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REVIEW

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The role of biofloc technology in sustainable aquaculture: nutritional insights and system efficiency

Nitesh Kumar Yadav[1*†], Songhita Paul[1†], Arun Bhai Patel[1], Sudhanshu Shekhar Mahanand[1], Pradyut Biswas[1], Tanmoy Gon Choudhury[1], Sampa Baidya[1] and Dharmendra Kumar Meena[2*]

Abstract

The aquaculture industry faces growing challenges due to the increasing global demand for fish products, leading to significant environmental impacts. To meet this demand sustainably, Biofloc Technology (BFT) has emerged as a key solution. BFT utilizes inorganic nitrogen from aquaculture wastewater to improve water quality while simultaneously producing biofloc, which serves as a nutritious feed source for aquatic animals. This results in lower feed conversion ratios (FCR), higher protein efficiency ratios (PER), and improved animal growth and welfare. Feed costs, a major financial burden in aquaculture, are significantly reduced through BFT, benefiting both established and novice farmers. Additionally, BFT conserves water and reduces land usage, addressing key limitations of traditional aquaculture systems. Despite its advantages, certain challenges need to be resolved for BFT to become a fully sustainable and widespread approach, ensuring aquaculture can meet the growing global demand for fish protein without compromising the environment. This review explores the potential and future directions of BFT in strengthening the aquaculture industry.

Keywords Biofloc Technology, Sustainability, Environmental effect, Aquaculture, Wastewater, FCR

Introduction

As the global population grows rapidly, food industries, including aquaculture, face increasing pressure to meet rising demand. Sustainable aquaculture practices that are environmentally friendly, economically feasible, and socially acceptable are essential [1–3]. However, in coastal regions, the rapid expansion of aquaculture is causing significant environmental degradation. Innovative solutions, such as Recirculating Aquaculture Systems (RAS), have been developed to manage wastewater efficiently and mitigate environmental impacts. However, the high operational and maintenance costs of RAS limit its accessibility for marginal farmers, especially in developing countries. A low-cost, scalable, and sustainable alternative is urgently needed. Additionally, ensuring an adequate supply of protein-rich bioresources in fish feed is crucial to support optimal growth, health, and productivity in aquaculture systems [4].

Biofloc Technology (BFT) is an innovative form of recirculating aquaculture system that sustains a diverse community of suspended microalgae, autotrophic, and heterotrophic bacteria with minimal water exchange [4]. It is primarily designed for intensive fish and shrimp culture, aiming to boost production while promoting

†Nitesh Kumar Yadav and Songhita Paul shared equal credit and are first authors.

*Correspondence:
Nitesh Kumar Yadav
niteshaqc1997@gmail.com
Dharmendra Kumar Meena
dkmeenafnb@gmail.com
[1] College of Fisheries, Central Agricultural University (I), Lembucherra, Agartala, Tripura (West) 799210, India
[2] ICAR-Central Inland Fisheries Research Institute, Barrackpore, Kolkata, West Bengal 700120, India

sustainable aquaculture practices [5, 6]. By utilizing microbial processes to improve water quality and provide natural feed, BFT helps reduce environmental impact and increases the efficiency of aquaculture systems.

BFT systems are increasingly recognized for their potential to enhance the sustainability of aquaculture over the long term. A key factor in BFT is the maintenance of an optimal carbon-to-nitrogen (C/N) ratio, achieved by adding external carbon sources to the system. This allows the system to recycle waste internally, with minimal to no water exchange [7]. The choice of carbon sources and their mode of application play crucial roles in the success of BFT systems. At the core of the process is the creation of a nitrogen cycle using heterotrophic microbes, which efficiently utilize nitrogenous waste [8]. BFT has rapidly gained popularity, especially in regions where water resources are limited and land for large-scale aquaculture is costly. The dynamics of water quality, along with the abundance of plankton and microbes, are key to successful aquaculture under this system [9]. Sustainable aquaculture aims to reduce water consumption, maximize production in smaller spaces, and utilize complementary natural food sources. In this context, BFT emerges as an eco-friendly approach that mitigates several negative impacts of traditional aquaculture practices [10].

