/N) ratios, aeration, and energy management. Addressing these challenges through advancements in automation, real-time monitoring, and sustainable energy solutions is essential for maximizing their potential. This review examines the principles, applications, and benefits of BFT and highlights its role in enhancing water quality, optimizing stocking densities, and improving the physiological and immunological performance of cultured species. By adopting BFT, the industry can achieve a sustainable and resilient framework, meeting the global demand for aquatic proteins while minimizing the environmental impact.

Key words: biofloc technology, sustainable approach, microbial protein, economic efficiency, organic carbon, nitrogen toxicity

Graphical Abstract:



The escalating global population necessitates substantial advancements in the food production sector, with aquaculture playing a pivotal role in addressing this demand (Piedrahita, 2003). However, the expansion of aquaculture requires careful consideration of its social, economic, and environmental sustainability (Sharifinia et al., 2019). In particular, coastal aquaculture intensification has resulted in increased organic matter accumulation in aquatic ecosystems, leading to environmental concerns (Piedrahita, 2003; Sharifinia et al., 2018, 2019). Efforts to establish high-density aquaculture operations to boost sustainable production have driven the rapid growth of the fish-farming industry (Arfuso et al., 2017; Guerrero et al., 2016). By 2025, global fish production is projected to reach 196 million tons, with aquaculture surpassing capture fisheries (Erkinharju et al., 2021). Despite these advancements, significant challenges persist, including compromised animal welfare due to overcrowding, elevated disease prevalence resulting from unfavorable environmental conditions, and reduced disease resistance to stress (Santos and Ramos, 2018). Overuse of antibiotics and chemical disinfectants to address these issues has exacerbated concerns about drug resistance and the emergence of superbugs (Kim et al., 2020). Addressing these challenges requires robust regulatory oversight, but inconsistencies in regulatory frameworks across countries and, in some cases, a complete lack of regulation pose significant obstacles (Ragasa et al., 2022). To promote sustainable aquaculture practices, eco-friendly technologies are increasingly being integrated into intelligent systems (Zhao et al., 2021 a). Higher productivity often necessitates increased feed input, which amplifies waste generation and it creates economic and environmental consequences. Only 20–30% of the nitrogen introduced into aquaculture systems is assimilated into fish biomass, with the remainder contributing to water pollution and elevated concentrations of harmful substances such as nitrite (NO_2) and ammonia (NH_3) (Liu et al., 2019). In recent years, recirculating aquaculture systems (RAS) have emerged as a viable solution for achieving sustainability through effective wastewater treatment (Gutierrez-Wing and Malone, 2006). These systems typically replace approximately 10% of total daily water volume (De Schryver et al., 2008). However, their adoption remains limited, particularly in developing nations, due to the high costs associated with operation and maintenance (Badiola et al., 2012; Ahmad et al., 2017; Karimanzira et al., 2017). Consequently, there is a pressing need for cost-effective, environmentally friendly, and sustainable technologies that are globally accessible to farmers.

Biofloc technology (BFT) has emerged as a promising and sustainable approach to aquaculture, offering an economical and environmentally friendly method to enhance microbial protein production and water quality (Li and Dai, 2025; Dinda et al., 2020). By utilizing beneficial microbes, BFT effectively mitigated the accumulation of NH_3 and NO_2 generated from feed waste, feces, and urine. This process fosters self-nitrification within aquaculture

systems, thereby eliminating the need for water exchange (Ekasari and Maryam, 2012; Dinda et al., 2020; Sgnaulin et al., 2018). The technology improves water quality and provides an alternative feed source for aquatic organisms by stimulating microbial growth (De Schryver et al., 2008). Compared to traditional aquaculture techniques, BFT technology offers a more sustainable approach with minimal water exchange and decreased feed intake, and transforms it into low-cost sustainable techniques for sustainable aquaculture development (De Schryver et al., 2008; Avnimelech and Kochba, 2009). Given increasing environmental concerns, BFT is gaining traction among aquaculture farms, providing benefits such as reduced water exchange, enhanced fish production, and minimized external contamination (Khanjani et al., 2024 a; Kim et al., 2019).

The operational success of BFT relies on intensive aeration and the addition of carbon sources, such as sucrose, glucose, and molasses, to stimulate microbial activity and remove excess NH_3 from the aquatic environment (Kim et al., 2020). This system is particularly suitable for freshwater species, such as carp, catfish, and tilapia, which dominate pond aquaculture production (Diatin et al., 2021). This review focuses on the current advancements in BFT, its practical applications, and its specific benefits for freshwater species, including common carp (*Cyprinus carpio*), Nile tilapia (*Oreochromis niloticus*), and various polyculture systems (Diatin et al., 2021; Zhang et al., 2018 b). It also explores the transition of traditional flow-through water culture systems to biofloc-based systems and highlights the potential of BFT to address key challenges in aquaculture. This review aimed to comprehensively understand the role of BFT in promoting sustainable, efficient, and eco-friendly aquaculture practices.

Principles of biofloc technology

Biofloc technology (BFT) is an innovative and sustainable aquaculture approach that capitalizes on natural interactions among microorganisms to enhance productivity, environmental sustainability, and economic efficiency (Liu et al., 2025; Sgnaulin et al., 2018). Bioflocs are complex aggregates suspended in aquatic environments and comprise floc-forming bacteria, filamentous algae, diatoms, protozoa, micro- and macroinvertebrates, uneaten feed, and fecal matter (Figure 1) (Dinda et al., 2020; Sgnaulin et al., 2018). These aggregates are formed through the flocculation of organic particles, creating clusters of bacteria, algae, and protozoa that enhance waste management, disease control, and water quality in high-density aquaculture systems (Avnimelech, 2007). BFT is regarded as a climate-resilient aquaculture practice (Ogello et al., 2024). Microorganisms within the BFT contribute to biosecurity, improve feed conversion ratios (FCR), and reduce feed costs while maintaining water quality (Khanjani et al., 2023). Converting nitrogenous waste into protein-rich bioflocs reduces environmental toxicity and recycles nutrients (Khanjani et al.,

2025). This dual functionality minimizes the ecological impact and boosts aquaculture productivity. One of the critical mechanisms in BFT is the transformation of NH_3 into microbial proteins, which improves water quality and supports high stocking densities with minimal water exchange (Emerenciano et al., 2017). This process also mitigates greenhouse gas emissions and enhances carbon sequestration by positioning BFT as an environmentally friendly solution (Jansson and Northen, 2010). These attributes make the BFT a cost-effective and practical option for aquaculture operators.

Biofloc development begins with the accumulation of organic waste, which serves as a substrate for floc-forming microorganisms (Dinda et al., 2020). The biofloc matrix primarily consists of extracellular polymeric substances (EPS) that bind components, such as polysaccharides, proteins, nucleic acids, lipids, and humic substances (De Schryver et al., 2008; Basuvaraj et al., 2015). The slow sinking rates of bioflocs ensure their prolonged suspension in water, facilitating their use as a continuous nutrient source for aquatic species and enhancing nutrient retention within the system (De Schryver et al., 2008). Optimal biofloc formation relies on maintaining a carbon-to-nitrogen (C/N) ratio of 15 or higher, supporting the growth of beneficial heterotrophic bacteria (Dinda et al., 2020). These bacteria efficiently convert nitrogenous waste into microbial biomass, thus reducing NH_3 toxicity and improving the overall system productivity. Carbon sources, such as molasses, cassava, sugarcane, and wheat bran, are commonly added to achieve the desired C/N ratio, while continuous aeration ensures microbial activity (Eding et al., 2006). Efficient BFT can produce bacterial biomass (0.5 g) per gram of added carbon, providing a reliable estimate of biomass generation (Ogello et al., 2021).

BFT has proven effective for various aquatic species, including catfish and shrimp, with additional enhancements, such as carbonation and bio-balls, by optimizing water quality and growth performance (Deswati et al., 2023). The probiotic properties of bioflocs enhance biosecurity by reducing pathogenic risk (Crab et al., 2012). A notable advantage of the BFT is its economic viability. With relatively low initial investments and sim-

ple requirements, such as sunlight, a carbon source, and aeration, BFT is an accessible alternative to conventional aquaculture systems (Ekasari and Maryam, 2012). Bioflocs also function as single-cell proteins (SCPs), offering a nutrient-dense feed option that promotes growth and profitability (Avnimelech, 2007). Moreover, BFT effectively addresses nitrogenous waste management challenges in traditional aquaculture systems by reducing nitrogenous waste retention from approximately 49% to 5% (Ogello et al., 2021). Additionally, this technology ensures a consistent year-round supply of live feed in hatcheries, improving fish seed production (Kagali et al., 2018; Ogello et al., 2018). For instance, studies on Pacific white shrimp (*Penaeus vannamei*) farming have demonstrated a 20% reduction in feed costs and a 30% increase in growth rates with BFT, compared to conventional systems (Emerenciano et al., 2013).

Biofloc and water quality dynamics

Rapid expansion of aquaculture is critical for addressing global protein shortages (Matos et al., 2006). However, the industry faces economic and environmental challenges, particularly water pollution and the associated risks of ecological harm caused by nutrient and organic matter accumulation in high-density systems (Piedrahita, 2003). Excessive organic loading in traditional aquaculture systems can degrade water quality, resulting in elevated levels of nitrogenous compounds such as NH_3 , NO_2 , and NO_3 , which are toxic to aquatic organisms (Avnimelech, 2007). Biofloc technology (BFT) offers a sustainable solution to these challenges by stabilizing the water quality through microbial nutrient cycling (Li et al., 2025; Emerenciano et al., 2013). Studies have demonstrated that BFT systems can maintain water quality parameters, such as temperature, pH, dissolved oxygen (DO), total ammonia nitrogen (TAN), NO_2 , and NO_3 within acceptable ranges for aquatic organisms (Emerenciano et al., 2013; Hwihiy et al., 2021). For instance, Rajkumar et al. (2016) reported a DO level of 4.07 mg/L, sufficient for *P. vannamei*, while alkalinity and hardness levels in BFT systems exceeded 4,000 mg/L and 100 mg/L, respectively, facilitating exoskeleton production and molting.

