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Biofloc Technology in Shrimp Aquaculture: A Review of Sustainability and Challenges.

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Abstract

Shrimp farming is a key player in global aquaculture, driven by efficient and sustainable production technologies. Biofloc Technology (BFT) has emerged as a pivotal solution to various aquaculture challenges, offering a cost-effective and environmentally friendly approach. BFT enhances water quality by promoting the growth of heterotrophic bacteria, which help reduce ammonia levels and improve biosecurity. It also minimizes water exchange, conserving vital water resources in areas facing scarcity. However, while BFT has proven highly beneficial for shrimp farming, it presents challenges such as the risk of disease outbreaks, potential overcrowding, and management complexities. This review evaluates the advantages and limitations of BFT, highlighting its impact on water quality improvement, biosecurity enhancement, and water conservation. It also discusses the need for optimized system management to mitigate disease risks and overcrowding issues. Recommendations include the use of appropriate carbon sources for microbial mass management, species selection tailored to BFT, and potential integration of alternative energy sources to reduce operational costs. This review emphasizes BFT's potential as a sustainable solution for small- and medium-scale aquaculture operations while acknowledging the necessity of addressing system challenges to maximize its efficacy.

Keywords: Aquaculture sustainability, Biofloc Technology, Disease management, Shrimp farming

1. Introduction

As the global population, currently estimated at 7.8 billion people, continues to grow, the demand for aquatic food is increasing proportionally (FAO, 2021). Meeting this demand sustainably requires the adoption of advanced technologies that are environmentally friendly and economically viable, supporting both ecological balance and socioeconomic aspects of production (Verdegem et al., 2013; Viegas et al., 2021). Biofloc technology (BFT) is a transformative solution in aquaculture, distinct from conventional systems such as raceways, recirculation aquaculture systems, and ponds. Unlike these systems, BFT employs a zero-waste approach by retaining, reutilizing, and purifying wastewater through bacterial activity under strong aeration, converting organic waste into protein-rich feed (Anongponyoskun et al., 2012; Avnimelech, 2015). This process not only minimizes harmful ammonia discharge into the environment but also enables the cultivation of high stocking densities, leading to increased yields per production cycle (Crab et al., 2007; Samocha, 2019; Robles-Porchas et al., 2020). Additionally, BFT reduces dependence on fishmeal and fish oil—costly and often unsustainably sourced feed components—by promoting microbial aggregates such as protozoa, algae, and diatoms, which serve as direct nutritional sources for shrimp (Correa et al., 2020). This auto-production of protein within the system lowers feed conversion ratios (FCR) and reduces input costs, making BFT an attractive option for both small- and large-scale farmers (De Schryver et al., 2008; Schveitzer et al., 2017; Manduca et al., 2021; Emerson et al., 2023). By facilitating the transition from extensive to intensive production systems, BFT addresses critical challenges in modern aquaculture. This review explores the unique operational mechanisms of BFT, emphasizing its potential to enhance productivity while ensuring sustainability in the aquaculture industry.

2. Principle of Operation

BFT can be initiated in tanks containing water by simply introducing nitrogenous sources (fish feed, or urea or adding pond water) to start the system (Figure 1). After that, a carbon source is uniformly spread on the surface of the tank water while applying sufficient aeration. This will stimulate bioflocs production, ensure proper mixing and avoid the accumulation of sludge (Avnimelech, 2012; Crab et al., 2012; Kasan et al., 2018). In other words, the combination of nitrogenous wastes, a carbon source and probiotics under sufficient aeration will quickly activate the inoculum resulting in the formation of a microbial biomass referred to as Bioflocs (Avnimelech, 2015; El-Sayed, 2021). This microbial biomass will generate the presence of heterotrophic bacteria, which decreases the ammonia concentration more rapidly than nitrification (Sudaryono et al., 2018; Simon et al., 2020). Heterotrophic bacteria utilize organic carbon as their energy source and require nitrogen to synthesize proteins, making them effective at assimilating nitrogenous waste in the system.(Avnimelech, 2012).