BFT offers a sustainable approach to aquaculture by reducing pollution loads, minimizing water treatment costs, and enhancing the growth performance of aquatic organisms through the in-situ production of microbial protein, thereby lowering feed expenses [11]. Despite these advantages, critical research gaps remain in optimizing BFT across different species, particularly in understanding the impact of C/N ratios on fish growth, health, and water quality parameters. Further research is needed to refine carbon source selection, improve microbial community management, and ensure long-term system sustainability. Additionally, assessing the nutritional value of biofloc and identifying essential research contributions to this field will enhance its practical applications. Addressing these gaps will be instrumental in maximizing the efficiency, scalability, and accessibility of BFT, particularly in developing countries where aquaculture expansion is necessary to meet food security demands while mitigating environmental concerns.

Nutritional value of biofloc

In addition to their bioactive properties, bioflocs offer significant nutritional value, making them a comprehensive food source for aquatic organisms [14, 17]. Bioflocs serve as both an energy source and a provider of bioactive compounds, contributing to improved growth performance and overall health of cultured species. Their nutritional profile includes proteins, lipids, vitamins, and minerals, which are produced by microbial communities through the breakdown of organic matter. As a result, bioflocs play a dual role in aquaculture by enhancing feed efficiency and promoting the immune system of aquatic organisms.

Azim and Little [18] have detailed that biofloc typically comprises 12–50% protein, 0.5–41% lipids, 14–59% carbohydrates, and 3–61% ash by dry weight. The proximate composition of biofloc in different culture systems is presented in Table 1. Marine bioflocs are particularly noted for their high amino acid content, including essential amino acids such as valine, lysine, leucine, phenylalanine, and threonine. However, they may be deficient in certain nutrients, notably vitamin C, arginine, methionine, and cysteine [19]. In addition to their amino acid profile, bioflocs are rich in various bioactive substances

Table 1 Proximate composition of biofloc in different studies (base of % dry weight)

S. No	Cultured Species	C:N Ratio	Protein	Lipid	Ash	Fibre	Reference
1.	*Labeo rohita*	10:1	35.40	1.1	15.38	15.03	Mahanand et al. [22]
2.	*Oreochromis niloticus*	10:1	33.95–36.25	2.42–2.88	13.91–14.87	-	Mabroke et al. [23]
3.	*Cyprinus carpio*	11:1 15:1 19:1 23:1	19.32–23.15	2.14–2.84	32.58–34.82	–	Minabi et al. [24]
4.	Red Tilapia *(Oreochromis sp)*	15:1	39.71–48.13	12.56–24.33	25.18–28.72	3.32–4.48	Widanarni et al. [25]
5.	*Macrobrachium rosenbergii*	15:1	15.9–32.6	0.67–1.97	26.2–44.4	–	Hosain et al. [26]
6.	*Penaeus monodon*	> 12:1	47.94	5.02	1.41	5.73	Promthale et al. [27]
7.	*Fenneropenaeus indicus*	10.4–12.1:1	18–23	17–22	3–4	–	Megahed and Mohamed, [28]
8.	*Fenneropenaeus merguiensis*	15:1	26.38–28.97	0.84–1.02	31.53–36.42	–	Khanjani et al. [12]
9.	*Procambarus clarkii*	-	44–44.1	4.5–6.7	12–16.4	3.4–4.9	Lunda et al. [29]
10.	GIFT (genetically improved farmed tilapia) tilapia	-	32.54–32.74	7.57–8.61	22.53–30.84	2.34–4.15	Prabu et al. [30]

that contribute to their nutritional value. These include essential fatty acids, carotenoids, free amino acids, chlorophylls, and trace minerals [20]. Such bioactive compounds play crucial roles in enhancing growth, reproduction, and immunity in aquaculture species. For instance, essential fatty acids are vital for cell membrane integrity and overall health, while carotenoids and chlorophylls can provide antioxidant benefits and support immune function. Bossier and Ekasari [21] emphasize that bioflocs are an excellent source of protein not only for tilapia and prawns but also for mussels. The nutrient-rich profile of bioflocs makes them a valuable component in aquaculture feeds, contributing to the nutritional requirements and overall well-being of cultured aquatic species. The incorporation of bioflocs into aquaculture systems can thus support better growth rates, improved reproductive performance, and enhanced disease resistance, highlighting their potential as a sustainable and effective feed ingredient.

