Biofloc Culture: Pioneering the Blue Revolution in Contemporary Aquaculture Practices

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SUMMARY

Blue revolution substantially introduces advanced trends in fisheries and aquaculture through the implementation of the latest techniques to combat the rising demand for seafood as well as protect the aquatic ecosystem. The aquaculture sector has been facing numerous challenges for decades owing to environmental degradation. Various modern technologies including biofloc innovate traditional aquaculture practices. Biofloc enhances the heterotrophic potential of bacteria, reduces water utilization as well as promotes the process of nutrient recycling. This technology potentially increased the growth as well as the health status of fish species through improving water quality. This chapter provides valuable insight regarding the most advanced technique called "Biofloc" in aquaculture practices. Furthermore, it highlights the economic as well as ecological benefits of biofloc and the ability to counteract the challenges of aquaculture practices. Biofloc subsidizes the feed conversion ratio which ultimately reduces the cost. These practices provide minerals, nutrients, and fatty acids to the rearing species throughout the day. Moreover, biofloc regulates sustainable ways to ensure high profitability as compared to traditional aquaculture practices. In conclusion, biofloc technology shows promising results through minimum water exchange, enhancing water quality as well as reducing the cost of production which ultimately leads to a high ratio of profitability when compared with local fisheries practices.

INTRODUCTION

Over the last 30 years, the aquaculture sector has grown exponentially to meet half of the world's fish demand. It plays a vital role in ensuring food security, increasing income, and fostering economic development (Custodio et al., 2020). Consequently, aquaculture is emerging as a substantial driver for economic expansion, poverty alleviation, and improved resource utilization by exploiting the potential of small, medium, and large-scale commercial aquaculture to generate vital income (Sharifinia et al., 2023). However, aquaculture necessitates suitable production systems that can maintain suitable water quality levels, support higher stocking densities of fish, ensure optimal health performance, and address biosecurity and environmental concerns in order to satisfy the increasing need for secure and foremost aquatic proteins (Khanjani et al., 2024).

Conventional intensive systems, such as earthen ponds, heavily depend on feed inputs, which require frequent water exchange protocols to ensure adequate water quality (Diatin et al., 2021). Unluckily, these systems still have multiple adverse environmental impacts, involving the fact that unprocessed wastewater having high amounts of pollutants i.e., nitrogenous and phosphorus compounds, that causing damage to the environment (Khanjani et al., 2022). The application of fertilizers, hormones and antibiotics to traditional intensive farming practices may pollute the water. An increase in emissions of gases has been encountered by aquaculture practices which leads to the greenhouse effect because of aquafeeds' significant contribution (Garlock et al., 2022).

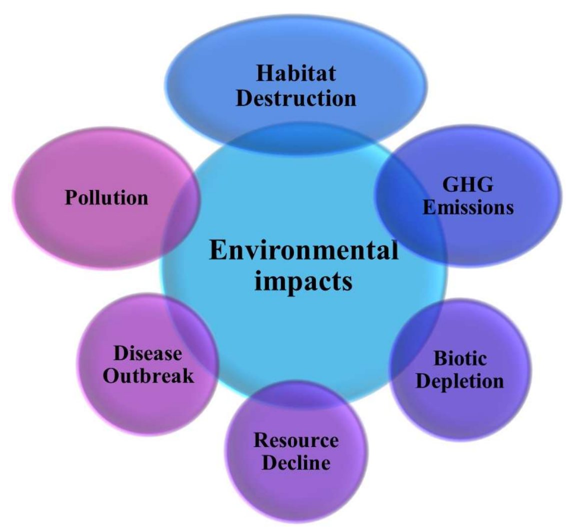

Fig 1. Environmental Impacts of Conventional Intensive Aquaculture System (Ahmed & Turchini, 2021)

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Fish feed has been identified as the main driver of raising greenhouse gas emissions in aquatic farming. This is primarily caused by the manufacturing and transportation of raw materials, energy consumption in aquafeed manufacturing factories, and a significantly high feed conversion ratio [FCR (Lertwanakarn et al., 2023)]. The rapid expansion of traditional culture systems is restricted due to multiple environmental challenges of culture systems i.e., pollution, habitat degradation, limited resources, etc (Fig 1). With the increasing importance of environmental awareness and sustainability, there is a notable shift towards alternative farming practices i.e., closed or intensified aquaculture practices. These practices tackle multiple ecosystem issues while offering cost effective and eco-sustainable solutions, that are better than the traditional extensive and semi-intensive farming practices (El-Saadony et al., 2021). As a result, ecologically sustainable management and farming practices continue to be a crucial need (Garlock et al., 2022).