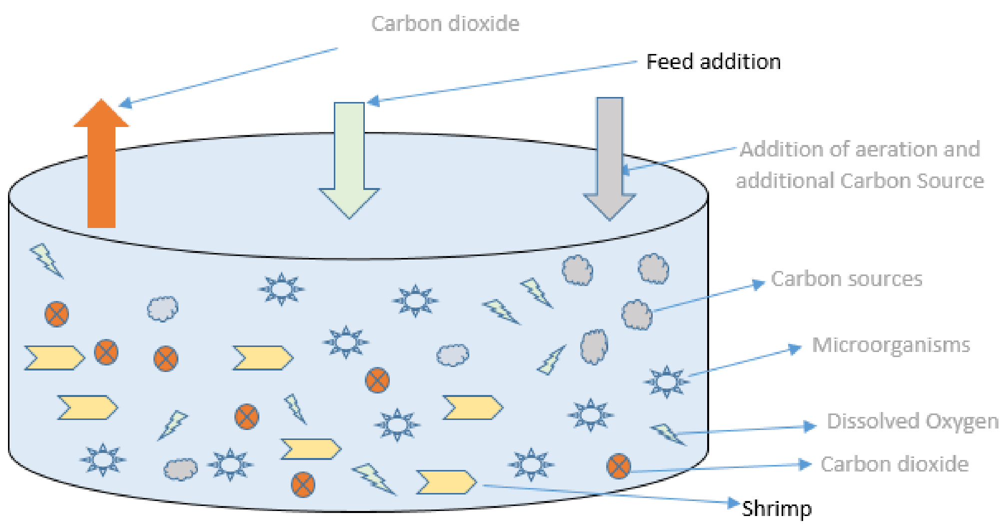

Figure 1. Biofloc cycle

2.1. Autotrophic vs Heterotrophic Bacteria

Another method for biofloc production is by generating autotrophs through the addition of fertilizers, fish/shrimp feed, and other ingredients (De Schryver et al., 2008; Ferreira et al., 2021). Autotrophic bacteria, in contrast to heterotrophic bacteria, obtain their energy from inorganic substances such as carbon dioxide and are involved in processes like nitrification, converting ammonia to nitrate in the system. The autotrophs are further converted into heterotrophs by adding a carbon source and maintaining the ratio of C: N (12–15:1). The amount of salinity and type of carbon used in the system affect the rate and duration of biofloc formation (Cho et al., 2007; Lima et al., 2019; Samocha, 2019). It has been observed that increasing salinity increases the density of biofloc formation, and the quality of the flocs are determined by the carbon source (Cho et al., 2007; Pinho & Emerenciano, 2021). So, to improve water quality and obtain faster growth of heterotrophic bacteria, the right quantity of carbonaceous organic matter-like molasses must be supplied. This is preferable to the addition of complex carbohydrates such as wheat flour, which might slow the process. A color change transition from green to brown is quickly observed, with the flocs building up during the process (Avnimelech,2007).

2.2. Environmental impact and water conservation

The BFT system is eco-friendly and constitutes a perfect remedy to the pressure on water resources for farmed aquatic animals. Water is fast becoming scarce and expensive to the point that aquaculture development is threatened. The earth's surface is rapidly being modified due to the high rate of evaporation from large surface ponds constructed through deforestation, which is causing climate change. Shrimp ponds constructed around mangroves and estuary ecosystems are generally large in surface area demanding large deforestation inevitably leading to global warming. These ponds release their ammonia wastes into the aquatic environment causing pollution. The multiplying effect has far-reaching consequences that are not only destructive to the aquatic organisms but also damaging to human welfare. Thus, several nations are now implementing laws prohibiting the discharge of contaminated effluents into the environment and the responsible usage of water. More so, the recent outbreak of shrimp diseases and its widespread have provoked the enactment of restrictive biosecurity measures, such as limiting water exchange rates (Joffre et al., 2018) and the usage of open ponds in shrimp culture in some countries.

3. Advantages of biofloc system

Biofloc technology (BFT) addresses key challenges in fish and shrimp farming (Hisano et al., 2021; Khanjani et al., 2022) (Table 1).

3.1. Water Quality Improvement

One of the primary benefits of Biofloc systems is their ability to enhance water quality. By adding carbohydrate sources, BFT promotes the growth of heterotrophic bacteria that help decompose nitrogenous compounds, which leads to cleaner and more stable water (Crab et al., 2007). These bacteria break down ammonia, reducing its levels, which is crucial for the health of the cultured species. Additionally, BFT stabilizes total suspended solids through aeration, making the environment safer for the aquatic organisms (Avnimelech, 2012; Kim et al., 2015). Compared to traditional pond-based systems, which typically require up to 30% water exchange to maintain water quality, BFT systems need less than 10% water exchange daily (Crab et al., 2012). The reduced water exchange in BFT systems also helps minimize the stress placed on local water resources and the surrounding environment, addressing water scarcity issues in aquaculture. In contrast, pond-based systems often rely on frequent water exchanges to maintain water quality, which can be resource-intensive and environmentally detrimental. These systems are susceptible to the accumulation of waste and nutrients, which can lead to eutrophication of surrounding water bodies, further exacerbating water quality concerns (Timmons & Ebeling, 2002). While recirculating aquaculture systems (RAS) also recycle water, they require significant energy inputs for pumps and filtration systems and are more technologically complex to operate (Boucher et al., 2020). Although RAS systems offer controlled water quality management, their high energy costs and maintenance requirements make them less resource-efficient compared to Biofloc systems.