Essential research contributions to BFT

Several notable studies have contributed to the understanding and optimization of BFT in aquaculture. Fimbres-Acedo et al. [31] assessed the impact of different photoautotrophic treatments—*Chlorella spp*., *Chlorella sorokiniana* 2805, and *C. sorokiniana* 2714—on Nile tilapia under biofloc conditions, finding that these treatments notably enhanced growth and productivity. Saha et al. [8] investigated various carbon-to-nitrogen (C/N) ratios (12, 15, 18, 21) for stinging catfish (*Heteropneustes fossilis*) and revealed that the C/N ratio profoundly influences water quality, growth, and health, with optimal ratios enhancing these parameters.

In another study, Laice et al. [32] demonstrated that the addition of synbiotics to a BFT system improved the growth performance and hematological parameters of Nile tilapia, with fish growing from an initial weight of 30–35 g to 77.28 g over 40 days. Azimi et al. [33] evaluated different C/N ratios (10:1, 15:1, and 20:1) for common carp (*Cyprinus carpio*) and found that a 20:1 ratio was optimal for physiological and immune responses as well as growth. Khanjani et al. [34] found that daily addition of molasses as a fresh biofloc source led to higher growth rates, increased productivity, and a reduction in costs by 15%, resulting in a 25% increase in profitability. However, a subsequent study by Khanjani et al. [35] indicated that different carbon sources, including barley flour, corn flour, molasses, and starch, did not significantly affect the growth performance of Nile tilapia fries. These findings underscore the diverse applications and potential of BFT in enhancing aquaculture efficiency.

Khanjani et al. [7] provided an in-depth analysis of various immunity parameters, blood and biochemical profiles, pathogen resistance, and antioxidant activity in aquaculture animals cultured in BFT systems. Their study highlighted that the presence of specific microbial organisms in BFT systems functions as natural probiotics, enhancing the innate immunity of the cultured species. They observed significant improvements in phagocytosis rates, NBT, MPO, ACH50, total immunoglobulin levels, lysozyme activity, and antioxidant enzymes such as SOD, CAT, and MDA compared to non-BFT cultured animals. The study concluded that fish and shellfish raised in BFT systems exhibit greater resistance to pathogens such as *A. hydrophila*, *V. harveyi*, *S. agalactiae*, and *E. tarda*.

In a separate study, Mabroke et al. [36] investigated the impact of feeding frequency on tilapia cultured in BFT systems. They found that feeding twice daily optimized feed utilization, reduced labor costs, and achieved the highest survivability rate (100%) and production levels (11.27 kg/m^3). This study underscores the benefits of strategic feeding practices in maximizing the efficiency and productivity of BFT aquaculture systems.

Impact of C/N ratios on fish growth, health, and water quality in BFT

Organic carbon sources

To maintain the desired C/N ratio in BFT systems, it is essential to accurately calculate the amounts of carbon source and feed required [8]. The C/N ratio is determined by the ratio of nitrogen to carbon entering the system from the feed needed by the organisms in the culture medium [11]. This ratio is managed through the addition of carbon sources, which initiate nitrogen immobilization and subsequently affect ammonia levels [9]. Commonly researched carbohydrates for this purpose include molasses, sugar, and glucose, as they release carbon into the system relatively quickly. However, the cost of these carbohydrates can add to production expenses, leading to the exploration of alternative regional ingredients in recent studies (Table 2). The key factors in this process are the speed at which carbon becomes available and its bioavailability for the specific fish species [37].