SUSTAINABLE BLUE REVOLUTION

The sustainable blue revolution is a strategy that highlights the significance of aquatic food systems for employment, economic growth, social development, and environmental recovery. A transformation is needed to create more effective, inclusive, resilient, and sustainable aquatic food systems to improve production, nutrition, environment, and quality of life (Laktuka et al., 2023). Various aquaculture methods such as pond culture, cage culture, pen culture, bio-floc culture, flow-through culture, and RAS (recirculatory aquaculture system) are employed worldwide to enhance fish output. Biofloc technology (BFT) is seen as a modern "blue revolution" since it enables the continual recycling and use of nutrients, hence decreasing water exchange and providing a solution to traditional aquaculture difficulties (Rashid et al., 2019).

Additionally, the blue revolution has increased the availability and accessibility of farmed fish in specific areas, which promotes food and nutritional security, especially in low-income nations and rural areas (Bene et al., 2016). A rise in aquaculture output has resulted in a consistent fish supply and lower costs, making them more accessible to low-income families. Fish are a valuable source of critical nutrients and protein, supplying approximately 19.9% of animal protein to over 3 billion people. In certain countries, like Africa, there is an anticipated decline in fish consumption in the upcoming decades, which might jeopardize food and nutritional security for already vulnerable populations. High intake of fish from the blue revolution can improve nutritional inadequacies in low-income malnourished communities in impoverished areas (Ahmed & Thompson, 2019).

Recirculating aquaculture approach

Recirculating Aquaculture Systems (RAS) display an excellent example of eco-sustainable aquaculture that is environment friendly, water-efficient, and extremely productive intensive farming systems that can raise aquatic animals under a controlled environment. These systems are more ecologically friendly and less subject to climate change's impacts on fish productivity (Ahmed & Turchini, 2021). It works in an indoor controlled environment with little influence from environmental elements like rainfall and global warming. However, energy consumption and greenhouse gas emissions are the most restrictive constraints on RAS. Despite its potential, RAS has not been extensively used, especially in poor nations, due to advanced and expensive system designs. More research is needed to build low-cost, energy-efficient RAS for increasing seafood yield and addressing climate change adaptation. Due to its advanced and expensive system, RAS approach has been replaced by an alternative approach (Ahmad et al., 2017).

BIOFLOC TECHNOLOGY (BFT)

Regarding this matter, there has been a great look for a cost-efficient, eco-friendly and sustainable practice for extensive adoption of environment friendly aquafarming approach named as "biofloc technology (BFT)" which utilizes recycled nutrients and waste products for sustainable yield (Walker et al., 2020). This approach depends on the generation of in situ microorganisms in the system, that benefit from minimum or no water exchange. The bacterial community plays two important roles in biofloc technology: controlling water quality parameters via absorbing nitrogenous compounds for in situ microbial generation, and in nutrition, improving farming effectiveness by minimizing feed conversion ratios and prices of feed (Zafar & Rana, 2022).

Being a closed system, biofloc technology offers the fundamental benefits of minimizing the discharge of water into rivers, lakes, and estuaries, which include the dispersal of animals, organic material, nutrients, and diseases. Furthermore, "vertical growth" benefits the surrounding areas on the basis of productivity, avoiding coastal or inland area degradation, reducing the loss of natural resources and eutrophication. In BFT, minimal release of water and recirculating water strategies serve to mitigate environmental degradation and transform such a system into a true "environmentally friendly system." This technique has several advantages, involving the effective utilization of water and land, the use of recycled nutrients and organic matter, and the reduction of disease penetration into the farming system, which can lead to increased biosecurity in a fish farm (El-Sayed et al., 2021). BFT requires an economical initial investment compared to other traditional fish farming technologies, as it simply requires sunlight, a carbon source, and aeration (Ogello et al., 2021).