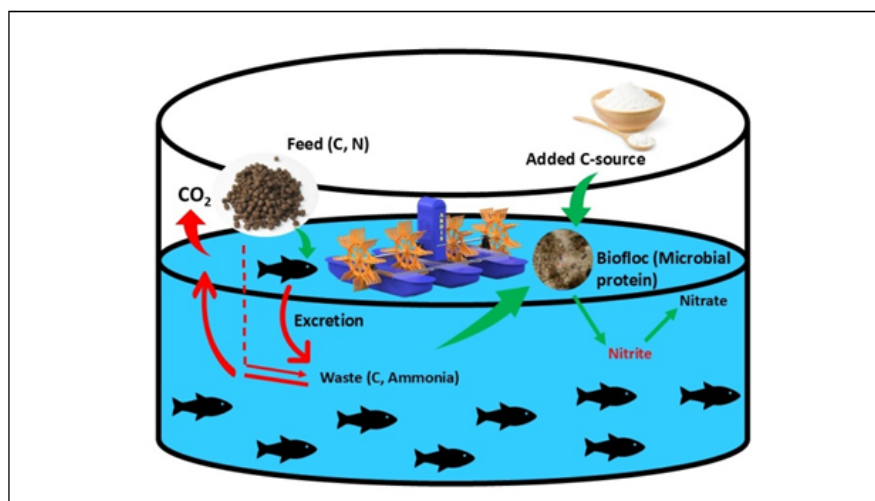


Figure 1. Biofloc system at first glance

The carbon-to-nitrogen (C/N) ratio is a critical parameter in BFT, driving microbial assimilation of nitrogen and mitigating the accumulation of toxic compounds (Chen et al., 2024; Ekasari and Maryam, 2012). A balanced C/N ratio, typically between 10:1 and 20:1, promotes the microbial uptake of NH_3 and NO_2 , thereby reducing their concentrations in the culture system (Zhao et al., 2014). Recent research by Dilmi et al. (2021) and Panigrahi et al. (2018) confirmed that elevated C/N ratios initially increased NO_2 levels due to nitrification, but led to their decline as denitrifying bacteria converted NO_3 into nitrogen gas. Similarly, Zhao et al. (2014) demonstrated that maintaining a C/N ratio of 15:1 to 23:1, facilitated by maize starch, significantly reduced TAN, nitrite nitrogen ($\text{NO}_2\text{-N}$), and nitrate-nitrogen ($\text{NO}_3\text{-N}$) concentrations without increasing the chemical oxygen demand (COD). Temperature plays a pivotal role in microbial metabolism and biofloc formation. Yang and Li (2009) noted that temperatures between 18°C and 25°C optimize microbial activity in BFT systems. However, Zhao et al. (2014) observed a decline in biofloc levels at lower temperatures, highlighting the importance of temperature regulation in maintaining water quality. The effectiveness of BFT in nitrogen cycling is further evidenced by the assimilation of up to 0.2 grams of nitrogen per square meter per day by biofloc-associated microorganisms when the C/N ratio exceeds 10:1 (Azim and Little, 2008). Although heterotrophic bacteria effectively reduce TAN levels by consuming organic carbon, denitrification is not instantaneous, with removal efficiencies ranging from 77% to 98% (De Schryver and Verstraete, 2009). Rajkumar et al. (2016) emphasized the superior performance of carbohydrate sources such as wheat and tapioca flour in reducing TAN compared to traditional clear-water systems. During the initial stages of BFT, floc formation is gradual, and floc volume increases over time (Rajkumar et al., 2016). Shrimp thrives at a floc volume of 50 mL; however, excessive floc volumes can lead to DO depletion, particularly in the morning, necessitating water adjustments to stabilize the conditions (Burford et al., 2003). The interplay between the nitrification and denitrification processes in BFT systems results in dynamic fluctuations in $\text{NO}_3\text{-N}$ levels, as observed by Hwihy et al. (2021). This balance underscores the robust capacity of bioflocs to stabilize water quality, providing an environmentally and economically sustainable approach to intensive aquaculture.

Factors influencing biofloc systems

Numerous interrelated factors shape the development and performance of BFT, including the carbon-to-nitrogen (C/N) ratio, carbon source, feeding regime, stocking density, salinity, lighting, and aeration level (Khanjani et al., 2022; Minaz and Kubilay, 2021). Integrating these factors is essential for optimizing BFT in aquaculture systems. Liu et al. (2019) demonstrated the importance of harmonizing C/N ratios, species density, carbon sources, and aeration strategies for enhanced production

efficiency. The size of the biofloc particles significantly affects their nutritional value and digestibility. Filter-feeding fish species, such as *Hypophthalmichthys molitrix* (silver carp) and *Hypophthalmichthys nobilis* (big-head carp), consume bioflocs with smaller particle sizes, aligning with their gill raker morphology (Zhao et al., 2021 b). Bioflocs produced in aquaculture systems, typically between 100 and 2000 μm (Zhao et al., 2014), are well suited for consumption by these species. Furthermore, operational parameters, including carbon sources and aeration, influence the nutritional composition of the bioflocs (Kumar et al., 2017). Paddle wheel aerators play a key role in maintaining bioflocs in suspension and achieving a proper mixing intensity. Chaignon et al. (2002) observed that higher mixing intensities lead to floc breakage, reducing their average size, while moderate intensities promote balanced aggregation and dispersion. Optimal floc sizes for aquaculture species range from 250 to 1200 μm , depending on the species requirement (de Barros and Valenti, 2003).

Dissolved oxygen (DO) levels critically affect the metabolic activity and structural properties of bioflocs. Dauda (2020) reported that higher DO levels favor the formation of larger compact flocs, improving their settling characteristics. At lower DO levels (0.5–2 mg/L), flocs exhibit poor settling capabilities with a high sludge volume index (SVI) of 250 mL/g, whereas higher DO levels (2–5 mg/L) result in reduced SVI (~100 mL/g) (Martins et al., 2003). Filamentous bacteria, which dominate under low DO conditions, hinder floc performance owing to their ability to obstruct gills at high concentrations. To mitigate the oxygen depletion caused by aerobic microbial metabolism, De Schryver et al. (2008) proposed nurturing bioflocs in external reactors before introducing them to culture systems, and the selection of carbon sources significantly influences biofloc formation and nutrient cycling. Carbon sources such as molasses, maize starch, and wheat bran are chosen based on their cost, biodegradability, and local availability (Salehizadeh and Van Loosdrecht, 2004). The type and quantity of organic carbon added determine the energy storage polymers within bioflocs, affecting their nutritional value (Tasleem et al., 2024; Oehmen et al., 2004). Azim et al. (2008) emphasized the need to balance protein and carbon content in feed formulations to optimize microbial assimilation and reduce nitrogen waste. Additionally, organic loading rates influence the competitive dynamics between filamentous and non-filamentous bacteria, with filamentous bacteria thriving at low substrate concentrations owing to their extended surface area (Martins et al., 2003).

Temperature is pivotal for microbial activity and biofloc properties, but it is challenging to control in outdoor ponds. Wilén et al. (2000) found that activated sludge flocs deflocculate more readily at colder temperatures (4°C) owing to reduced microbial activity. Conversely, at higher temperatures (30–35°C), excessive production of extracellular polymeric substances (EPS) can lead to

sludge thickening, with SVI values exceeding 500 mL/g (Suresh et al., 2018). In tropical regions, where water temperatures often remain within optimal ranges, the effects of temperature on BFT are more manageable, whereas colder climates require additional interventions to maintain efficiency (Khanjani et al., 2024 b). Lighting and salinity also influence the dynamics of the bioflocs. Khanjani and Sharifinia (2021) noted that light exposure affects the growth of photosynthetic microorganisms within bioflocs, contributing to nutrient cycling and oxygen production. Similarly, salinity levels impact microbial community composition, with higher salinity favoring halotolerant species (Khanjani and Alizadeh, 2024). Adjusting these factors in line with the target species requirements ensures an optimal biofloc performance.

Microbial and plankton communities in biofloc

Microorganisms (MOs) play a crucial role in the life cycles of organisms and ecosystems (Dobrovol'skaya et al., 2015). Various microbial groups in aquaculture systems contribute positively by removing contaminants that serve as food sources and recycling organic matter (Ekasari and Maryam, 2012). However, they can also have adverse effects, such as causing diseases under unfavorable environmental conditions (Abakari et al., 2021; Karigar and Rao, 2011). Studies examining the biofloc community structure and composition in shrimp farming (Anand et al., 2014; Ballester et al., 2010; Ju et al., 2008) have categorized microorganisms into five overlapping groups: floc-forming organisms, saprophytes, nitrifying bacteria, algae grazers, and pathogenic bacteria (e.g., *Vibrio* spp.). To ensure the effective functioning of a BFT system and the achievement of its objectives, species from all these groups must remain suspended within the water column, actively performing their roles and interacting with other species (Kumar et al., 2021). Microalgae (phytoplankton) in BFT systems can be classified into two main groups: eukaryotes (e.g., diatoms and chlorophytes) and prokaryotes (e.g., cyanobacteria). These organisms play a pivotal role in BFT systems by utilizing nitrogenous compounds to synthesize proteins and sugars, and produce oxygen in the presence of light (Khoa et al., 2020). Various algal genera and species have been identified in BFT systems, including *Scenedesmus quadricauda*, *Coelastrum*, *Pediastrum duplex*, *Cyclotella*, *Navicula*, *Synedra*, *Fragilaria*, *Orthoseira*, *Rhabdonema*, *Ulothrix*, *Skeletonema*, *Cylindrotheca*, *Hemiaulus*, *Phymatodocis*, *Cyanobacteria*, *Chlorophyta*, *Bacillariophyta*, *Euglenophyta*, and *Dinophyta* (Brito et al., 2014; Ferreira-Marinho et al., 2014; Monroy-Dosta et al., 2013). Manan et al. (2017) observed that algae from Chlorophyceae (green algae), Bacillariophyceae (diatoms), and Cyanophyceae (blue-green algae) were the predominant species during the early stages of BFT aquaculture. In some cases, species of Dinophyceae (dinoflagellates) are also present.

Avnimelech and Kochba (2009) highlighted that the availability of $\text{NO}_3\text{-N}$ in BFT systems supports the pro-

liferation of phytoplankton, as heterotrophic bacteria primarily consume NH_3 in the culture environment. However, limited light and the addition of a carbon source often lead to a decline in plankton density (Jiang et al., 2020). Rajkumar et al. (2016) observed that introducing a carbon source favors microbial growth over microalgae. Bioflocs host many beneficial microorganisms, including copepods, ciliates, rotifers, nematodes, bacteria, and protozoa (Rajkumar et al., 2016; Azim and Little, 2008). In a study on the effects of feeding strategies on *Oreochromis niloticus*, Mohammady et al. (2023) identified 22 species of phytoplankton in BFT systems, predominantly belonging to Cyanobacteria, Chlorophyceae, and Bacillariophyta. Chlorophyceae and Cyanobacteria were found to dominate these systems. Similarly, Green (2010) linked higher chlorophyll levels in BFT systems to improved productivity of *Ictalurus punctatus*. Schrader et al. (2011) also reported that diatoms were co-dominant alongside Cyanobacteria and Chlorophyceae in the phytoplankton communities of BFT systems with *I. punctatus*. The rapid growth of Chlorophyceae, especially its small unicellular or colonial forms, is believed to enhance DO levels, thereby supporting aquaculture systems (Schrader et al., 2011).