3.2. Biosecurity Enhancement

Biosecurity is a crucial consideration in aquaculture, and Biofloc technology provides several advantages in improving the biosecurity of cultured species. Biofloc systems are known to reduce ammonia levels by up to 50% compared to conventional systems, thereby alleviating stress on the organisms and enhancing their resistance to diseases (Avnimelech, 2012; Emerenciano et al., 2013). For instance, shrimp species like *Litopenaeus vannamei* exhibit increased resistance to infections such as the infectious myonecrosis virus (IMNV) and Vibrio bacteria in BFT systems (Liu et al., 2017; Dawood et al., 2018). This reduction in pathogen load contributes to healthier, more robust organisms, thereby improving survival rates and productivity. In comparison, traditional pond-based systems are more prone to disease outbreaks due to the accumulation of organic matter and pathogens in the water. While these systems can implement biosecurity measures such as chemical treatments or antibiotics, they often prove less effective at controlling pathogens than Biofloc systems, which naturally create a beneficial microbial environment (Timmons & Ebeling, 2002). Recirculating aquaculture systems (RAS), on the other hand, are designed to control pathogens through filtration and UV treatment, offering high biosecurity. However, RAS are more expensive to maintain and require constant monitoring to ensure proper system functioning (Boucher et al., 2020).

3.3. Water Conservation and Efficient Feed Use

Water conservation is another significant advantage of Biofloc systems. The ability of BFT to reduce water exchange rates—often to less than 10% daily—makes it highly water-efficient compared to other aquaculture systems, which typically require more frequent exchanges (Crab et al., 2012). This feature is particularly important in regions facing water scarcity or environmental degradation. In addition, BFT systems provide more efficient feed utilization by supporting the growth of zooplankton, such as copepods, which can serve as live feed for shrimp and fish. These zooplankton blooms, promoted by the microbial activity in the Biofloc system, boost growth and survival rates of cultured species (Lukwambe et al., 2019; Nevejan et al., 2018). The copepods, rich in beneficial nutrients, improve the growth of shrimp, further enhancing the overall productivity of the system. In contrast, traditional pond-based systems typically rely on high levels of external feed input and more frequent water exchanges to maintain water quality, which leads to higher operational costs and inefficiencies. These systems are more dependent on external water sources, often leading to waste buildup and a reduction in feed efficiency. While recirculating aquaculture systems (RAS) offer water-efficient recycling, they also demand significant external feed input and can be more complex and costly to operate. RAS systems may have more control over water quality but are not as efficient in utilizing microbial or in-situ live feed sources like BFT, making them less feed-efficient (Boucher et al., 2020).

3.4. Environmental Sustainability and Cost Efficiency

Biofloc technology is also considered environmentally sustainable due to its low environmental impact. By minimizing the need for water exchange and reusing organic waste within the system, BFT significantly reduces the risk of water pollution and nutrient runoff (Avnimelech, 2007). The ability of Biofloc systems to self-sustain microbial populations that naturally break down organic waste further enhances their environmental sustainability. In addition, the low capital costs of Biofloc systems, combined with the reduced need for external feed, antibiotics, and chemicals, make them an economically viable option for small-scale producers (Crab et al., 2012). This makes BFT particularly attractive for resource-limited settings where traditional aquaculture systems might be too expensive or unsustainable. Traditional pond-based systems have a lower initial capital investment but are less environmentally sustainable due to their reliance on frequent water exchanges and the potential for nutrient buildup in the surrounding environment. These systems can be more prone to pollution and water scarcity issues, especially in regions with limited access to fresh water (Timmons & Ebeling, 2002). Recirculating aquaculture systems (RAS), while offering superior control over environmental factors and water quality, require substantial investment in infrastructure and energy consumption, making them less cost-effective, particularly for small-scale or low-resource operations (Boucher et al., 2020).