Functionally, biofloc technology operates on the basis of a heterotrophic process in which unused nutrients, uneaten feeds, and faces are transformed into functional biofloc, sometimes called single-cell proteins (SCP). These SCP are loosely linked by bacterial mucus, forming distinct floating clumps that serve as nutritious food supplies for cultured species. An effective BFT system results in a 30% reduction in fish feed expenses due to the fact that every pallet is utilized approximately two times (i.e., as both SCP and fresh pellet), which increases aquaculture profitability and productivity. In addition to providing vital nutrients, biofloc also possesses a probiotic effect that safeguards the biosecurity of BFT systems (Kim et al., 2014). Biofloc promotes appropriate water quality in culture systems by producing its own proteins using ammonia. Maintaining the flocs within BFT in aquaculture systems necessitates minimal water exchange, thereby making it possible to stock large numbers of fish and increasing fish production. Aquapreneurs find BFT economically feasible due to the aforementioned characteristics (Ogello et al., 2021).

At present, biofloc technology is known by various alternative categories: the zero-exchange autotrophic heterotrophic system, the suspended bacterial-based system, the single-cell protein production system, and the microbial floc systems. However, scholars are trying to keep the word "BFT, or Biofloc Technology," so that there is a clear reference, especially following the publication of the chapter. Furthermore, extensive research in the field of nutrition has been devoted to BFT as a source of protein in mixed feeds. This protein source is generated as "biofloc meal," mostly within bioreactors. Furthermore, the rapid dissemination and extensive proliferation of BFT farms globally have prompted substantial research endeavors to investigate the processes associated with BFT production systems (Prabu et al., 2017).

BFT: paving the way for sustainable solutions in aquaculture to support SDGs

The advancement of a sustainable aquaculture sector should be prioritized by promoting the development of systems that, despite being very efficient and highly profitable, simultaneously minimize resources, including water, space, energy, and money. Additionally, these systems should have a reduced impact on the environment (Khanjani & Sharifinia, 2020). Apart from contributing to the sustainable development goal (SDG) 14, the development of sustainable aquaculture can contribute to various objectives, such as ending poverty (SDG 1) and hunger, achieving food security, improving nutrition (SDG 2), and promoting long-lasting, inclusive, and sustainable economic growth (SDG 8) (FAO, 2017).

The Biofloc technique is one of the strategies that achieve the aforementioned goals of increasing aquaculture productivity and sustainability by optimizing feed nutrient usage. This may be accomplished using two distinct methodologies, namely enhancing the quality of the feed and optimizing the feeding strategy to ensure effective delivery and utilization of nutrients, as well as recycling nutrients through implementing improvements to the culture system (Minaz & Kubilay, 2021). Microbes play a pivotal role in nutrient cycles and are responsible for a number of natural biogeochemical processes that remove nutrients from aquatic systems. Unconsumed portion of feed is the main contributor to nutrient loss in an aquaculture system, as well as from the processes of digestion and metabolism of the feed (Han et al., 2019). In an aquaculture system, reusing waste nutrients may be achieved in two ways: first, by lower-trophic-level organisms that feed on these particles directly or indirectly by converting the nutrients into microbial biomass. The cultured species or other animals can then use this microbial biomass as a food source (Bossier & Ekasari, 2017).

A historical overview of biofloc technology

Biofloc technology was pioneered by Aquacop at the French Research Institute for Exploitation of the Sea in 1975. The effectiveness of the system was subsequently enhanced by the addition of carbon sources (Liu et al., 2019). Originally, the purpose of developing BFT was to prevent the emergence of diseases in raising species by cultivating beneficial microbes without the need for water exchange and by regulating the introduction of viral and bacterial pathogens through water effluent. Initially, in BFT studies, an active microbial suspension system was utilized, known as 'microbial soup', for the purpose of shrimp and fish culture. The idea of the 'heterotrophic food chain' was subsequently formulated by retaining unconsumed feed and waste within ponds or tanks. Later on, a novel approach called BFT was devised, which combines a system that uses a carbon substrate and does not exchange water to effectively remove nitrogen (Yu et al., 2023a).

The widespread acceptance of biofloc technology did not occur until the 2000s, primarily due to the prevailing belief that clear water is more effective than highly turbid water containing biofloc for animal reproduction (Dauda, 2020). However, the implementation of BFT on a range of aquaculture species, including Tilapia, Channel Catfish, Pacu, African Cichlid, Golden Carp, and Shrimp, commenced in the late 2000s. Furthermore, BFT has been implemented in small-scale commercial aquaculture operations in Indonesia and Malaysia since 2002, where it is still undergoing further development. Presently, BFT is being effectively implemented on a large scale throughout Asia, Latin America, Central America, the United States, South Korea, Brazil, Italy, China, and other regions. Although BFT has received recent interest, further study on BFT is necessary despite its scientific and economic expansion (Khanjani et al., 2022).