Cyanobacteria and Chlorophytes often dominate phytoplankton communities in various environments, including brackish water and marine BFT systems (Vinatea et al., 2010). However, in freshwater, brackish water, and marine systems where Cyanobacteria and Chlorophytes are prevalent, Bacillariophyta (diatoms) appear sporadically (Schrader et al., 2011; Vinatea et al., 2010). Mohammady et al. (2023) suggested suspended particle accumulation in BFT systems creates less favorable conditions for diatoms but promotes mixotrophic Cyanobacteria, reducing diatoms and decreasing photosynthetically active radiation. The formation of zooplankton communities increases as nitrogen waste and biofloc growth intensify in the presence of a carbon source (Mabroke et al., 2021). Said and Taha (2022) reported that biofloc systems consistently showed higher zooplankton abundance than clear water systems, with Rotifera, Protozoa, and Copepoda being the dominant groups (Mohammady et al., 2023). Azim and Little (2008) similarly identified Protozoa, Rotifera, and Oligochaeta as the primary zooplankton taxa in biofloc systems. Gao et al. (2019) noted that carbon supplementation promoted biofloc formation, which is a significant feed source for zooplankton growth. Singh et al. (2024) emphasized that increased biofloc levels elevate organic matter, further boosting zooplankton populations, especially protozoa. Madoni et al. (2018) observed that free bacteria in BFT encourage the dominance of ciliated protozoa, while protozoa enhanced bacterial growth by releasing nutrient salts and stimulants that improve bacterial carbon uptake (Jürgens and Matz, 2002). In summary, the microbial and plankton communities are integral to the functionality and sustainability of BFT systems. Microorganisms play diverse roles in nutrient recycling and contaminant removal, serving as

feed sources and maintaining ecological balance (Ak-insemolu, 2018). Phytoplankton, including eukaryotic algae and prokaryotic cyanobacteria, significantly contribute to the assimilation of nitrogenous compounds that produce oxygen and support higher trophic levels (Jürgens and Matz, 2002). The dynamic interactions among microorganisms, algae, and zooplankton within BFT systems are essential for optimizing aquaculture productivity and maintaining water quality (Yun et al., 2022).

Biofloc and aquatic organism performance

Biofloc technology (BFT) has been extensively studied for its positive effects on fish growth performance, feed utilization, and overall health (Table 1). Research indicates that fish cultured in BFT systems exhibit improved growth performance, protein efficiency ratios (PER), and reduced feed conversion ratios (FCR), suggesting the effective utilization of biofloc as a supplementary food source (Khanjani et al., 2024 a). Azim and Little (2008) reported a 44–46% increase in the growth of *O. niloticus* in a bioflocculant system. Mirzakhani et al. (2019) also found that *O. niloticus*, raised under biofloc conditions, exhibited growth rates between 71.8% and 319.9% faster, underscoring the effectiveness of biofloc as a food source. Similarly, a study on *Clarias gariepinus* also showed significantly improved growth performance and feed utilization, with fish exhibiting higher specific growth rates (SGR) and better FCR in BFT systems than in traditional systems (Putra et al., 2017). Zablon et al.

(2022) highlighted that BFT enhances protein utilization efficiency, improving growth rates even with lower dietary protein levels. For instance, Adineh et al. (2019) observed higher PER and lower FCR in fish within BFT groups, while Abbaszadeh et al. (2019) reported significantly lower FCR in biofloc-reared fish groups. This is because of the nutritional composition of biofloc, which contributes to enhanced feed utilization by providing essential amino acids, lipids, vitamins, and minerals, thereby improving fish growth rates (Khanjani et al., 2023). Additionally, bioflocs stimulate digestive enzyme activity, facilitating better nutrient digestion in the fish gut and improving feed efficiency and growth performance (Abbaszadeh et al., 2019). Beyond growth metrics, biofloc systems have been shown to boost immunity and survival rates in fish. Liu et al. (2019) found that biofloc enhances immune responses, increasing survival rates across various fish species. Ekasari et al. (2015) reported that *O. niloticus* broodstock raised in BFT systems had higher larval survival rates than those in clear water systems, indicating a positive effect of BFT on larval survival. Similarly, Haridas et al. (2017) observed that bioflocs significantly increased the survival rate of *Mugil cephalus* during the nursery phase, suggesting enhancements in fish immune function and overall health. Additionally, Kim et al. (2018) reported a 26.3% increase in the growth of *Paralichthys olivaceus* in biofloc systems, further suggesting that biofloc enhances fish immunity and growth potential.

Table 1. Effect of different carbon sources on the biofloc system of various fish species

Carbon source		C/N ratio	Fish species	Observed effect	References
1	2	3	4	5	
Carbohydrates	Tapioca starch	13:1	Yellow catfish (<i>Pelteobagrus vachelli</i>)	Increased weight gain ratio	(Deng et al., 2018)
	Longan powder	24:1	Nile tilapia (<i>Oreochromis niloticus</i>)	Better water quality and gut microbiome	(Li et al., 2018)
	Sugarcane molasses and rice bran	20:1	Common carp (<i>Cyprinus carpio</i>)	Improves growth performance, immune and antioxidant status	(Ebrahimi et al., 2020)
	Sugarcane molasses and tapioca flour	15:1	<i>O. niloticus</i>	Enhanced growth performance and feed conversion ratio (FCR)	(Rind et al., 2023)
	Molasses	15:1	<i>O. niloticus</i>	Improved survival rates; starch-treated biofloc yielded the highest survival rates	(Khanjani et al., 2021)
	Mannan oligosaccharides	15:1	<i>O. niloticus</i>	Increased growth performance by 11.72% and 27.57%, respectively	(Kishawy et al., 2020)
	Sucrose and rice bran	15:1	African catfish (<i>Clarias gariepinus</i>)	Low survival rates (27%) in the rice bran-treated groups	(Dauda et al., 2017)
	Sugar beet molasses, sugar and corn starch	20:1	<i>C. carpio</i>	Improved growth performance and FCR; daily feeding rates reduced by 25%	(Abbaszadeh et al., 2019)
	Glucose	15–25:1	Kao-ping minnow (<i>Opsariichthys kaopingensis</i>)	Improved growth parameters and strengthened antioxidant system	(Yu et al., 2020)
	Sugarcane molasses	15:1	<i>O. niloticus</i>	Optimized nitrogen control and growth	(Martins et al., 2019)
	Molasses	15:1	<i>C. gariepinus</i>	Boosted growth with microbial synergy	(Yusuf et al., 2015)

Table 1 – contd.

1	2	3	4	5
	Molasses	10:1–20:1	<i>O. niloticus</i>	Higher survival rates and improved water quality (Pérez-Fuentes et al., 2016)
	Corn flour, wheat flour, sugar	12:1	<i>O. niloticus</i>	The weight of the fish enhanced in the sugar-fed group (García-Ríos et al., 2019)
	Wheat milling by-product and rice bran	15:1	<i>O. niloticus</i>	Better growth performance and immune parameters (Mansour and Esteban, 2017)
	Glucose	10-20:1	<i>O. niloticus</i>	Enhanced growth and physiological status (Li et al., 2018)
	Tapioca starch	16:1	<i>O. niloticus</i>	Higher average daily growth and survival rates (Nootong et al., 2011)
	Glucose	16:1	Genetically improved farmed tilapia (<i>O. niloticus</i>)	Increased final biomass of fish (Luo et al., 2017)
	Wheat flour	20:1	Mixed sex <i>O. niloticus</i>	Enhanced fish welfare and biomass (Azim and Little, 2008)
	Sugar beet molasses and wheat flour	15:1 and 20:1	<i>O. niloticus</i>	Significant improvement in the growth and immunological parameters (Mirzakhani et al., 2019)
	Molasses and starch	15:1	<i>O. niloticus</i>	Improved health status (Shourbela et al., 2021)
	Tapioca, wheat, corn and sugar bagasse	15:1	<i>Labeo rohita</i>	Improved metabolic response in the tapioca added BFT system (Ahmad et al., 2019)
	Raw rice bran and fermenting rice bran	15:1	<i>C. gariepinus</i>	Fermented rice bran improved growth, feeding efficiencies, and whole-body carcass composition (Romano et al., 2018)
	Tapioca flour	15:1	<i>O. niloticus</i>	Enhanced growth and digestive enzyme response were noted (Pai et al., 2024)
	Fermented and non-fermented wheat bran and rice bran	20:1	<i>C. carpio</i>	Fermentation of wheat and rice bran improved water quality and growth performance in juvenile <i>C. carpio</i> (Abiri et al., 2022)
Organic salt	Sodium acetate		<i>O. niloticus</i>	The weight of the fish increased by 22% compared to recirculating aquaculture system (Luo et al., 2014)
Organic acids and alcohol	Glycerol	15:1	<i>O. niloticus</i>	Increased growth and survival rates (Kishawy et al., 2020)
	Glycerol	15:1	<i>C. gariepinus</i>	Increased total biofloc production and higher survival rates (Dauda et al., 2017)
	Glycerol	15:1	<i>O. niloticus</i>	Increased growth performance (Shourbela et al., 2021)
Biodegradable polymers	Plant cellulose	13:1	<i>P. vachelli</i>	Increased weight gain ratio (Deng et al., 2018)
	Polyhydroxybutyrate-hydroxy valerate (PHBV) Longan powder	22:1	<i>O. niloticus</i>	Improved water quality (Li et al., 2018)

Influence of carbon sources on biofloc efficacy

The choice of carbon source in BFT significantly influences fish growth performance, water quality, feed utilization, and survival rates (Table 1) (Ekasari and Maryam, 2012). Heterotrophic bacteria in BFT systems rely on organic carbon to immobilize NH_3 and facilitate microbial protein synthesis, thereby reducing toxic NH_3 levels (Avnimelech, 2009). Adding organic carbon sources adjusts the C/N ratio, promotes microbial activity, and improves the overall water quality (Avnimelech, 2007; Ebeling et al., 2006). The type of carbon source used affects the nutritional composition and efficiency of the biofloc, thereby impacting fish growth, FCR, and

survival rates. For instance, simple carbon sources, such as molasses and starch, have significantly improved fish survival and growth performance owing to enhanced water quality and nutrient availability (Khanjani et al., 2023). Complex carbohydrates and prebiotics, such as mannanoligosaccharides (MOS), provide superior results by enhancing microbial activity and nutrient content in BFT systems (Kishawy et al., 2020). Furthermore, mixtures of carbon sources have been found to yield a better growth performance than single sources (Wang et al., 2016). However, inappropriate carbon sources, such as rice bran, can lead to poor survival rates owing to inadequate microbial growth and carbon availability (Dauda et

al., 2017). The following table summarizes the effects of various carbon sources on fish growth performance and survival rates in BFT systems.

Impact of carbon-to-nitrogen ratio on fish

The C/N ratio is a critical factor for maintaining the effectiveness of BFT systems (Ekasari and Maryam, 2012). Achieving an optimal C/N ratio ensures nitrogen toxicity control and promotes the growth of heterotrophic bacteria that utilize NH_3 and improve water quality. Carbon sources and feed mixtures with C/N ratios greater than 10 are recommended for optimal BFT conditions (Ebeling et al., 2006). Most fish feeds possess a C/N ratio of 9 or 10, requiring supplementary inputs to increase the ratio to the more desirable range of 12–15 (Asaduzzaman et al., 2010). Table 1 summarizes various studies on C/N ratios and their effects on different fish species.