Table 1 Comparative analysis of Biofloc Technology (BFT) with other aquaculture systems

Aspect	Biofloc Technology (BFT)	Traditional Pond-Based Systems	Recirculating Aquaculture Systems (RAS)
Water Quality Improvement	Improves water quality by reducing ammonia and nitrogenous compounds via heterotrophic bacteria (Crab et al., 2007). Requires <10% water exchange daily (Crab et al., 2012).	Requires frequent water exchange (up to 30%) to maintain water quality, leading to water resource depletion (Timmons & Ebeling, 2002).	Provides high control over water quality but requires significant energy for filtration and pumping (Boucher et al., 2020).
Biosecurity Enhancement	Enhances biosecurity by improving resistance to pathogens like *Vibrio* and *IMNV* (Liu et al., 2017; Dawood et al., 2018). Reduces disease risks naturally.	More prone to disease outbreaks due to waste accumulation and pathogens in water. Requires additional biosecurity measures such as antibiotics.	High biosecurity through filtration and UV treatment but requires constant monitoring and high maintenance costs (Boucher et al., 2020).
Water Conservation	Reduces water exchange rates (<10% daily) and helps minimize water usage in aquaculture (Crab et al., 2012).	Higher water exchange rates (up to 30%) required, which is resource-intensive.	Water is recycled, but energy-intensive filtration and pumps are required, making it less water-efficient than BFT.
Feed Efficiency	Supports growth of zooplankton (copepods) as live feed, enhancing shrimp growth by 25-30% (Lukwambe et al., 2019; Nevejan et al., 2018).	Dependent on external feed inputs, leading to higher feed costs.	Requires high external feed inputs and does not utilize microbial live feed like BFT.

Environmental Sustainability	Low environmental impact; minimizes waste and nutrient runoff. Reduces water pollution by reusing organic waste in-situ (Avnimelech, 2007).	Can lead to eutrophication and water pollution due to excess nutrient accumulation.	High energy consumption and complex filtration systems, which may increase environmental footprint.
Cost Efficiency	Low initial capital costs, low feed requirements, and no need for antibiotics, making it economically viable for small-scale producers (Crab et al., 2012).	Low capital investment but high operational costs due to frequent water exchanges and external feed inputs.	High initial investment and operational costs due to energy consumption and complex systems.

4. Challenges and Opportunities in Biofloc Systems

Biofloc Technology (BFT) has gained considerable attention for its potential to revolutionize aquaculture systems by offering cost-effective solutions to feed supplementation, improving nutrient recycling, and enhancing water quality. However, its implementation is not without challenges, and these must be balanced against the system's many opportunities.

4.1. Challenges in Biofloc Systems

One of the primary challenges of BFT is the risk of disease outbreaks, particularly when system management is insufficient. The complex nature of BFT systems requires careful monitoring and management, and without proper oversight, disease risks can increase (Silva et al., 2020). Moreover, BFT is not suitable for all species, as it primarily supports filter-feeding organisms such as shrimps, Oreochromis sp., and Mugil liza. The system functions optimally with species that can directly feed on the flocs; therefore, the species choice significantly influences the design of the biofloc system. For instance, shrimp culture densities in BFT can reach 100–150 individuals per m^3, whereas conventional systems usually maintain densities of 10–15 individuals per m^3 (Kim et al., 2015; Liu et al., 2017).

Overcrowding is another concern, and incorporating alternative energy sources like solar or wind energy for aeration could reduce operational costs and enhance system efficiency (Nookuea et al., 2016). However, some species, such as tropical fish species like *Colossoma macropomum*, may experience suboptimal growth in BFT systems compared to conventional pond systems due to issues such as water turbidity and increased nitrite levels (Nevejan et al., 2018). To address these, continuous water monitoring systems and automatic filtration units are recommended.

Another significant challenge is the management of microbial mass in BFT. The type of carbon source used in the system directly influences the microbial composition and its nutritional properties, which are critical for the growth of cultured organisms. For example, specific carbon sources stimulate the growth of certain protozoa, bacteria, and algae, and this can impact the efficiency of nutrient assimilation by the cultured species (Emerenciano et al., 2013; Dawood et al., 2018). Additionally, the microbial mass in BFT often lacks sufficient levels of essential vitamins, such as vitamin C and vitamin B12, which are necessary for optimal growth (Liu et al., 2017). Supplementary feeding with fortified diets is, therefore, recommended to address these deficiencies.