Principles of biofloc technology

The basic concept of biofloc technology focuses on the control of microbial communities, specifically enabling the growth of a significant number of beneficial microorganisms inside the aquaculture system. BFT is based primarily on the idea of nitrogenous waste recycling by multiple microbial species (biofloc) with the inclusion of inorganic carbon, which improves the quality of water and growth efficiency of raised aquatic organisms (Mugwanya et al., 2021). A number of critical factors must be carefully evaluated, checked, and maintained on a regular basis in order to establish an ideal culture environment for biofloc. In order to establish an ideal culture condition for biofloc, it is essential to consistently monitor and maintain a number of essential parameters. Neglecting these parameters may lead to the demise of the beneficial microbial community, an overabundance of pathogenic microbes in the culture system, or an increase in biological oxygen demand (BOD) (McCusker et al., 2023).

Biofloc formation: In the water column, biofloc generates heterogeneous macroaggregates made up of floc-forming bacteria, diatoms, filamentous microalgae, protozoa, micro- and macro-invertebrates, waste products, and unused feed. When suspended particulates reach ≥5 mL/L, BFT is deemed to be entirely mature (Emerenciano et al., 2017). The key elements influencing the production of floc are temperature, dissolved oxygen, hydrogen ion concentration, source of organic carbon, organic loading rate, and the intensity of mixing. In BFT, the formation of biofloc can be achieved by three methods: the natural transition approach entails the development of autotrophs by using fertilizers, feed, and other ingredients (Nisar et al., 2022); the inoculum approach comprises the addition of prepared biofloc into fresh culture water; and the customization approach involves incorporating probiotics into the system to create a more favorable environment (Liu et al., 2017) as presented in fig 2.

Nutritional value of biofloc: Biofloc carries a wide range of beneficial nutrients and performs the role as a suitable aquafeed source, providing multiple bioactive compounds (Ahmad et al., 2017). Multiple drivers can influence the nutritional value of biofloc i.e., choosing feed, floc volume in the system, and animals' capability to ingest, digest and absorb the single celled proteins. Microbial proteins produced by the heterotrophic bacterial community in biofloc technology act as a nutritive food source for finfish and shellfish. Biofloc aggregation constitutes several qualitative elements like 49% crude protein content, 4% fiber content, 2.6% crude fat level, 6% ash content, and an energy level is about 20 kJ/g. The nutritional makeup of floc is characterized by the availability of biochemical compounds, particle size, and ingesting or digesting capability of rearing species. When particle size is < 99µm and > 47µm, shows higher viability for Tilapia, Shrimp, and Asian Green Mussels due to their high nutritional content. Particle size > 99µm shows high protein and fat concentration while particle size < 47µm exhibits high amino acid content (Nisar et al., 2022).

Factors influencing quality and quantity of biofloc: The nutrition of floc relies primarily on the C:N ratio, dietary protein content, the strength of available light, and the environmental settings of the system. Carbon to nitrogen ratio > 15 with minimal or no water exchange, leads to the best quantity and best quality of biofloc in the system that improves growth performance, survival rate, and immunity of reared species (Wang et al., 2015). Furthermore, floc quality is also influenced by the carb sources, e.g., biofloc extracted from glycerol based BFT contains more protein, vitamin C, and n-6 fatty acids in contrast to biofloc obtained from glucose based BFT. The concentration of essential and non-essential amino acids was consistent in biofloc obtained from glucose and glycogen base BFT, but considerably higher in biofloc obtained from starch based BFT. A reduced dietary protein content permits for increased starch level and boosts the growth of floc in no or minimum water renewal systems (Mansour & Esteban, 2017). Light intensity triggers the photosynthetic processes, in result improves the development of green biofloc. The green biofloc offers supplementary nutrients which give multiple benefits to reared species (Khanjani et al., 2024).