Abakari et al. [38] noted that carbonaceous substrates in BFT systems can produce a range of effects on bacterial communities, water quality, culture organisms, and the characteristics of bioflocs. These effects are attributed to the efficiency of maintaining the C/N ratio, the products of degradation, or other factors. In an experiment with common carp (*Cyprinus carpio L.*), Minabi et al. [24] used sugarcane molasses as the organic carbon source. Their results indicated that increasing organic carbon raised the C/N ratio and enhanced the bioflocculation process, which in turn increased the concentration of heterotrophic bacteria. They found that a C/N ratio of 19:1 improved water quality and

Table 2 Different BFT based on carbon source and C/N ratio along with the result obtained as reported by different researchers

Carbon source	C/N	Species	Crude Protein (%)	Net wt gain (gm)	FCR	Reference
Broken rice flour	15:1	*Oreochromis niloticus*	30.43	79.53	1.92	Zaki et al. [40]
Broken wheat grain flour	15:1	*Oreochromis niloticus*	30.43	67.53	2.09	Zaki et al. [40]
Glucose	10.8:1	*Opsariichthys kaopingensis*	36	5.29	1.86	Yu et al. [43]
Molasses	20:1	*Cyprinus carpio*	20–30	24.8	2.7	Ebrahimi et al. [44]
Policaprolactone (PCL)	< 20:1	*Clarias gariepinus*	33	142.63	1.17–1.37	Chen et al. [45]
Pure cane sugar	20:1	*Oreochromis niloticus*	43–40.9	16	1.0	Fimbres-Acedo et al. [31]
Rice bran	20:1	*Cyprinus carpio*	20–30	35.3	2.6	Ebrahimi et al. [44]
Sugarcane molasses	(12, 15, 18, 21	*Heteropneustes fossilis*	30	343.56	1.32	Saha et al. [8]
Sugarcane molasses	19:1	*Cyprinus carpio L*	77.31 (DW)	45.19	1.60	Minabi et al. [24]

growth parameters, but when the ratio was increased to 23:1, it negatively impacted feed conversion ratio (FCR), protein efficiency ratio (PER), and feed intake. A lower C/N ratio effectively maintained nitrogenous compounds at non-toxic levels, ensuring stable water quality. However, when the C/N ratio exceeded 20:1, it led to the accumulation of dissolved salts and settled biomass, disrupting system stability. Elevated nitrogenous compounds can inhibit nitrification, deteriorating water quality and ultimately impairing the growth performance of tilapia [39]. Additionally, Zaki et al. [40] reported that using flour and bran as carbon sources significantly improved water quality, leading to higher growth rates and lower FCR in fish.

Proximate composition

Saha et al. [8] investigated the effects of different C/N ratios (12, 15, 18, 21) on stinging catfish (*Heteropneustes fossilis*) in BFT systems. They found that biofloc treatments significantly improved growth performance in stinging catfish, with the CN15 treatment exhibiting the highest protein content and the lowest moisture level. There were no significant differences in lipid and ash content among the CN15, CN18, and CN21 treatments. As the C/N ratio increased, ash content rose while lipid content decreased. Das et al. [41] conducted a similar study and confirmed these findings, noting that stinging catfish grew faster in BFT systems compared to non-BFT systems. They also observed lower feed conversion ratios (FCR) and higher protein efficiency ratios (PER), indicating that a C/N ratio of up to 20:1 did not adversely affect fish growth performance.

Similarly, Hwihy et al. [42] found that Nile tilapia (*Oreochromis niloticus*) in BFT systems showed increased protein consumption and more efficient conversion of diet to body mass, further supporting the benefits of BFT for optimizing growth and feed efficiency.

Fish health

BFT offers several advantages, including reduced water usage, enhanced productivity, and improved biosecurity, making it a promising innovative method in aquaculture. Despite these benefits, there is a limited amount of research on the health status of fish in BFT systems. Contrary to some beliefs, BFT can effectively manage disease outbreaks and reduce their spread [46]. For example, Long et al. [47] studied genetically improved farmed tilapia (GIFT) in BFT systems and found no significant differences in hematological parameters such as white blood cell (WBC) and red blood cell (RBC) counts, hemoglobin, or hematocrit levels. However, they observed increased serum glutathione peroxidase and lysozyme activities, suggesting positive effects on growth, digestive enzyme activities, and immunity in the BFT-treated fish.