4.2. Opportunities in Biofloc Systems

Despite these challenges, BFT presents several unique opportunities. One of its key benefits is the ability to reduce the amount of supplementary feed required by providing low-crude protein sources in smaller quantities, which lowers overall feed costs compared to traditional aquaculture systems. The system also supports a diverse range of microbial flocs that contribute to a dynamic and constantly evolving nutritional environment, which can be harnessed for better feeding practices (De Schryver et al., 2008; Anand et al., 2021).

Recent studies have revealed that heterotrophic bacteria in bioflocs produce single-cell proteins that serve as a food source for species like carps, shrimps, and tilapia (Emerenciano et al., 2013; Poli et al., 2019). Nutritional analyses of biofloc indicate that it is rich in crude protein (50%), crude lipid (2.5%), fiber (4%), and energy (22 kJ/g), although its nutritional value can vary depending on the biochemical compounds present, particle size, and the digestibility of the organisms consuming it (Simon et al., 2020; Hosain et al., 2021). Biofloc systems also achieve a lower feed conversion ratio (FCR) of 1.2–1.29, compared to 1.52 in clear water systems, highlighting the efficiency of the system in converting feed into growth (Nevejan et al., 2018).

In terms of scalability, BFT has the potential to address the growing demand for juvenile fish in tropical countries, where fish seed production is increasing. Live food, such as rotifers, copepods, and Artemia nauplii, is crucial for juvenile fish due to their small size and high nutritional requirements (Ferreira et al., 2021). BFT systems provide an efficient and cost-effective way to produce these live foods in high densities, using fish waste diets (Nevejan et al., 2018). Moreover, studies have shown that BFT can produce mixed zooplankton communities in outdoor conditions, offering a diverse and stable food source for cultured organisms (Sudaryono et al., 2018).

Furthermore, biofloc systems help reduce the need for expensive and fragile microalgal pastes and are more resistant to oxidation, ensuring a longer shelf life for live food products. These systems not only provide more natural and species-specific nutrients but also contribute to improved water quality, making them a sustainable option for aquaculture in tropical regions (De Schryver et al., 2008; Panigrahi et al., 2019). In sum, BFT offers a promising solution for high-quality fish and shrimp seedling production, with scalability and cost-effectiveness making it a viable option for future aquaculture systems.

5. The threat in biofloc systems

A major hitch of this technology is the high need for continuous aeration to suspend the solid mass in the system so that active metabolism by bacteria will lead to protein production (flocs) (Avnimelech, 2012; Abakari et al., 2022). This will also lead to the avoidance of sludge accumulation, which can disrupt the system. The constant drop in pH and alkalinity due to nitrification is a delicate operation that can be fatal in case of interruption of electricity or poor management. Therefore, there is a need to stabilize the system by constant addition of sufficient carbon to enable the metabolism of solid wastes by bacteria to generate protein (Mirzakhani et al., 2019; Martins et al., 2019; Ferreira et al., 2021). BFT requires a start-up period to generate the flocs and after that, there is an increase in the accumulation of ammonia, suspended solids, and microbial mass which must be kept under control (Avnimelech, 2012). When this occurs, the pH drops requiring alkalinity supplementation to balance the system immediately (Hargreaves, 2006; Furtado et al., 2015).

The establishment of an indoor biofloc system for commercial purposes is relatively expensive and not easily affordable to small-scale farmers in developing countries (De Schryver et al., 2008). Unfortunately, biofloc systems exposed to sunlight lead to an inconsistent and seasonal performance in production (Emerenciano et al., 2013). The system start-up period for flocs production generally takes time and also for the conversion of autotrophs to heterotrophs which requires several days (Ferreira et al., 2021).

6. Recommendations for Future Research and Industry Adoption

Biofloc Technology (BFT) shows significant promise for improving the sustainability of aquaculture, but further research and industry adoption are required to optimize its use across a broader range of species and systems. One of the key areas for future research is the optimization of BFT for different aquaculture species. While BFT has demonstrated success in shrimp farming, particularly with *Litopenaeus vannamei* (Liu et al., 2017; Dawood et al., 2018), there is a need for additional studies to explore its applicability to other species, including tropical fish such as tilapia and catfish. These investigations would help tailor microbial communities and feeding strategies to suit the needs of various species, thus broadening the system's reach in global aquaculture operations (Avnimelech, 2012). Additionally, biosecurity remains a significant challenge in aquaculture, and while BFT has been shown to improve disease resistance, further research is needed to enhance biosecurity measures in larger-scale, commercial BFT systems. Specific probiotic strains could be incorporated into these systems to strengthen pathogen resistance, particularly for diseases like the infectious myonecrosis virus (IMNV) and Vibrio infections (Panigrahi et al., 2020). Moreover, applying molecular techniques to monitor and manage microbial communities could provide insights into developing more robust biosecurity strategies (Hussain et al., 2021).