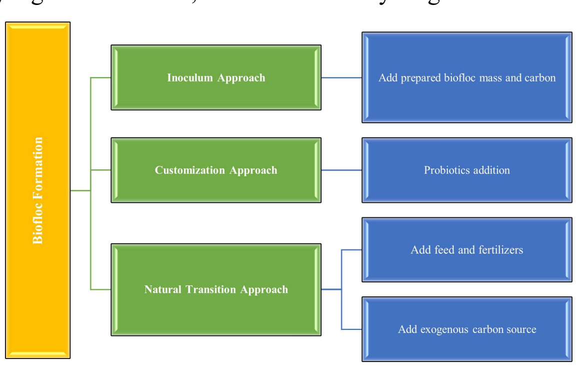

Fig 2. Approaches of Biofloc formation (Nisar et al., 2022)

Carbon dynamics: To maintain biofloc, adding organic carbon sources is crucial to raise the carbon content in the water and feed to maintain the carbon-to-nitrogen ratio (C/N). Biofloc technology (BFT) uses active phytoplankton, flocculants, protozoa, and microalgae to control ammonia nitrogen levels and sustain nutritional balance in aquatic environments (Azhar et al., 2020). Internal flocculation structures in BFT are essential and consist of bacteria, protozoa, algae, and other zooplankton. BFT has probiotic properties and can suppress harmful bacteria due to the presence of active chemicals such as bromophenol, carotenoids, chlorophyll, poly-β-hydroxybutyrate (PHB), and phytosterol (Abakari et al., 2021). BFT possesses antibacterial qualities like polyhydroxyalkanoate (PHA) and poly-β-hydroxybutyrate (PHB), which can promote the formation of beneficial microbial cells in the gut and modify the gut flora (Li et al., 2023). BFT relies on different organic carbon sources to sustain heterotrophic bacteria. Several researchers have been explored different carbon sources for the culturing of different aquatic species under BFT as shown in table 1. Compared to water-soluble substrates, solid carbon-based substrates need to undergo the degradation of dissolved organic carbon (DOC) first. Hence, carbonaceous substrates that are not soluble in water release DOC at a slower rate, resulting in a considerably slower elimination of ammonia (Abakari et al., 2021).

Microbial dynamics: Microbial manipulation is a major factor influencing the activity of biofloc system. Aquaculture systems include several microbial communities that can exert beneficial effects like eliminating pollutants, acting as a food source for other organisms, and facilitating the decomposition of organic materials, but some microbial groups can also exhibit detrimental impacts, such as causing diseases in unfavorable environmental circumstances. Microbial proliferation in the biofloc system may be assessed by

Table 1. Different carbon sources in different case studies in BFT

Carbon sources	Reported Species	References
Glycerol, Molasses, Starch	Oreochromis niloticus	Shourbela et al., 2021
Corn Flour, Wheat Flour, Sugar	Oreochromis niloticus	Garcia-Rios et al., 2019
Molasses, Tapioca Flour	Oreochromis niloticus	Rind et al., 2023
Rice Flour, Molasses	Penaeus monodon	Kumar et al., 2017
Sugarcane Molasses	Cyprinus carpio L.	Minabi et al., 2020

employing an Imhoff cone, a cone-shaped vessel with markings that allow for the measurement of settled biofloc amount, which in turn indicates the microbial composition (Ogello et al., 2021).

Bacteria play a vital role in biofloc technology by converting organic waste, eliminating harmful substances and serving as food supply for farmed species. Of the many kinds of bacteria found in the BFT system, the two most significant are nitrifying and heterotrophic. The breakdown of waste, unsummed food, and dead organic matter is the primary function of heterotrophic bacteria like Bacillus in the BFT system. This leads to bioremediation, improved water quality, growth, and the health of the raised species (Adel et al., 2017). The beneficial heterotrophic bacteria found in biofloc are more numerous and diverse, including Nitrospira, Bacillus, Acinetobacter, and Micrococcus. Through the process of nitrification, chemoautotrophs affect water quality (Khanjani et al., 2022).

Bacterial associated communities in biofloc: Biofloc organisms (BFOs) are crucial in biofloc technology for controlling nitrogen levels in water. Microalgae, comprising eukaryotes and prokaryotes, are crucial in biofloc systems since they produce proteins and carbohydrates from nitrogenous compounds and release oxygen (Bossier & Ekasari, 2017). Fungi are heterotrophs that compete with bacteria for nutrients like carbohydrates. Zooplankton species including rotifers, protozoans, crustaceans, and nematodes are crucial for nutrient recycling, water quality control, and feeding of raised species. Protozoa inhabit organic particles and consume bacteria, whereas nematodes offer a rich source of live food. The BFOs community promptly responds to environmental changes, including both living and non-living factors, that affect their production, biodegradation capabilities, and abundance. The proliferation of BFOs is influenced by the farmed species, environmental conditions, food availability, and carbon supply (Khangembam et al., 2017).