Nutritional value of biofloc

Biofloc is recognized as a continuous, *in situ* supplemental food source that provides essential nutrients, such as proteins (including essential amino acids), polyunsaturated fatty acids, vitamins, and minerals for aquatic organisms (Razaet al., 2024; Azim and Little, 2008; Luo et al., 2014). The development of microbial flocs aids in recycling residual feed and waste, enhances nutrient reutilization, and improves feed assimilation in zero-water exchange systems (Avnimelech, 2007). The proximate value of bioflocs significantly affects the biochemical composition of aquatic organisms. For herbivorous and omnivorous fish and crustaceans, bioflocs with over 50% CP, 4% fiber, 7% ash, and an energy content of 22 kJ/g on a dry matter basis are deemed suitable (Webster and Lim,

2002). The C/N ratio also affects the nutritional composition of the bioflocs. For example, in the cultivation of *O. kaopingensis*, C/N ratios of 15:1 to 25:1 increased the protein content of bioflocs by 22% compared with a ratio of 10.8:1 (Yu et al., 2020). However, in a culture of *C. gariepinus*, a 10:1 C/N ratio resulted in a higher CP content of 47.3% (Dauda et al., 2017). These variations highlight the influence of species-specific factors, the established C/N ratio, and the carbon source used for the nutritional content of bioflocs. More complex carbohydrates produce flocs with a lower protein content (Ekasari et al., 2015). For instance, using glycerol as a carbon source with a C/N ratio of 10:1 resulted in flocs with 13.5% and 27% protein, which were lower than flocs with C/N ratios of 15:1 or 20:1 (Dauda et al., 2017). However, a C/N ratio of 10.8:1 with glucose in a BFT system produced flocs with reduced protein content (Yu et al., 2020). The essential amino acid composition of the carbon sources used in bioflocs varies, and the protein quality is closely linked to essential amino acids (Zhang et al., 2018 b). Therefore, it is important to obtain flocs with an amino acid profile that matches or closely aligns with the needs of farmed animals in order to investigate their potential as feed (Oliveira et al., 2024). To discern patterns in the nutritional profile of bioflocs, it is necessary to consider factors inherent to the crop, such as species, density, and salinity, in addition to the diet used (Zhang et al., 2018 a). Additionally, understanding whether the composition of bioflocs can be influenced by factors such as the type of biofloc (autotrophic or heterotrophic), the use of inoculum, its origin, and the percentage of carbon in the feed's protein and carbohydrate contents is critical (Oliveira et al., 2024).

Table 2. Different stocking densities in biofloc systems

Carbon source	C/N ratio	Fish species	System type	Stocking density	References
1	2	3	4	5	6
Tapioca starch and plant cellulose	13:1	<i>P. vachelli</i>	BFT	72 fish/300 L tank	(Deng et al., 2018)
Polyhydroxybutyrate-hydroxy valerate + LP (PHBVL)	22–24:1	<i>O. niloticus</i>	<i>In-situ</i> and <i>ex-situ</i> systems	40 fish/30 L tank	(Li et al., 2018)
Sugarcane molasses and rice bran	20:1	<i>C. carpio</i>	BFT	4.5 kg/m ³	(Ebrahimi et al., 2020)
Sugarcane molasses and tapioca flour	15:1	<i>O. niloticus</i>	BFT	25 fish/1000 L tank	(Rind et al., 2023)
Molasses	15:1	<i>O. niloticus</i>	BFT	1.53 g/L	(Khanjani et al., 2021)
Glycerol and mannan oligosaccharides	15:1	<i>O. niloticus</i>	BFT	25 fish/20 L tank	(Kishawy et al., 2020)
Glycerol, sucrose and rice bran	15:1	<i>C. gariepinus</i>	BFT	500 fish/m ³	(Dauda et al., 2017)
Sugar beet molasses, sugar and corn starch	20:1	<i>C. carpio</i>	BFT	8.02 kg/m ³	(Abbaszadeh et al., 2019)
Glucose	15–25:1	<i>O. kaopingensis</i>	BFT	30 fish/100 L tank	(Yu et al., 2020)
Sugarcane molasses	15:1	<i>O. niloticus</i>	BFT	25 fish/37.5 L tank	(Martins et al., 2019)

Table 2 – contd.

1	2	3	4	5	6
Molasses	15:1	<i>C. gariepinus</i>	Super intensive culture system	50 fish/100 L tank	(Yusufet al., 2015)
Molasses	10:1–20:1	<i>O. niloticus</i>	BFT	75 fish/m ³	(Pérez-Fuentes et al., 2016)
Corn flour, wheat flour, sugar	12:1	<i>O. niloticus</i>	BFT	3 fish/L	(García-Ríos et al., 2019)
Wheat milling byproduct and rice bran	15:1	<i>O. niloticus</i>	BFT	2 kg fish/m ³	(Mansour and Esteban, 2017)
Glucose	10–20:1	<i>O. niloticus</i>	BFT	0.45 g/fish	(Li et al., 2018)
Tapioca starch	16:1	<i>O. niloticus</i>	BFT	3.0 kg/m ³	(Nootong et al., 2011)
Sodium acetate		<i>O. niloticus</i>	BFT	45 kg/m ³	(Luo et al., 2014)
Glucose	16:1	GIFT (<i>O. niloticus</i>)	BFT	2.6 kg/m ³	(Luo et al., 2017)
Wheat flour	20:1	Mixed sex <i>O. niloticus</i>	Light-limited tank culture system	12 kg/m ³	(Azim and Little, 2008)
Sugar beet molasses and wheat flour	15:1 and 20:1	<i>O. niloticus</i>	BFT	10 fish/50 L tank	(Mirzakhani et al., 2019)
Glycerol, molasses and starch	15:1	<i>O. niloticus</i>	BFT	280 fish/m ³	(Shourbela et al., 2021)
Tapioca, wheat, corn and sugar bagasse	15:1	<i>Labeo rohita</i>	BFT	50 fish/300 L tank	(Ahmad et al., 2019)
Tapioca flour	15:1	<i>O. niloticus</i>	Hybrid system (BFT+RAS)	229 fish/m ³	(Pai et al., 2024)
Raw rice bran and fermented rice bran	15:1	<i>C. gariepinus</i>	BFT	25 fish/180 L tank	(Romano et al., 2018)
Fermented and non-fermented wheat bran and rice bran	20:1	<i>C. carpio</i>	BFT	25 fish/70 L tank	(Abiri et al., 2022)

Impact of stocking density on the growth performance of fishes

Increasing stocking density (SD) is a crucial strategy for improving the productivity and profitability of fish production (Fauji et al., 2018). However, high SD can lead to long-term stress, negatively impacting welfare, immune function, antioxidant responses, growth, and feed utilization (Liu et al., 2018). However, high-density populations can increase competition for feed, boost feed intake, elevate nutrient concentrations, and accelerate water quality deterioration (Branson, 2008). Long-term strains associated with dense populations can adversely affect the health of fish. It is essential to determine the appropriate stocking density for each species and its life stage in various production systems to avoid adverse outcomes (Oliveira et al., 2024). For instance, Adineh et al. (2019) reported that the expected carp growth in a clear water system was inhibited at 12 kg/m³ SD, indicating that high density hindered growth. In contrast, growth was significantly higher in the BFT system at the same SD, suggesting that biofloc may act as a probiotic, reduce stress, and provide dietary benefits (Liu et al., 2018). Table 2 displays the stocking densities of different fish species in the BFT systems.

Biofloc and physiological responses of fishes

Digestive enzymes

One critical mechanism by which bioflocs improve the digestion of cultured aquatic organisms is the enhancement of digestive enzyme activity (Yu et al., 2020). Ballester et al. (2010) demonstrated that biofloc is a practical, low-cost alternative to traditional culture systems because the flocs produced are rich in proteins, lipids, carbohydrates, and ash, making them suitable for aquaculture food by improving digestive enzymes. Digestive enzymes, such as amylase and protease, which are produced by digestive glands, are essential for food breakdown, primarily occurring in the stomach with absorption in the intestines (Xu and Pan, 2013). Bioflocs may contain unknown components that offer comprehensive nutrients and bioactive substances that may influence the digestion of fish (Ju et al., 2008). Bioflocs stimulate digestive enzyme production or activity, although a slight decrease in amylase and protease activity in aquatic organisms raised in BFT systems indicates potential disruption of the intestinal microflora balance (Xu et al., 2012). Long et al. (2015) showed that the BFT system significantly improved the activity of intestinal amylase and lipase in GIFT with glucose as a carbon source. This enhances the digestive activity and ultimately improves the growth

performance of fish. Juveniles of *O. niloticus* reared in a BFT system with molasses as an external carbon source (C/N ratio of 20:1) for 60 days showed improved activity of digestive enzymes, such as trypsin, protease, amylase, and lipase (Monroy-Dosta et al., 2025). Endogenous digestive enzymes produced by bioflocs and exogenous microbial enzymes such as proteases have been shown to improve growth performance and protein utilization in aquatic organisms (Najdegerami et al., 2016). The stocking density of the biofloc also significantly influences the digestive enzyme activity of animals (Liu et al., 2017). In this regard, Liu et al. (2018) found that when *O. niloticus* fingerlings were reared at different stocking densities (166 organisms m⁻³ (LD; low density), 333 organisms m⁻³ (MD; middle density), and 600 organisms m⁻³ (HD; high density)) for an experimental period of 120 days in a BFT system, the digestive enzymes were strongly influenced, and the HD group had lower activity of lipase, trypsin, and amylase. This shows that a high stocking density can significantly impair the digestion of farmed species. Studies explored that feeding rate can influence the digestive performance of the aquaculture species, and it was proved by Najdegerami et al. (2016), who carried out a study on *C. carpio* raised in a BFT system with 25% daily feed with a commercial diet and 75% biofloc for an experimental period of 30 days with beet molasses as an added carbon source, showing a notably improved activity of protease and pepsin. This revealed that the microbial community in the flocs stimulated digestion and led to nutritional adaptation of *C. carpio*.

Antioxidant enzymes

Superoxide dismutase (SOD), a key antioxidant enzyme in fish, converts superoxide anions into hydrogen peroxide, thereby protecting against ROS-induced damage and maintaining the metabolic balance of ROS. This enzyme represents the first line of defense against oxidative stress (Kim et al., 2019). Catalase (CAT), an enzyme found in the mitochondria and peroxisomes, further breaks hydrogen peroxide into water and oxygen, creating a fundamental antioxidant defense (Menaga et al., 2019). Biofloc has been shown to increase SOD and CAT activity in fish, and low levels of these enzymes can lead to the accumulation of free radicals, resulting in cell damage (Yu et al., 2023). Biofloc systems also enhance antioxidant enzyme activity in aquatic organisms by reducing oxidative stress caused by reactive oxygen species (ROS). Key antioxidant enzymes, including SOD and CAT, can protect cells by converting ROS into less harmful substances (Kim et al., 2019; Menaga et al., 2019). Adineh et al. (2019) exposed the 60-day BFT system raised Caspian roach (*Rutilus caspicus*) to a salinity (13 g/L) stress for 72 days, and the findings revealed that the SOD and CAT activities were lower compared to the fish raised in the clear water system. This showed an improved antioxidant defense system of the biofloc-raised animals. Even though the BFT systems stimulate SOD and CAT activity in animals, factors such as stocking

density strongly influence it. This fact was supported by the findings of Nageswari et al. (2022) in biofloc-raised *Pangasianodon hypophthalmus* at different stocking densities, such as 150, 180, 210, 240, and 270 g/m³, with finger millet flour as the added carbon source. The activities of SOD and CAT were higher in the BFT system with a stocking density of 150 g/m³. However, variations in antioxidant enzyme activity have been observed depending on the species and conditions (Haridas et al., 2017).