Similarly, Haghparast et al. [48] conducted research on common carp *(Cyprinus carpio*) using cane molasses as a carbon source and found that stress levels were markedly decreased, though antioxidative enzyme activity and hematological parameters remained unaffected. Saha et al. [8] reported improved health indicators, including increased hemoglobin, RBC, and hematocrit levels, in stinging catfish (*Heteropneustes fossilis*) in a BFT system, which suggests enhanced resilience to stressful environments. Hwihy et al. [42] observed that the WBC count in Nile tilapia (*Oreochromis niloticus*) was better in BFT systems compared to controls, while mean corpuscular hemoglobin (MCH) and mean corpuscular hemoglobin concentration (MCHC) remained stable, indicating that BFT does not induce anaemia. Additionally, Zafar et al. [49] noted favorable levels of various blood parameters for stinging catfish, reinforcing the positive health outcomes associated with BFT.

Yu et al. [50] found that a higher carbon–nitrogen ratio in BFT systems was linked to improved carcass composition in crucian carp (*Carassius auratus*). Abduljabbar et al. [51] also observed that Nile tilapia reared with zero water exchange (WE), 10% WE, and 20% WE (control) in BFT systems showed increased RBC counts and hemoglobin levels, alongside reduced cortisol levels, liver function enzymes, and urea. This indicates that BFT systems support the welfare of reared fish, minimizing stress and maintaining internal homeostasis. Additionally, BFT treatments increased plasma total protein and albumin while decreasing plasma lipid profiles, demonstrating higher growth, reduced stress levels, and improved feed utilization in intensive monoculture systems [52]. Similar to its contributions in fish farming, BFT has significantly enhanced shrimp aquaculture by improving water quality, optimizing feed utilization, and promoting sustainable production. The biofloc system helps maintain a stable microbial community, which enhances nitrogen recycling and reduces the accumulation of harmful metabolites [53]. Additionally, the nutrient-rich microbial flocs serve as a natural feed source, improving shrimp growth, survival, and immunity. BFT has also been instrumental in minimizing disease outbreaks by promoting beneficial microbial populations, ultimately reducing the need for antibiotics and other chemical treatments.

Water quality parameters

Adjusting the carbon-to-nitrogen (C/N) ratio can enhance water quality in BFT systems by utilizing nitrogen and fostering the regeneration of bacterial cells, which helps to reduce waste effluent from the culture system [11]. Saha et al. [8] conducted a 10-week indoor study on *Heteropneustes fossilis* cultured with zero water exchange to assess the impact of varying C/N ratios. The study found no significant differences in dissolved oxygen (DO) and temperature among the treatments. However, pH, total ammonia nitrogen (TAN), and nitrite nitrogen levels showed an inverse relationship with the C/N ratio, while total dissolved solids (TDS) and total suspended solids (TSS) increased with higher C/N ratios.

Increasing the C/N ratio in biofloc systems leads to enhanced microbial activity, particularly heterotrophic bacterial proliferation, which utilizes organic carbon for growth. This increased bacterial biomass, along with aggregated organic matter and biofloc particles, contributes to higher total suspended solids (TSS) [24]. Additionally, elevated carbon inputs stimulate microbial flocculation, resulting in the accumulation of particulate organic matter in the water column. Consequently, as TSS rises, total dissolved solids (TDS) may also increase due to the mineralization of organic matter and the subsequent release of dissolved ions into the system [54].

In a similar vein, Soliman et al. [55] investigated the effects of different carbohydrate sources—sugarcane molasses (MO) and wheat flour (WF)—on water quality, biofloc quality, and the growth and productivity of Nile tilapia in BFT-based cement ponds, as illustrated in Fig. 1. Their findings indicated that pH, unionized ammonia, and nitrite levels were significantly lower in the MO and WF treatments compared to the control. Conversely, nitrate and total suspended solids levels were notably higher in these treatments, highlighting the impact of carbon sources on water quality parameters and biofloc performance.