Roles of different microbial interactions in BFT: Ammonia is absorbed in aquaculture systems through three primary pathways: photoautotrophic absorption by algae in the presence of light, chemoautotrophic bacteria, and heterotrophic bacterial assimilation (El-Sayed, 2021). Chemoautotrophic bacteria carry out nitrification by oxidizing ammonia to nitrite and ultimately to nitrate. Ammonia oxidizing bacteria convert ammonia into nitrite and then transform into nitrate by nitrite oxidizing bacteria. Heterotrophic bacteria incorporate inorganic nitrogen and organic carbon into their biomass (Chen et al., 2023).

Water quality management: Monitoring water quality metrics is crucial for the optimal functioning of biofloc technology in aquaculture. Table 2 presents optimum levels of many crucial water quality parameters.

Biofloc system design and infrastructure: Inexpensive biofloc tanks can be constructed by utilizing a wire mesh framework with plastic lining or walls made entirely of concrete for water storage. During the construction process, put a 3-4mm iron mesh on top of a two-layer brick framework that has been placed on the floor. To facilitate the drainage of extra sludge, a central drainage pipe is placed at a 20–21° angle from the tank's borders to its center (Ogello et al., 2021). Traditional earthen ponds lacking liner material can be transformed into biofloc systems to enhance productivity. To achieve this, the pond should be positioned in a manner that allows wind to facilitate efficient water mixing. Additionally, it is recommended to construct a 2m3 structure at the inlet point using bamboo trees, which should be regularly filled with biodegradable waste to generate biofloc. Biofloc serves as a direct food source for fish (Abakari et al., 2022). To achieve suitable biofloc development in tanks or ponds, it is essential to use an aeration system, additional carbon, manipulation of microbes, and water quality control (Harun et al., 2019).

Feeding Practices: Feeding rates for the species in the biofloc treatments can be changed based on their daily intake and sampling. Initially, the feeding behavior of the species during several days rationed at 3–1.6% of the total standing biomass daily. Feed rations are to be divided into two to five times daily and given at adjusted intervals. Feed quantity should be decreased in the BFT culture system, and feed cost may be significantly decreased by lowering the protein content. Shrimps exhibit improved growth and survival rates when provided with a diet of 20–30% protein (6% fat), as opposed to the 40% protein diet commonly employed in commercial closed-pond systems. The decreased protein diet offers enhanced nutrition through flocs and minimizes the production of nitrogen waste (Debbarma et al., 2022).

Species suitability, selection, and stocking density for biofloc culture: Biofloc technology is most suitable for those species that can obtain nutritional advantages by consuming floc directly and can withstand extremely high solid concentrations. It is recommended to choose fish with omnivorous feeding habits for successful BFT. Important considerations for selecting an appropriate species for biofloc technology include: Does the species have a high tolerance for a significant concentration of solids? Is the species possessing the ability to filter feed or can it directly consume the flocs? Does the species exhibit tolerance to environmental changes resulting from fluctuations in bacterial loads and limited water renewal? Does the species exhibit strong tolerance to high stocking densities? (Kamruzzaman et al., 2023). Some of the suitable species for BFT are air-breathing fishes such as Asian Stinging Catfish, Climbing Perch, Walking Climbing Iridescent Sharks; and non-air-breathing fishes like Common carp, Nile Tilapia, Rohu, Milkfish; and Shellfishes like Prawns and Shrimps. It is advised that tilapia seeds be stocked in tanks based on BFT at a density of 12.5 grams per liter, and a 10,000-liter tank is predicted to have a carrying capacity of 0.4 kg per liter (McCusker et al., 2023).