Immune response in biofloc systems

Biofloc technology (BFT) has emerged as a sustainable approach to aquaculture to enhance the immune response and health of farmed animals (Ekasari and Maryam, 2012). The presence of antibacterial compounds and organic materials in bioflocs significantly influences total protein in fish serum, including immunoglobulins (Uribe et al., 2011) and antibacterial peptides (Najdegerami et al., 2016). Beneficial bacteria in bioflocs colonize the gastrointestinal tract of fish, positively affecting their biological and immunological status (Zhao et al., 2012). This fact was further supported by the study of Long et al. (2015) in the GIFT strain of *O. niloticus* raised in the BFT system. The findings revealed that BFT did not negatively affect the hematological parameters of fish, such as red blood cells, white blood cells, and hemoglobin content. In addition, there was no significant effect on serum SOD and total protein levels, which was due to the abundance of natural microorganisms and bioactive compounds such as carotenoids, fat-soluble vitamins, and other immunostimulatory compounds that may stimulate the immune response of cultured fish. Previous studies have consistently shown that BFT systems can improve hematological parameters in *C. gariepinus* (Fauji et al., 2018) and *L. rohita* (Kamilya et al., 2017). Adjusting the C/N ratio in BFT systems can further amplify immune activity and antioxidant capacity and improve resistance to pathogens (Panigrahi et al., 2018). Various research has highlighted the immunostimulatory role of heterotrophic bacteria in farmed fishes such as *C. gariepinus* (Romano et al., 2018), *Carassius auratus gibelio* (Zhang et al., 2018 b), and *C. carpio* (Abbaszadeh et al., 2019) and revealed that bioflocs have improved the immune status of fish. Enhanced immune performance in biofloc-raised animals is due to factors such as enhanced water quality, as noted for *C. carpio* raised in BFT systems (Crab et al., 2012), high-quality biofloc as a food source (Abbaszadeh et al., 2019), and improved stress resistance in the biofloc environment (Faujiet al., 2018).

Stocking density can significantly influence the immune response of fish raised in the BFT system (Liu et al., 2018). Elevated cortisol and glucose levels under high stocking densities (280 g/m³) were noted in biofloc-raised *O. niloticus* (Shourbela et al., 2021). Bioflocs have been found to mitigate the effects of high stocking density stress by maintaining lower serum alanine aminotransferase (ALT) and aspartate aminotransferase (AST) activities, indicating reduced liver damage com-

pared to animals reared in clear water systems (Adineh et al., 2019). Lysozyme activity, an essential component of innate immunity, is significantly enhanced in fish raised in BFT systems (Mansour and Esteban, 2017). Similarly, myeloperoxidase (MPO) activity is stimulated in biofloc environments, promoting antibacterial responses through hypochlorous acid production during respiratory bursts (Sontakke and Haridas, 2018). The degree of MPO stimulation varies depending on the carbon source used for biofloc production (Verma et al., 2016). By stabilizing the water quality, reducing stress, and promoting microbial activity, bioflocs can improve the overall health and resilience of fish.

Future prospectus

BFT significantly improves water quality, lowers feed costs, and has a smaller environmental impact; thus, it has enormous potential for the future of sustainable aquaculture. BFT provides a resource-efficient solution to the growing demand for seafood worldwide, particularly in urban aquaculture and water-scarce areas. While genetic development may result in species better suited to biofloc conditions, incorporating other protein sources, such as insect meal and algae, might further enhance sustainability. Automated feeding systems, IoT-based sensors, and AI-driven monitoring are expected to improve BFT operations, thereby increasing their scalability and efficiency. The possible extension of biofloc systems to multitrophic aquaculture and bivalves could improve productivity and nutrient recycling. BFT is anticipated to play a significant role in climate-resilient fish farming, supporting sustainable seafood production and food security globally, with increasing interest from commercial aquaculture and government support.

Conclusion

Biofloc technology (BFT) has emerged as an innovative solution to address key challenges in modern aquaculture, enhancing productivity, sustainability, and environmental management. By leveraging microbial processes, BFT reduces reliance on conventional feed and water exchange systems, improves nutrient recycling, and enhances the water quality. This aligns with the growing demand for sustainable practices that support the expansion of aquaculture. BFT has proven to be effective across diverse aquatic species, including tilapia, carp, shrimp, and catfish, demonstrating adaptability to various environments and stocking densities. Additionally, it enhances fish health by boosting immune responses, antioxidant activity, and digestive enzyme production, thereby enabling high-density aquaculture without compromising fish welfare. Despite its advantages, implementing BFT poses challenges such as managing carbon-to-nitrogen (C/N) ratios, aeration, stocking density, and energy requirements. The choice of carbon source is critical for maintaining the quality and cost-effectiveness of biofloc. Integrating the BFT with innovations such as automation, real-time monitoring, and alternative energy

sources can further enhance its scalability and efficiency. In summary, BFT represents a transformative approach to sustainable aquaculture that addresses environmental concerns, while boosting productivity. Turning waste into resources exemplifies a circular, eco-friendly solution that aligns with the global sustainability goals. With continued advancements, BFT has the potential to reshape aquaculture, making it more resilient and sustainable for the growing global population.

Acknowledgements

The authors acknowledge the support of the Director, ICAR, Central Institute of Fisheries Education, Mumbai. The authors extend their appreciation to the Deanship of Scientific Research and Graduate Studies at King Khalid University for supporting this work through the Large Project number, R.G.P. 2/690/46 and the authors acknowledge the Research Center for Advanced Materials (RCAMS) at King Khalid University, Saudi Arabia for their valuable technical support.

References

- Abakari G., Luo G., Kombat E.O. (2021). Dynamics of nitrogenous compounds and their control in biofloc technology (BFT) systems: A review. *Aquac. Fish.*, 6: 441–447.
- Abbaszadeh A., Keyvanshokoo S., Yavari V., Naderi M. (2019). Proteome modifications of Pacific white shrimp (*Litopenaeus vannamei*) muscle under biofloc system. *Aquac. Nutr.*, 25: 358–366.
- Abiri S.A., Chitsaz H., Najdegerami E.H., Akrami R., Jalali A.S. (2022). Influence of wheat and rice bran fermentation on water quality, growth performance, and health status of common carp (*Cyprinus carpio* L.) juveniles in a biofloc-based system. *Aquaculture*, 555: 738168.
- Adineh H., Naderi M., Hamidi M.K., Harsij M. (2019). Biofloc technology improves growth, innate immune responses, oxidative status, and resistance to acute stress in common carp (*Cyprinus carpio*) under high stocking density. *Fish Shellfish Immunol.*, 95: 440–448.
- Ahmad I., Babitha Rani A.M., Verma A.K., Maqsood M. (2017). Biofloc technology: an emerging avenue in aquatic animal healthcare and nutrition. *Aquac. Int.*, 25: 1215–1226.
- Ahmad I., Leya T., Saharan N., Babitha Rani A.M., Rathore G., Gora A.H., Bhat I.A., Verma A.K. (2019). Carbon sources affect water quality and haemato-biochemical responses of *Labeo rohita* in zero-water exchange biofloc system. *Aquac. Res.*, 50: 2879–2887.
- Akinsemolu A.A. (2018). The role of microorganisms in achieving the sustainable development goals. *J. Clean. Prod.*, 182: 139–155.
- Anand P.S., Kohli M.P.S., Kumar S., Sundaray J.K., Roy S.D., Venkateshwarlu G., Sinha A., Pailan G.H. (2014). Effect of dietary supplementation of biofloc on growth performance and digestive enzyme activities in *Penaeus monodon*. *Aquaculture*, 418: 108–115.
- Arfuso F., Guerrero M.C., Fortino G., Fazio F., Santulli A., Piccione G. (2017). Water temperature influences growth and gonad differentiation in European sea bass (*Dicentrarchus labrax*, L. 1758). *Theriogenology*, 88: 145–151.
- Asaduzzaman M., Rahman M.M., Azim M.E., Islam M.A., Wahab M.A., Verdegem M.C.J., Verreth J.A.J. (2010). Effects of C/N ratio and substrate addition on natural food communities in freshwater prawn monoculture ponds. *Aquaculture*, 306: 127–136.
- Avnimelech Y. (2007). Feeding with microbial flocs by tilapia in minimal discharge bio-flocs technology ponds. *Aquaculture*, 264: 140–147.