Abduljabbar et al. [51] evaluated three different BFT systems: BFT with no water exchange (WE), BFT with 10% WE, and a 20% WE control, to assess the impact of water exchange on system performance. Their study revealed that total suspended solids (TSS) levels were

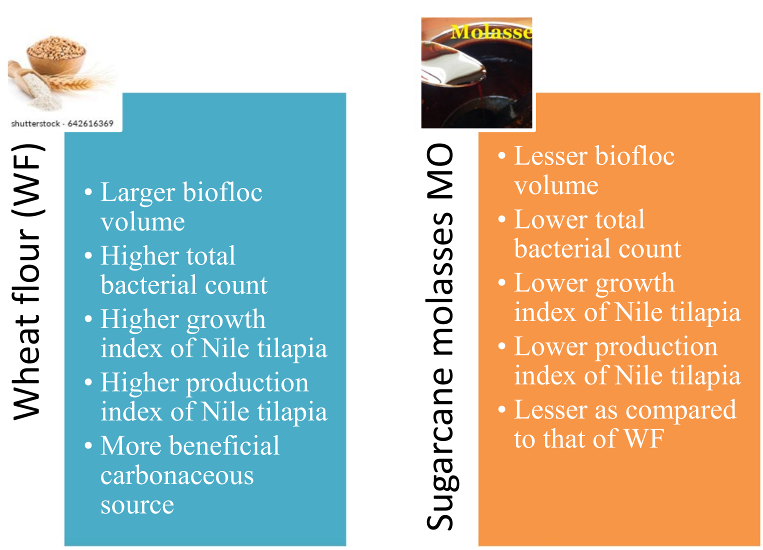

Fig. 1 Comparison of WF and MO

significantly higher in both the BFT and BFT with 10% WE systems compared to the control. This increase in TSS was attributed to the elevated C/N ratios in the biofloc systems [9]. Similarly, Haghparast et al. [48] observed higher TSS loads in BFT systems for *Cyprinus carpio* across various C/N ratios compared to the control. Dilmi et al. [56] reported consistent findings with Nile tilapia, noting that nitrite levels decreased as the C/N ratio increased, further supporting the influence of C/N adjustments on water quality in biofloc systems.

Microorganisms and their role in the biofloc system

Microorganisms are essential to all organisms and ecosystems, playing a crucial role in aquaculture by facilitating contaminant removal, recycling organic matter, and serving as a food source. However, under adverse conditions, some microorganisms can become pathogenic [12]. In BFT systems, microbial communities regulate water quality, provide nutrition, and help control pathogens [57]. The key microbial groups in BFT include photoautotrophic organisms (e.g., microalgae), chemoautotrophic nitrifying bacteria, and heterotrophic organisms such as fungi, ciliates, protozoans, and zooplankton like rotifers, copepods, and nematodes [12].

Studies on biofloc community structure in shrimp farming [58, 59] categorize microorganisms into floc-forming organisms, saprophytes, nitrifying bacteria, algae grazers, and pathogenic bacteria (e.g., *Vibrio* spp.). These microorganisms must remain suspended in the water column to function effectively [59]. Floc-forming microbes play a critical role by secreting extracellular polymeric substances (EPS), which facilitate floc formation and enhance system stability [60].

Biofloc systems can be classified into green water biofloc, which is exposed to natural light and relies on both algal and bacterial processes, and brown water biofloc, which operates in closed environments where bacterial processes regulate water quality [61]. The microbial community in biofloc includes photoautotrophic algae and heterotrophic organisms such as bacteria, rotifers, ciliates, protozoans, and nematodes [62]. A high C:N ratio is essential for optimal heterotrophic bacterial growth, promoting nitrogen assimilation and the removal of toxic ammonium and nitrite [63]. The microbial protein generated in biofloc serves as a valuable dietary component for cultured species, with studies indicating higher nitrogen content in shrimp biomass from BFT systems compared to non-biofloc cultures [64].