Biosecurity measures: Various biosecurity measures must be considered to ensure the effective implementation of a BFT system. This chapter provides a quick discussion of a few significant measurements. It is essential that the seed's quality be examined to identify any potential diseases. Water quality is also an important element that needs to be checked and examined on a regular basis. Disinfection of vehicles in the farming area is a prevalent practice due to the vehicle's circulation within several fish farming sectors (Hasimuna et al., 2020). Preventive measures regarding pathogens should be implemented in all production units, including ponds, cages, tanks, and aquariums. Moreover, it is crucial to ensure that the transfer of equipment between ponds is adequately spaced out, particularly in the case of net transfers, as they are the instruments most likely to come into direct contact with animals. To effectively limit the activities of birds and crabs, it is necessary to ensure that the entire pond is enclosed with fencing specifically designed for this purpose. Farm workers should regularly wash their hands; this rule particularly applies to those who handle animals directly. Further, it is critical to maintain consistent visits for an updated record of safeguarding practices (Subasinghe et al., 2023).

Benefits of biofloc technology

Biofloc technology effectively regulates water quality by allowing bacterial communities to thrive on dissolved organics, which are then consumed by raised species, eliminating the need for water exchange. The presence of heterotrophic bacteria in BFT, which is the most essential working mechanism, increases the weight gain and feed conversion ratio of the reared species (Bossier & Ekasari, 2017). Biofloc can serve as an economical substitute for fish meal, which is a costly and limited protein source in the fish feed sector. Biofloc paste can be collected and treated as an

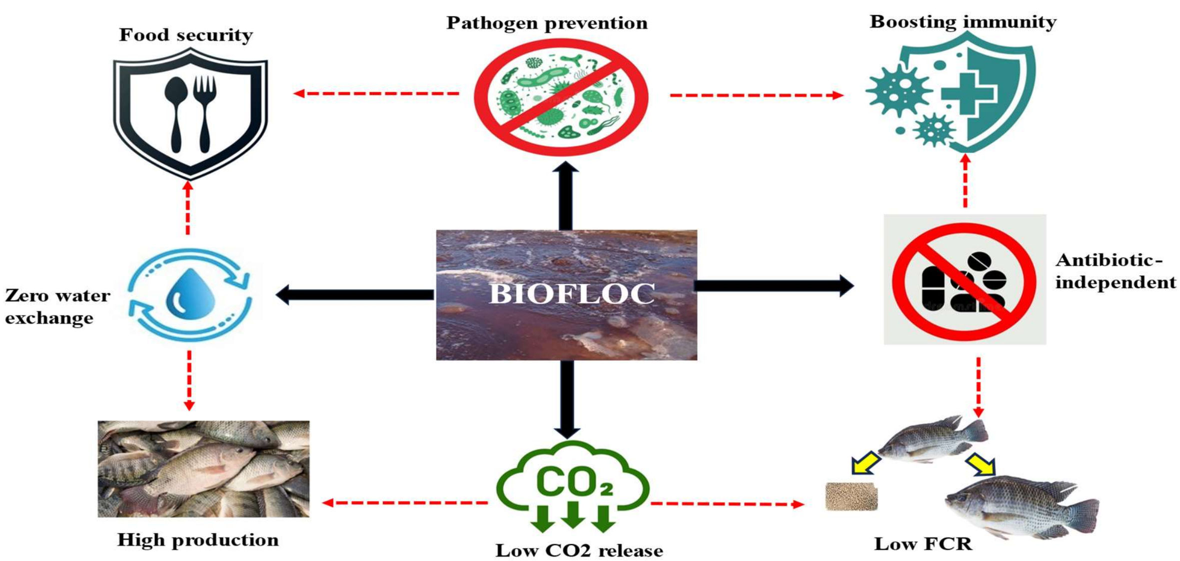

Fig 3. Advantages of Biofloc Technology (Yu et al., 2023b)

Table 2. Water quality parameters for successful BFT

Parameter	Ideal range	Key considerations	References
Temp	28–30°C	Temperatures below 20°C significantly hinder the development of the microbial population in BFT.	Emerenciano et al., 2017
DO	4mg L^{-1}	Aeration must be managed within a range appropriate for the biomass of the rising species.	McCusker et al., 2023
Ph	6.8–8 (freshwater)	Beyond the optimum range, raising animals exhibits a variety of biological and chemical reactions.	Emerenciano et al., 2017
Alkalinity	100–150mg L^{-1}	Buffering capacity must be examined and modified because autotrophic and heterotrophic bacteria use inorganic carbon in BFT.	Martins et al., 2017
TAN	1mg L^{-1}	When pH rises, ammonium turns to ammonia, which is more hazardous to aquatic species; thus, it may remain close to zero.	McCusker et al., 2023
NO_2-	0	Nitrite causes a variety of physiological difficulties in raising animals.	McCusker et al., 2023
NO_3-	< 20mg L^{-1}	Nitrate levels below 20 mg/L are safe for many aquatic organisms.	Emerenciano et al., 2017
TSS	5–15mL L^{-1}	Lack of suspension results in quick consumption of dissolved oxygen, which releases toxic gasses to farmed species.	Harun et al., 2019
Salinity	Variable	Certain species, such as shrimp, grow in brackish water BFT at 15 ppt salinity. Other species, such as Nile tilapia, have shown variations ranging from 0 to 12 ppt.	Hosain et al., 2021