- Avnimelech Y. (2009). Biofloc technology: A practical guide book. World Aquaculture Society, Baton Rouge, USA.
- Avnimelech Y., Kochba M. (2009). Evaluation of nitrogen uptake and excretion by tilapia in bio floc tanks, using ^{15}N tracing. *Aquaculture*, 287: 163–168.
- Azim M.E., Little D.C. (2008). The biofloc technology (BFT) in indoor tanks: water quality, biofloc composition, and growth and welfare of Nile tilapia (*Oreochromis niloticus*). *Aquaculture*, 283: 29–35.
- Azim M.E., Little D.C., Bron J.E. (2008). Microbial protein production in activated suspension tanks manipulating C: N ratio in feed and the implications for fish culture. *Bioresour. Technol.*, 99: 3590–3599.
- Badiola M., Mendiola D., Bostock J. (2012). Recirculating Aquaculture Systems (RAS) analysis: Main issues on management and future challenges. *Aquac. Eng.*, 51: 26–35.
- Ballester E.L.C., Abreu P.C., Cavalli R.O., Emerenciano M., De Abreu L., Wasielesky Jr W. (2010). Effect of practical diets with different protein levels on the performance of *Farfante penaeus paulensis* juveniles nursed in a zero exchange suspended microbial flocs intensive system. *Aquac. Nutr.*, 16: 163–172.
- Basuvaraj M., Fein J., Liss S.N. (2015). Protein and polysaccharide content of tightly and loosely bound extracellular polymeric substances and the development of a granular activated sludge floc. *Water Res.*, 82: 104–117.
- Branson E.J. (2008). Fish welfare. John Wiley & Sons.
- Brito L.O., Arana L.A.V., Soares R.B., Severi W., Miranda R.H., da Silva S.M.B.C., Coimbra M.R.M., Gálvez A.O. (2014). Water quality, phytoplankton composition and growth of *Litopenaeus vannamei* (Boone) in an integrated biofloc system with *Gracilaria birdiae* (Greville) and *Gracilaria domingensis* (Kützinger). *Aquac. Int.*, 22: 1649–1664.
- Burford M.A., Thompson P.J., McIntosh R.P., Bauman R.H., Pearson D.C. (2003). Nutrient and microbial dynamics in high-intensity, zero-exchange shrimp ponds in Belize. *Aquaculture*, 219: 393–411.
- Chaignon V., Lartiges B.S., El Samrani A., Mustin C. (2002). Evolution of size distribution and transfer of mineral particles between flocs in activated sludges: An insight into floc exchange dynamics. *Water Res.*, 36: 676–684.
- Chen Z., Li J., Zhai Q., Chang Z., Li J. (2024). Nitrogen cycling process and application in different prawn culture modes. *Rev. Aquac.*, 16: 1580–1602.
- Crab R., Defoirdt T., Bossier P., Verstraete W. (2012). Biofloc technology in aquaculture: beneficial effects and future challenges. *Aquaculture*, 356: 351–356.
- Dauda A.B. (2020). Biofloc technology: a review on the microbial interactions, operational parameters and implications to disease and health management of cultured aquatic animals. *Rev. Aquac.*, 12: 1193–1210.
- Dauda A.B., Romano N., Ebrahimi M., Karim M., Natrah I., Kamarudin M.S., Ekasari J. (2017). Different carbon sources affects biofloc volume, water quality and the survival and physiology of African catfish *Clarias gariepinus* fingerlings reared in an intensive biofloc technology system. *Fish. Sci.*, 83: 1037–1048.
- de Barros H.P., Valenti W.C. (2003). Food intake of *Macrobrachium rosenbergii* during larval development. *Aquaculture*, 216: 165–176.
- De Schryver P., Verstraete W. (2009). Nitrogen removal from aquaculture pond water by heterotrophic nitrogen assimilation in lab-scale sequencing batch reactors. *Bioresour. Technol.*, 100: 1162–1167.
- De Schryver P., Crab R., Defoirdt T., Boon N., Verstraete W. (2008). The basics of bio-flocs technology: the added value for aquaculture. *Aquaculture*, 277: 125–137.
- Deng M., Chen J., Gou J., Hou J., Li D., He X. (2018). The effect of different carbon sources on water quality, microbial community and structure of biofloc systems. *Aquaculture*, 482: 103–110.
- Deswati D., Zein R., Suparno S., Pardi H. (2023). Modified biofloc technology and its effects on water quality and growth of catfish. *Sep. Sci. Technol.*, 58: 944–960.
- Diatin I., Shafruddin D., Hude N., Sholihah M.A., Mutsmir I. (2021). Production performance and financial feasibility analysis of farming catfish (*Clarias gariepinus*) utilizing water exchange system, aquaponic, and biofloc technology. *J. Saudi Soc. Agric. Sci.*, 20: 344–351.
- Dilmi A., Refes W., Meknachi A. (2021). Effects of C/N ratio on water quality, growth performance, digestive enzyme activity and antioxidant status of Nile tilapia *Oreochromis niloticus* (Linnaeus, 1758) in biofloc based culture system. *Turk. J. Fish. Aquat. Sci.*, 22.
- Dinda R., Mandal A., Das S.K. (2020). Neem (*Azadirachta indica* A. Juss) supplemented biofloc medium as alternative feed in common carp (*Cyprinus carpio* var. *communis* Linnaeus) culture. *J. Appl. Aquac.*, 32: 361–379.
- Dobrovol'skaya T.G., Zvyagintsev D.G., Chernov I.Y., Golovchenko A.V., Zenova G.M., Lysak L.V., Manucharova N.A., Marfenina O.E., Polyanskaya L.M., Stepanov A.L., Umarov M.M. (2015). The role of microorganisms in the ecological functions of soils. *Eur. Soil Sci.*, 48: 959–967.
- Ebeling J.M., Timmons M.B., Bisogni J.J. (2006). Engineering analysis of the stoichiometry of photoautotrophic, autotrophic, and heterotrophic removal of ammonia–nitrogen in aquaculture systems. *Aquaculture*, 257: 346–358.
- Ebrahimi A., Akrami R., Najdegerami E.H., Ghiasvand Z., Koohsari H. (2020). Effects of different protein levels and carbon sources on water quality, antioxidant status and performance of common carp (*Cyprinus carpio*) juveniles raised in biofloc based system. *Aquaculture*, 516: 734639.
- Eding E.H., Kamstra A., Verreth J.A.J., Huisman E.A., Klapwijk A. (2006). Design and operation of nitrifying trickling filters in recirculating aquaculture: a review. *Aquac. Eng.*, 34: 234–260.
- Ekasari J., Maryam S. (2012). Evaluation of biofloc technology application on water quality and production performance of red tilapia *Oreochromis* sp. cultured at different stocking densities. *Hayati J. Biosci.*, 19: 73–80.
- Ekasari J., Rivandi D.R., Firdausi A.P., Surawidjaja E.H., Zairin Jr M., Bossier P., De Schryver P. (2015). Biofloc technology positively affects Nile tilapia (*Oreochromis niloticus*) larvae performance. *Aquaculture*, 441: 72–77.
- Emerenciano M., Gaxiola G., Cuzon G. (2013). Biofloc technology (BFT): A review for aquaculture application and animal food industry. *IntechOpen*.
- Emerenciano M.G.C., Martínez-Córdova L.R., Martínez-Porchas M., Miranda-Baeza A. (2017). Biofloc technology (BFT): A tool for water quality management in aquaculture. *Water Quality*, 5: 92–109.
- Emerenciano M.G.C., Fitzsimmons K., Rombenso A.N., Miranda-Baeza A., Martins G.B., Lazzari R., Fimbres-Acedo Y.E., Pinho S.M. (2021). Biofloc technology (BFT) in tilapia culture. In *Biology and aquaculture of tilapia* (pp. 258–293). CRC Press.
- Erkinharju T., Dalmo R.A., Hansen M., Seternes T. (2021). Cleaner fish in aquaculture: Review on diseases and vaccination. *Rev. Aquac.*, 13: 189–237.
- Fauji H., Budiardi T., Ekasari J. (2018). Growth performance and robustness of African Catfish *Clarias gariepinus* (Burchell) in biofloc-based nursery production with different stocking densities. *Aquac. Res.*, 49: 1339–1346.
- Ferreira-Marinho Y., Otavio-Brito L., da Silva C.V.F., dos Santos I.G.S., Olivera-Gálvez A. (2014). Effect of addition of *Navicula* sp. on plankton composition and postlarvae growth of *Litopenaeus vannamei* reared in culture tanks with zero water exchange. *Lat. Am. J. Aquat. Res.*, 42: 427–437.
- Gao F., Liao S., Liu S., Bai H., Wang A., Ye J. (2019). The combination use of *Candida tropicalis* HH8 and *Pseudomonas stutzeri* LZ301 on nitrogen removal, biofloc formation and microbial communities in aquaculture. *Aquaculture*, 500: 50–56.
- García-Ríos L., Miranda-Baeza A., Coelho-Emerenciano M.G., Huerta-Rábago J.A., Osuna-Amarillas P. (2019). Biofloc technology (BFT) applied to tilapia fingerlings production using different carbon sources: Emphasis on commercial applications. *Aquaculture*, 502: 26–31.
- Green B.W. (2010). Effect of channel catfish stocking rate on yield and water quality in an intensive, mixed suspended-growth production system. *N. Am. J. Aquac.*, 72: 97–106.