In addition to microbial contributions, biofloc naturally supports diverse planktonic communities, including rotifers, protozoans, crustaceans, and nematodes. These organisms play a vital role in nutrient recycling, water quality maintenance, and enhancing the nutritional value of biofloc as a feed source [65]. Zooplankton presence in biofloc systems has been linked to improved growth rates and feed conversion efficiency [66], while phytoplankton contributes by absorbing excess nutrients and producing dissolved oxygen [63]. The microbial diversity in biofloc systems is influenced by factors such as carbon sources and the cultured species, highlighting the critical role of microorganisms in sustaining productive and environmentally friendly aquaculture systems.

Economic importance and socio-economic prospects of BFT

BFT offers significant economic benefits by reducing feed costs, improving water use efficiency, and enhancing the sustainability of aquaculture [67]. One of the primary economic advantages of BFT is its ability to recycle organic waste into microbial biomass, providing an in-situ protein-rich feed source that reduces dependency on expensive commercial feeds [35]. This not only lowers production costs but also enhances farmers' profitability. Additionally, BFT minimizes water exchange, reducing the expenses associated with water usage and wastewater management, making it an environmentally and economically viable alternative to traditional aquaculture systems. From a socio-economic perspective, BFT has the potential to create new employment opportunities in rural and coastal communities, promoting self-sufficiency and food security [11]. The technology is particularly beneficial for small-scale and resource-limited farmers, as it allows for high-density culture with minimal land and water requirements [57]. Furthermore, by reducing the environmental footprint of aquaculture, BFT aligns with global sustainability goals, making it an attractive option for policymakers and investors seeking to promote responsible aquaculture practices. Expanding research, training programs, and financial support for BFT adoption could further enhance its role in improving livelihoods and ensuring long-term economic growth in the aquaculture sector.

Advantages and disadvantages of BFT in aquaculture

BFT is a sustainable and eco-friendly zero-water exchange aquaculture system with several notable advantages. Its environmental benefits include reduced need for water treatment, leading to lower feed costs and increased profitability. BFT efficiently converts toxic nitrogenous compounds into non-toxic forms, promoting better health and growth of the cultured animals [13]. It is also effective in larviculture, producing large quantities of live food, and serves as a natural biosecurity agent by eliminating the need for environmentally harmful antibiotics [68]. Additionally, BFT conserves valuable resources such as water and land without adverse environmental impacts [31]. It enhances gonadal formation and maturation, aiding ovarian development [69, 70], and generally leads to a lower incidence of common fish diseases due to improved immune system function and reduced biological stress [11]. The technology is attractive for its ability to maintain water quality, improve feed conversion ratios (FCR), reduce production costs, and replace conventional, expensive feeds with alternative protein sources [71].

However, BFT also has some drawbacks. High water temperatures in BFT systems can create optimal conditions for microbial growth, increasing the risk of disease outbreaks. The system's high aeration requirements lead to significant energy consumption to meet the biological oxygen demand of the animals. Additionally, the accumulation of organic load in the system can degrade water quality if not properly managed. From an ethical standpoint, there may be concerns about consumer acceptance of fish cultured in BFT systems, which needs to be addressed [11, 72].

Application of BFT for sustainable aquaculture and future prospects

Recent research highlights that BFT has gained significant attention as an eco-friendly, cost-effective, and sustainable approach for improving water quality while simultaneously producing microbial protein for aquatic species. Recognized for its dual benefits—economic efficiency and environmental sustainability—BFT plays a crucial role in maintaining water quality, enhancing feed conversion ratios (FCR), enabling the use of low-protein diets, reducing production costs, and replacing expensive conventional feeds with alternative protein sources [12–15].

A key aspect of BFT is the strategic use of carbon, either through external supplementation or by increasing carbon content in feed. This process supports microbial growth and facilitates the nitrogen cycle, as illustrated in Fig. 2. The carbon-to-nitrogen (C/N) ratio is particularly critical, as it promotes the growth of heterotrophic bacteria, which consume nitrogenous waste and convert it into microbial biomass—an additional nutritional source for cultured species [16]. This self-sustaining water treatment mechanism reduces the need for frequent water exchanges, making BFT a more resource-efficient system. However, careful monitoring of carbon inputs is essential, as excessive microbial activity may lead to oxygen depletion and other negative side effects.