Abbreviations: Temp, temperature; DO, dissolved oxygen; BFT, biofloc technology; TAN, total ammonia nitrogen; TSS, total suspended solids; NO_2-, Nitrite; NO_3-, nitrate.

ingredient for preparing formulated feed in local hatcheries. The economic impacts of BFT are broad: floc in BFT can replace commercial feeds without adversely affecting aquatic species' survival or growth performance, and protein utilization efficiency is two times higher in BFT systems than in traditional aquaculture systems (Mugwanya et al., 2021). Shortly biofloc system helps in disease control, nutritional security, high production, use of little or zero water, less utilization of limited resources, etc (Fig 3).

Drawbacks of BFT systems

Despite several benefits of biofloc technology, there are multiple drawbacks that prevent efficient production. Even if a high bacterial population is encouraged, then the proliferation of heterotrophic bacteria may generate significant turbidity in the system, resulting in the blocking of rearing species gills, particularly those that are not adapted to turbid conditions (Soaudy et al., 2023). An imbalance in the microbial population may elevate the risk of contamination due to the accumulation of nitrate compounds. BFT is constrained by many reasons such as increased energy requirements for mixing and aeration, along with a two-week initiation period for microbe development, potentially extending production cycles. There is also a need for supplementation with alkalinity to maintain optimal conditions for the proliferation of biofloc in the system. However, sunlight-exposed BFT systems may experience irregular and seasonal performance. Additional concerns include the possibility of the overabundance of filamentous biofloc leading to floc expansion, system fluctuation, and insufficient nitrogen removal. (Mugwanya et al., 2021).

Advanced BFT application in the aquaculture industry and future directions

Biofloc technology has incredible commercial potential, but it requires more development to ensure its long-term viability. Therefore, this technology is being integrated with the latest approaches such as the Internet of Things (IoT), artificial intelligence (AI), cloud computing, 5G, automatic identification, satellite images, machine learning, in situ sensor networks, and robots (Antonucci & Costa, 2020). Integration of emerging innovations such as BFT and IoT/ICT is considered highly beneficial for the progress of the aquaculture sector. Applying IoT and ICT to BFT enables cost reduction in production and labor through automatic water quality management. Additionally, it enhances productivity by providing efficient growth for rearing organisms. Consequently, these advantages may result in beneficial impacts on the surrounding environment. However, it is needed to address several issues encountered in the future, like the high expenses associated with IoT implementation, limited accessibility for aquaculture farmers, the short lifespan and low reliability of sensors (Yu et al., 2023).

CONCLUSION

The worldwide conflict of increased seafood demand, water shortages, and limited land resources needs sustainable aquaculture practices. Biofloc technology (BFT) provides eco-friendly and sustainable solutions to increase aquaculture production by serving as a cost-effective substitute for fishmeal, offering benefits such as improved biosecurity, reduced feed utilization, lower pathogenic introduction, higher growth, survival rates, and reduced water exchange. Future studies should concentrate on expanding BFT to carnivorous species and investigating varied carbon sources to maximize advantages. Despite the constraints of information dissemination system improvement, standardization and scaling up, the future for biofloc fish farming is optimistic. Integrating IoT and ICT with BFT allows for vital and effective management, productivity and cost reduction. However, challenges including rising IoT expenses and restricted IoT applications for farmers persisted. Technological developments are crucial for effectively integrated sensors by addressing issues such as short life spans, low consistency and non-standardization. Marketing should prioritize promoting organic aquaculture products from BFT ponds. Overall, integrating BFT with digital technologies holds great promise for sustainable aquaculture, addressing environmental, social, and economic challenges.

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