- Guerrera M.C., Arfuso F., Rizzo M., Saoca C., Fazio F., Fortino G., Santulli A., Piccione G. (2016). Gonadal sexual differentiation of European sea bass (*Dicentrarchus labrax*, L. 1758) of fingerlings in different size classes. *Mar. Freshw. Behav. Physiol.*, 49: 347–354.
- Gutierrez-Wing M.T., Malone R.F. (2006). Biological filters in aquaculture: trends and research directions for freshwater and marine applications. *Aquac. Eng.*, 34: 163–171.
- Haridas H., Verma A.K., Rathore G., Prakash C., Sawant P.B., Babitha Rani A.M. (2017). Enhanced growth and immuno-physiological response of Genetically Improved Farmed Tilapia in indoor bio-floc units at different stocking densities. *Aquac. Res.*, 48: 4346–4355.
- Hwihy H., Zeina A., Abu Husien M., El-Damhougy K. (2021). Impact of Biofloc technology on growth performance and biochemical parameters of *Oreochromis niloticus*. *Egypt. J. Aquat. Biol.*, 25: 761–774.
- Jansson C., Norrhen T. (2010). Calcifying cyanobacteria – the potential of biomineralization for carbon capture and storage. *Curr. Opin. Biotechnol.*, 21: 365–371.
- Jiang W., Ren W., Li L., Dong S., Tian X. (2020). Light and carbon sources addition alter microbial community in biofloc-based *Litopenaeus vannamei* culture systems. *Aquaculture*, 515: 734572.
- Ju Z.Y., Forster I., Conquest L., Dominy W. (2008). Enhanced growth effects on shrimp (*Litopenaeus vannamei*) from inclusion of whole shrimp floc or floc fractions to a formulated diet. *Aquac. Nutr.*, 14: 533–543.
- Jürgens K., Matz C. (2002). Predation as a shaping force for the phenotypic and genotypic composition of planktonic bacteria. *Antonie Van Leeuwenhoek*, 81: 413–434.
- Kagali R.N., Ogello E.O., Sakakura Y., Hagiwara A. (2018). Fish-processing wastes as an alternative diet for culturing the minute rotifer *Proales similis* de Beauchamp. *Aquac. Res.*, 49: 2477–2485.
- Kamiliya D., Debbarma M., Pal P., Kheti B., Sarkar S., Singh S.T. (2017). Biofloc technology application in indoor culture of *Labeo rohita* (Hamilton, 1822) fingerlings: The effects on inorganic nitrogen control, growth and immunity. *Chemosphere*, 182: 8–14.
- Karigar C.S., Rao S.S. (2011). Role of microbial enzymes in the bioremediation of pollutants: A review. *Enzyme Res.*, 2011: 805187.
- Karimanzira D., Keesman K., Kloas W., Baganz D., Rauschenbach T. (2017). Efficient and economical way of operating a recirculation aquaculture system in an aquaponics farm. *Aquac. Econ. Manag.*, 21: 470–486.
- Khanjani M.H., Sharifinia M. (2021). Production of Nile tilapia *Oreochromis niloticus* reared in a limited water exchange system: The effect of different light levels. *Aquaculture*, 542: 736912.
- Khanjani M.H., Alizadeh M. (2024). Effects of different salinity levels on performance of Nile tilapia fingerlings in a biofloc culture system. *Ann. Anim. Sci.*, 24: 235–245.
- Khanjani M.H., Alizadeh M., Mohammadi M., Aliabad H.S. (2021). The effect of adding molasses in different times on performance of Nile tilapia (*Oreochromis niloticus*) raised in a low-salinity bio-floc system. *Ann. Anim. Sci.*, 21: 1435–1454.
- Khanjani M.H., Mohammadi A., Emerenciano M.G.C. (2022). Microorganisms in biofloc aquaculture system. *Aquac. Rep.*, 26: 101300.
- Khanjani M.H., Mozanzadeh M.T., Sharifinia M., Emerenciano M.G.C. (2023). Biofloc: A sustainable dietary supplement, nutritional value and functional properties. *Aquaculture*, 562: 738757.
- Khanjani M.H., Sharifinia M., Emerenciano M.G.C. (2024 a). Biofloc technology (BFT) in aquaculture: What goes right, what goes wrong? A scientific-based snapshot. *Aquac. Nutr.*, 2024: 7496572.
- Khanjani M.H., Mohammadi A., Emerenciano M.G.C. (2024 b). Water quality in biofloc technology (BFT): An applied review for an evolving aquaculture. *Aquac. Int.*, 32: 9321–9374.
- Khanjani M.H., Zahedi S., Sharifinia M., Hajirezaee S., Singh S.K. (2025). Biological removal of nitrogenous waste compounds in the biofloc aquaculture system – a review. *Ann. Anim. Sci.*, 25: 3–21.
- Khoa T.N.D., Tao C.T., Van Khanh L., Hai T.N. (2020). Super-intensive culture of white leg shrimp (*Litopenaeus vannamei*) in outdoor biofloc systems with different sunlight exposure levels: Emphasis on commercial applications. *Aquaculture*, 524: 735277.
- Kim J.H., Kim S.K., Kim J.H. (2018). Bio-floc technology application in flatfish *Paralichthys olivaceus* culture: Effects on water quality, growth, hematological parameters, and immune responses. *Aquaculture*, 495: 703–709.
- Kim J.H., Kang Y.J., Kim K.I., Kim S.K., Kim J.H. (2019). Toxic effects of nitrogenous compounds (ammonia, nitrite, and nitrate) on acute toxicity and antioxidant responses of juvenile olive flounder, *Paralichthys olivaceus*. *Environ. Toxicol. Pharmacol.*, 67: 73–78.
- Kim J.H., Sohn S., Kim S.K., Hur Y.B. (2020). Effects on hematological parameters, antioxidant and immune responses, AChE, and stress indicators of olive flounders, *Paralichthys olivaceus*, raised in bio-floc and seawater challenged by *Edwardsiella tarda*. *Fish Shellfish Immunol.*, 97: 194–203.
- Kishawy A.T., Sewid A.H., Nada H.S., Kamel M.A., El-Mandrawy S.A., Abdelhakim T.M., El-Murr A.E.I., Nahhas N.E., Hozzein W.N., Ibrahim D. (2020). Mannan oligosaccharides as a carbon source in Biofloc boost dietary plant protein and water quality, growth, immunity and *Aeromonas hydrophila* resistance in Nile tilapia (*Oreochromis niloticus*). *Animals*, 10: 1724.
- Kumar S., Anand P.S.S., De D., Deo A.D., Ghoshal T.K., Sundaray J.K., Ponniah A.G., Jithendran K.P., Raja R.A., Biswas G., Lalitha N. (2017). Effects of biofloc under different carbon sources and protein levels on water quality, growth performance and immune responses in black tiger shrimp *Penaeus monodon* (Fabricius, 1978). *Aquac. Res.*, 48: 1168–1182.
- Kumar V., Roy S., Behera B.K., Swain H.S., Das B.K. (2021). Biofloc microbiome with bioremediation and health benefits. *Front. Microbiol.*, 12: 741164.
- Li C., Dai L. (2025). Multifunctional applications of biofloc technology (BFT) in sustainable aquaculture: a review. *Fishes*, 10: 353.
- Li C., Ge Z., Dai L., Chen Y. (2025). Integrated application of biofloc technology in aquaculture: a review. *Water*, 17: 2107.
- Li J., Liu G., Li C., Deng Y., Tadda M.A., Lan L., Zhu S., Liu D. (2018). Effects of different solid carbon sources on water quality, biofloc quality and gut microbiota of Nile tilapia (*Oreochromis niloticus*) larvae. *Aquaculture*, 495: 919–931.
- Liu G., Zhu S., Liu D., Guo X., Ye Z. (2017). Effects of stocking density of the white shrimp *Litopenaeus vannamei* (Boone) on immunities, antioxidant status, and resistance against *Vibrio harveyi* in a biofloc system. *Fish Shellfish Immunol.*, 67: 19–26.
- Liu G., Ye Z., Liu D., Zhao J., Sivaramasamy E., Deng Y., Zhu S. (2018). Influence of stocking density on growth, digestive enzyme activities, immune responses, antioxidant of *Oreochromis niloticus* fingerlings in biofloc systems. *Fish Shellfish Immunol.*, 81: 416–422.
- Liu H., Li H., Wei H., Zhu X., Han D., Jin J., Yang Y., Xie S. (2019). Biofloc formation improves water quality and fish yield in a freshwater pond aquaculture system. *Aquaculture*, 506: 256–269.
- Liu G., Verdegem M., Ye Z., Zhao J., Xiao J., Liu X., Liang Q., Xiang K., Zhu S. (2025). Advancing aquaculture sustainability: a comprehensive review of biofloc technology trends, innovative research approaches, and future prospects. *Rev. Aquac.*, 17: e12970.
- Long L., Yang J., Li Y., Guan C., Wu F. (2015). Effect of biofloc technology on growth, digestive enzyme activity, hematology, and immune response of genetically improved farmed tilapia (*Oreochromis niloticus*). *Aquaculture*, 448: 135–141.
- Luo G., Gao Q., Wang C., Liu W., Sun D., Li L., Tan H. (2014). Growth, digestive activity, welfare, and partial cost-effectiveness of genetically improved farmed tilapia (*Oreochromis niloticus*) cultured in a recirculating aquaculture system and an indoor bio-floc system. *Aquaculture*, 422: 1–7.
- Luo G., Li W., Tan H., Chen X. (2017). Comparing salinities of 0, 10 and 20 in biofloc genetically improved farmed tilapia (*Oreochromis niloticus*) production systems. *Aquac. Fish.*, 2: 220–226.
- Mabroke R.S., Zidan A.E.N.F., Tahoun A.A., Mola H.R., Abo-State H., Suloma A. (2021). Feeding frequency affect feed utilization of tilapia under biofloc system condition during nursery phase. *Aquac. Rep.*, 19: 100625.
- Madoni S.N., Costa P.B., Coburn J.W., Galpin A.J. (2018). Effects of foam rolling on range of motion, peak torque, muscle activa-

- tion, and the hamstrings-to-quadriceps strength ratios. *J. Strength Cond. Res.*, 32: 1821–1830.
- Manan H., Moh J.H.Z., Kasan N.A., Suratman S., Ikhwanuddin M. (2017). Identification of biofloc microscopic composition as the natural bioremediation in zero water exchange of Pacific white shrimp, *Penaeus vannamei*, culture in closed hatchery system. *Appl. Water Sci.*, 7: 2437–2446.
- Mansour A.T., Esteban M.Á. (2017). Effects of carbon sources and plant protein levels in a biofloc system on growth performance, and the immune and antioxidant status of Nile tilapia (*Oreochromis niloticus*). *Fish Shellfish Immunol.*, 64: 202–209.
- Martins A.M.P., Heijnen J.J., Van Loosdrecht M.C.M. (2003). Effect of dissolved oxygen concentration on sludge settleability. *Appl. Microbiol. Biotechnol.*, 62: 586–593.
- Martins G.B., da Rosa C.E., Tarouco F.D.M., Robaldo R.B. (2019). Growth, water quality and oxidative stress of Nile tilapia *Oreochromis niloticus* (L.) in biofloc technology system at different pH. *Aquac. Res.*, 50: 1030–1039.
- Matos J., Costa S., Rodrigues A., Pereira R., Pinto I.S. (2006). Experimental integrated aquaculture of fish and red seaweeds in Northern Portugal. *Aquaculture*, 252: 31–42.
- Menaga M., Felix S., Charulatha M., Gopalakannan A., Panigrahi A. (2019). Effect of *in-situ* and *ex-situ* biofloc on immune response of Genetically Improved Farmed Tilapia. *Fish Shellfish Immunol.*, 92: 698–705.
- Minaz M., Kubilay A. (2021). Operating parameters affecting biofloc technology: carbon source, carbon/nitrogen ratio, feeding regime, stocking density, salinity, aeration, and microbial community manipulation. *Aquac. Int.*, 29: 1121–1140.
- Mirzakhani N., Ebrahimi E., Jalali S.A.H., Ekasari J. (2019). Growth performance, intestinal morphology and nonspecific immunity response of Nile tilapia (*Oreochromis niloticus*) fry cultured in biofloc systems with different carbon sources and input C: N ratios. *Aquaculture*, 512: 734235.
- Mohammady E.Y., Soaudy M.R., Ali M.M., El-Ashry M.A., Abd El-Karim M.S., Jarmolowicz S., Hassaan M.S. (2023). Response of Nile tilapia under biofloc system to floating or sinking feed and feeding rates: Water quality, plankton community, growth, intestinal enzymes, serum biochemical and antioxidant status. *Aquac. Rep.*, 29: 101489.
- Monroy-Dosta M.D.C., De Lara-Andrade R., Castro-Mejía J., Castro-Mejía G., Coelho-Emerenciano M.G. (2013). Composición y abundancia de comunidades microbianas asociadas al biofloc en un cultivo de tilapia. *Rev. Biol. Mar. Oceanogr.*, 48: 511–520.
- Monroy-Dosta M.D.C., Becerril-Cortés D., Lazo J.P., Mena-López A., Negrete-Redondo P., Noguera-Torres E., Navarro-Guillén C., Mata-Sotres J.A. (2025). Effect of biofloc culture on the daily rhythmicity of the activity and expression of digestive enzymes in tilapia, *Oreochromis niloticus*. *Aquac. Nutr.*, 6617425.
- Nageswari P., Verma A.K., Gupta S., Jeyakumari A., Chandrakant M.H. (2022). Optimization of stocking density and its impact on growth and physiological responses of *Pangasianodon hypophthalmus* (Sauvage, 1878) fingerlings reared in finger millet based biofloc system. *Aquaculture*, 551: 737909.
- Najdegerami E.H., Bakhshi F., Lakani F.B. (2016). Effects of biofloc on growth performance, digestive enzyme activities and liver histology of common carp (*Cyprinus carpio* L.) fingerlings in zero-water exchange system. *Fish Physiol. Biochem.*, 42: 457–465.
- Nootong K., Pavasant P., Powtongsook S. (2011). Effects of organic carbon addition in controlling inorganic nitrogen concentrations in a biofloc system. *J. World Aquac. Soc.*, 42: 339–346.
- Oehmen A., Yuan Z., Blackall L.L., Keller J. (2004). Short-term effects of carbon source on the competition of polyphosphate accumulating organisms and glycogen accumulating organisms. *Water Sci. Technol.*, 50: 139–144.
- Ogello E.O., Wullur S., Sakakura Y., Hagiwara A. (2018). Composting fishwastes as low-cost and stable diet for culturing *Brachionus rotundiformis* Tschugunoff (Rotifera): Influence on water quality and microbiota. *Aquaculture*, 486: 232–239.
- Ogello E.O., Outa N.O., Obiero K.O., Kyule D.N., Munguti J.M. (2021). The prospects of biofloc technology (BFT) for sustainable aquaculture development. *Sci. Afr.*, 14: e01053.
- Ogello E., Muthoka M., Outa N. (2024). Exploring regenerative aquaculture initiatives for climate-resilient food production: Harnessing synergies between technology and Agroecology. *Aquac. J.*, 4: 324–344.
- Oliveira L.K., Wasielesky Jr W., Tesser M.B. (2024). Fish culture in biofloc technology (BFT): Insights on stocking density carbon sources, C/N ratio, fish nutrition and health. *Aquac. Fish.*, 9: 522–533.
- Pai M., Verma A.K., Krishnani K.K., Varghese T., Hittinahalli C.M., Verma M.K. (2024). Stocking density optimization and its impact on growth and physiological responses of Nile tilapia (*Oreochromis niloticus*) reared in hybrid biofloc-RAS culture system. *Aquaculture*, 588: 740920.
- Panigrahi A., Saranya C., Sundaram M., Kannan S.V., Das R.R., Kumar R.S., Rajesh P., Otta S.K. (2018). Carbon: nitrogen (C: N) ratio level variation influences microbial community of the system and growth as well as immunity of shrimp (*Litopenaeus vannamei*) in biofloc based culture system. *Fish Shellfish Immunol.*, 81: 329–337.
- Pérez-Fuentes J.A., Hernández-Vergara M.P., Pérez-Rostro C.I., Fogel I. (2016). C: N ratios affect nitrogen removal and production of Nile tilapia *Oreochromis niloticus* raised in a biofloc system under high density cultivation. *Aquaculture*, 452: 247–251.
- Piedrahita R.H. (2003). Reducing the potential environmental impact of tank aquaculture effluents through intensification and recirculation. *Aquaculture*, 226: 35–44.
- Putra I., Rusliadi R., Fauzi M., Tang U.M., Muchlisin Z.A. (2017). Growth performance and feed utilization of African catfish *Clarias gariepinus* fed a commercial diet and reared in the biofloc system enhanced with probiotic. *F1000Res.*, 6: 1545.
- Ragasa C., Agyakwah S.K., Asmah R., Mensah E.T.D., Amewu S., Oyih M. (2022). Accelerating pond aquaculture development and resilience beyond COVID: Ensuring food and jobs in Ghana. *Aquaculture*, 547: 737476.
- Rajkumar M., Pandey P.K., Aravind R., Vennila A., Bharti V., Purushothaman C.S. (2016). Effect of different biofloc system on water quality, biofloc composition and growth performance in *Litopenaeus vannamei* (Boone, 1931). *Aquac. Res.*, 47: 3432–3444.
- Raza B., Zheng Z., Yang W. (2024). A review on biofloc system technology, history, types, and future economical perceptions in aquaculture. *Animals*, 14: 489.
- Rind K.H., Habib S.S., Ujan J.A., Fazio F., Naz S., Batool A.I., Ullah M., Attaullah S., Khayyam K., Khan K. (2023). The effects of different carbon sources on water quality, growth performance, hematology, immune, and antioxidant status in cultured Nile Tilapia with biofloc technology. *Fishes*, 8: 512.
- Romano N., Dauda A.B., Ikhsan N., Karim M., Kamarudin M.S. (2018). Fermenting rice bran as a carbon source for biofloc technology improved the water quality, growth, feeding efficiencies, and biochemical composition of African catfish *Clarias gariepinus* juveniles. *Aquac. Res.*, 49: 3691–3701.
- Said M.M., Taha E.M. (2022). Biofloc effects on body composition, plasma protein, lipid profile, zooplankton community, and economics of Nile tilapia fingerlings reared under different stocking densities. *Egypt. J. Aquat. Biol. Fish.*, 26: 593–611.
- Salehizadeh H., Van Loosdrecht M.C.M. (2004). Production of polyhydroxyalkanoates by mixed culture: recent trends and biotechnological importance. *Biotechnol. Adv.*, 22: 261–279.
- Santos L., Ramos F. (2018). Antimicrobial resistance in aquaculture: Current knowledge and alternatives to tackle the problem. *Int. J. Antimicrob. Agents*, 52: 135–143.
- Schrader K.K., Green B.W., Perschbacher P.W. (2011). Development of phytoplankton communities and common off-flavors in a biofloc technology system used for the culture of channel catfish (*Ictalurus punctatus*). *Aquac. Eng.*, 45: 118–126.
- Sgnaulin T., de Mello G.L., Thomas M.C., Garcia J.R.E., de Oca G.A.R.M., Emerenciano M.G.C. (2018). Biofloc technology (BFT): An alternative aquaculture system for piracanjuba *Brycon orbignyanus*? *Aquaculture*, 485: 119–123.
- Sharifinia M., Taherizadeh M., Namin J.I., Kamrani E. (2018). Ecological risk assessment of trace metals in the surface sediments of the Persian Gulf and Gulf of Oman: Evidence from subtrapi-