BFT is currently applied primarily to herbivorous, detritivorous, and bottom-dwelling species such as tilapia and shrimp. Expanding its use to carnivorous fish with modifications in carbon sources and system design presents a promising area for future research. Further advancements should focus on optimizing biofloc concentrations to enhance growth, immunity, feed utilization, and nitrogen management while improving overall system efficiency. Scaling up BFT could benefit from compartmentalizing system components to ensure better control and performance.

Despite its advantages, BFT faces challenges such as high energy consumption, increased operational costs, and the need for continuous aeration, which limit its

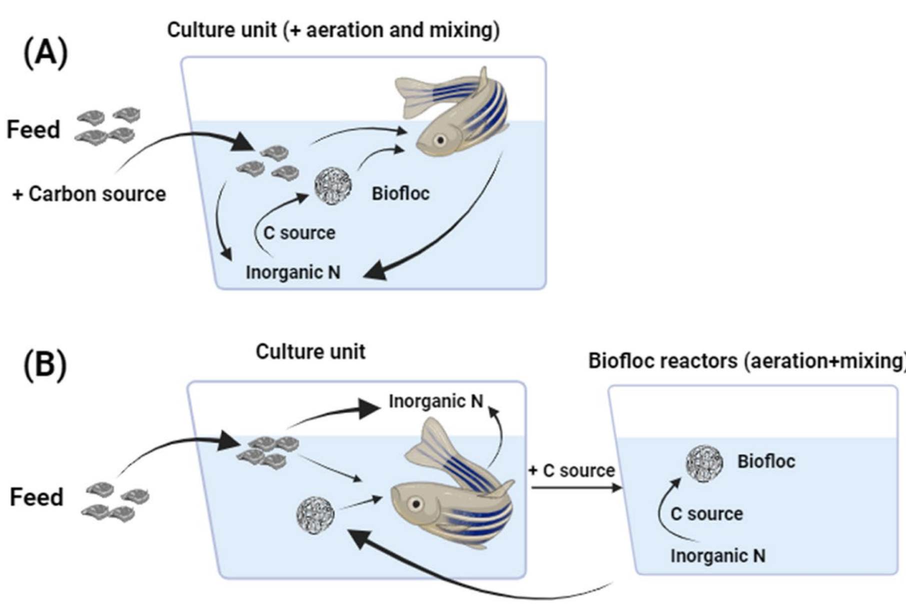

Fig. 2 Schematic representation of how bioflocs can be implemented in aquaculture systems (Reprinted from Crab et al. [16])

widespread adoption. Future research should explore species-specific adaptations and microbial diversity to enhance pathogen control and waste remediation. Additionally, knowledge dissemination and consumer awareness regarding the safety and benefits of BFT-cultured fish will be essential for its broader acceptance. Overall, while BFT holds great potential for sustainable aquaculture, continued research and technological innovations are necessary to overcome current limitations and expand its applicability across different aquaculture systems.

Conclusion

BFT has gained significant attention in aquaculture due to its sustainability, cost-effectiveness, and environmental benefits. It is predominantly utilized in shrimp farming and, to a lesser extent, in finfish culture. While its fundamental principles are well-established, further advancements are necessary to enhance system efficiency, optimize nutrient utilization, and improve overall sustainability. Regular dissemination of research findings is essential to equip farmers with best management practices and address operational challenges. To ensure that BFT contributes effectively to meeting the growing demand for fish protein, efforts should focus on maximizing production while minimizing costs, making the technology more accessible and economically viable for a wider range of aquaculture practitioners.

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NKY & SP: Conceptualization, Writing-Original draft, Writing- review and editing. ABP: Supervision, Writing- review and editing. SSM: Writing-review and editing. PB & TGC: Writing- review and editing. DKM: Conceptualization, Writing- review and editing. All the authors have read and approved the final version of the manuscript.

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