Long-term environmental sustainability is another critical area requiring more focused research. While BFT has demonstrated clear advantages in terms of water quality improvement and waste reduction (Boucher et al., 2020), the full life-cycle environmental impact, including energy use, greenhouse gas emissions, and resource efficiency, remains understudied. Comprehensive studies comparing BFT with other systems, such as Recirculating Aquaculture Systems (RAS), would help establish clear sustainability benchmarks and guide policy and industry decision-making on the adoption of these technologies (Crab et al., 2012). Scalability is a crucial challenge for BFT, particularly when transitioning from small-scale operations to larger, commercial systems. Future research should focus on optimizing BFT systems for large-scale operations, taking into account factors such as system size, feed management, and operational costs. This research should aim to improve the cost-effectiveness of BFT and reduce the operational challenges associated with aeration and nutrient supplementation (Kim et al., 2015). Additionally, industry collaborations and pilot projects can help refine BFT systems and make them more accessible to commercial aquaculture producers, especially in regions with limited resources (Timmons & Ebeling, 2002).

Improving feed conversion ratios (FCR) within BFT systems is another key area for future research. Studies have demonstrated that copepods produced in BFT systems can significantly enhance shrimp growth (Lukwambe et al., 2019), but further optimization of microbial communities and carbohydrate sources is needed to improve the feed efficiency for both fish and shrimp. Research into more efficient feeding strategies, particularly for low-resource farmers, could help improve productivity and reduce feed costs, which remain one of the largest expenses in aquaculture (Zeng et al., 2020). Integrating BFT with other sustainable aquaculture technologies presents an exciting opportunity for improving resource efficiency. Investigating the potential of combining BFT with Integrated Multi-Trophic Aquaculture (IMTA) systems, where different species are cultivated in tandem, could optimize nutrient cycling and reduce waste (Samocha, 2019). Future research should explore how BFT can work synergistically with other aquaculture systems, such as algae cultivation or biofilters, to create a holistic and sustainable production model. Finally, to promote the widespread adoption of BFT, policy development and industry guidelines are essential. Governments and industry bodies should collaborate to develop regulations and guidelines specific to BFT systems, focusing on water quality management, biosecurity protocols, and waste management practices. Establishing clear frameworks for BFT adoption will help incentivize its use and facilitate its integration into the broader aquaculture industry (Crab et al., 2012).

7. Conclusion

Generally, and based on research, it has been revealed and demonstrated that BFT is an ideal panacea for modern aquaculture operations due to its sustainability. The extra fact that biofloc technology operates on the principle of recycling wastes into nutrients for culture organisms has greatly distinguished the system. Wastes such as nitrogenous wastes become microbial biomass, which is utilized by cultured organisms as important feed nutrients. Many research has observed that shrimps are healthiest and grow best in BFT because they have high levels of algae, bacteria, and other natural biota. This microbial biomass contains some beneficial bacteria that are referred to as probiotics. Probiotics are microbial cells that are viable and have a beneficial effect on the health of their host. It is also known to improve intestinal equilibrium and have an enzymatic role in digestion. Moreover, it is very effective in inhibiting the occurrence of pathogenic microorganisms, and anti-mutagenic and anti-carcinogenic actions of its host. Biofloc is thus a growth booster and an increased immune fortifier.

Biofloc systems are multifaceted and so, farmers must be skilled to be able to realize economic benefits. Although BFT respond valuably to the challenges of aquaculture; solving environmental, social, and economic challenges, it however lacks the disposition to satisfy specific growing desires in other important aquaculture species. The basic requirement in any given production technology is its diversity in utilization of culture different species to attract investment. This is lacking in biofloc technology. Yet, it is a major spotlight technology highly debated due to its success in shrimp production. The most, valued seafood commodity traded worldwide.

Author Contributions

Morfow Nkeze Paul: Original draft preparation, validation, Conceptualization, Benedicta Oshuware Oben: reviews and editing, Atabong Paul Agendia: editing, formatting & submission process, Nor Azman Kasan: supervision. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

Not applicable

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Conflicts of Interest

The authors declare no conflict of interest.

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