- cal estuaries of the Iranian coastal waters. *Chemosphere*, 191: 485–493.
- Sharifinia M., Daliri M., Kamrani E. (2019). Estuaries and coastal zones in the northern Persian gulf (Iran). In *Coasts and estuaries* (pp. 57–68). Elsevier.
- Shourbela R.M., Khatib S.A., Hassan M.M., Van Doan H., Dawood M.A. (2021). The effect of stocking density and carbon sources on the oxidative status, and nonspecific immunity of Nile tilapia (*Oreochromis niloticus*) reared under biofloc conditions. *Animals*, 11: 184.
- Singh T., Mandal A., Holeyappa S.A., Khairnar S.O., Tyagi A. (2024). Growth performance and physiological responses of striped catfish (*Pangasianodon hypophthalmus*) under different carbohydrates supplemented biofloc aquaculture systems. *Aquaculture*, 579: 740252.
- Sontakke R., Haridas H. (2018). Economic viability of biofloc based system for the nursery rearing of milkfish (*Chanos chanos*). *Int. J. Curr. Microbiol. Appl. Sci.*, 7: 2960–2970.
- Suresh A., Grygoliwicz-Pawlak E., Pathak S., Poh L.S., bin Abdul Majid M., Dominiak D., Bugge T.V., Gao X., Ng W.J. (2018). Understanding and optimization of the flocculation process in biological wastewater treatment processes: A review. *Chemosphere*, 210: 401–416.
- Tasleem S., Alotaibi B.S., Masud S., Habib S.S., Acar Ü., Gualandi S.C., Ullah M., Khan K., Fazio F., Khayyam K. (2024). Biofloc system with different carbon sources improved growth, haematology, nonspecific immunity, and resistivity against the *Aeromonas hydrophila* in Common Carp, *Cyprinus carpio*. *Aquac. Res.*, 2024: 7652354.
- Uribe C., Folch H., Enríquez R., Moran G.J.V.M. (2011). Innate and adaptive immunity in teleost fish: a review. *Vet. Med.*, 56: 486–503.
- Verma A.K., Rani A.B., Rathore G., Saharan N., Gora A.H. (2016). Growth, non-specific immunity and disease resistance of *Labeo rohita* against *Aeromonas hydrophila* in biofloc systems using different carbon sources. *Aquaculture*, 457: 61–67.
- Vinatea L., Gálvez A.O., Browdy C.L., Stokes A., Venero J., Haveman J., Lewis B.L., Lawson A., Shuler A., Leffler J.W. (2010). Photosynthesis, water respiration and growth performance of *Litopenaeus vannamei* in a super-intensive raceway culture with zero water exchange: interaction of water quality variables. *Aquac. Eng.*, 42: 17–24.
- Wang C., Pan L., Zhang K., Xu W., Zhao D., Mei L. (2016). Effects of different carbon sources addition on nutrition composition and extracellular enzymes activity of bioflocs, and digestive enzymes activity and growth performance of *Litopenaeus vannamei* in zero-exchange culture tanks. *Aquac. Res.*, 47: 3307–3318.
- Webster C.D., Lim C. (2002). Editors. *Nutrient requirements and feeding of finfish for aquaculture*. CABI Publishing.
- Wilén B.M., Nielsen J.L., Keiding K., Nielsen P.H. (2000). Influence of microbial activity on the stability of activated sludge flocs. *Colloids Surf. B Biointerfaces*, 18: 145–156.
- Xu W.J., Pan L.Q. (2013). Enhancement of immune response and antioxidant status of *Litopenaeus vannamei* juvenile in biofloc-based culture tanks manipulating high C/N ratio of feed input. *Aquaculture*, 412: 117–124.
- Xu W.J., Pan L.Q., Zhao D.H., Huang J. (2012). Preliminary investigation into the contribution of bioflocs on protein nutrition of *Litopenaeus vannamei* fed with different dietary protein levels in zero-water exchange culture tanks. *Aquaculture*, 350: 147–153.
- Yang S.F., Li X.Y. (2009). Influences of extracellular polymeric substances (EPS) on the characteristics of activated sludge under non-steady-state conditions. *Process Biochem.*, 44: 91–96.
- Yu Y.B., Lee J.H., Choi J.H., Choi Y.J., Jo A.H., Choi C.Y., Kang J.C., Kim J.H. (2023). The application and future of biofloc technology (BFT) in aquaculture industry: A review. *J. Environ. Manag.*, 342: 118237.
- Yu Z., Li L., Zhu R., Li M., Wu L.F. (2020). Effects of bioflocs with different C/N ratios on growth, immunological parameters, antioxidants and culture water quality in *Opsariichthys kaopingensis* Dybowski. *Aquac. Res.*, 51: 805–815.
- Yun H.S., Kim D.H., Kim J.G., Kim Y.S., Yoon H.S. (2022). The microbial communities (bacteria, algae, zooplankton, and fungi) improved biofloc technology including the nitrogen-related material cycle in *Litopenaeus vannamei* farms. *Front. Bioeng. Biotechnol.*, 10: 883522.
- Yusuf M.W., Utomo N.B.P., Yuhana M. (2015). Growth performance of catfish (*Clarias gariepinus*) in biofloc-based super intensive culture added with *Bacillus* sp. *J. Fish. Aquat. Sci.*, 10: 523.
- Zablon W.O., Ogello E.O., Getabu A., Omondi R. (2022). Biofloc system improves protein utilization efficiency and growth performance of Nile tilapia, *Oreochromis niloticus* fry: Experimental evidence. *Aquac. Fish.*, 2: 94–103.
- Zhang J., Hu Y., Ai Q., Mao P., Tian Q., Zhong L., Xiao T., Chu W. (2018 a). Effect of dietary taurine supplementation on growth performance, digestive enzyme activities and antioxidant status of juvenile black carp (*Mylopharyngodon piceus*) fed with low fish meal diet. *Aquac. Res.*, 49: 3187–3195.
- Zhang M., Li Y., Xu D.H., Qiao G., Zhang J., Qi Z., Li Q. (2018 b). Effect of different water biofloc contents on the growth and immune response of gibel carp cultured in zero water exchange and no feed addition system. *Aquac. Res.*, 49: 1647–1656.
- Zhao P., Huang J., Wang X.H., Song X.L., Yang C.H., Zhang X.G., Wang G.C. (2012). The application of bioflocs technology in high-intensive, zero exchange farming systems of *Marsupenaeus japonicus*. *Aquaculture*, 354: 97–106.
- Zhao Z., Xu Q., Luo L., Wang C.A., Li J., Wang L. (2014). Effect of feed C/N ratio promoted bioflocs on water quality and production performance of bottom and filter feeder carp in minimum-water exchanged pond polyculture system. *Aquaculture*, 434: 442–448.
- Zhao S., Zhang S., Liu J., Wang H., Zhu J., Li D., Zhao R. (2021 a). Application of machine learning in intelligent fish aquaculture: A review. *Aquaculture*, 540: 736724.
- Zhao Z., Xu Q., Luo L., Qiao G., Wang L., Li J., Wang C. (2021 b). Effect of bio-floc on water quality and the production performance of bottom and filter feeder carp fed with different protein levels in a pond polyculture system. *Aquaculture*, 531: 735906.

Received: 8 V 2025

Accepted: 18 VIII 2025