Biofloc Systems for Sustainable Aquaculture

Subjects: Agriculture, Dairy & Animal Science
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The increasing global population has led to an increase in food demand; consequently, aquaculture is one of the food production sectors that has offered opportunities to alleviate hunger, malnutrition, and poverty. However, the development of a sustainable aquaculture industry has been hindered by the limited availability of natural resources as well as its negative impact on the surrounding environment. Hence, there is an urgent need to search for better aquacultural production systems that, despite their high productivity and profitability, utilize fewer resources such as water, energy, land, and capital in conjunction with a negligible impact on the environment. Biofloc technology (BFT) is one of the most exciting and promising sustainable aquaculture systems; it takes into account the intensive culture of aquatic species, zero water exchange, and improved water quality as a result of beneficial microbial biomass activity, which, at the same time, can be utilized as a nutritious aquaculture feed, thus lowering the costs of production. Furthermore, BFT permits the installation of integrated multi-trophic aquaculture (IMTA) systems in which the wastes of one organism are utilized as feed by another organism, without a detrimental effect on co-cultured species.

biofloc technology | aquaculture | integrated multi-trophic aquaculture | sustainability

1. Introduction

According to the Food and Agriculture Organization, aquaculture is one of the food production sectors that offers a golden opportunity to alleviate hunger, malnutrition, and poverty through income generation and better use of natural resources [1]. With the increasing human population, projected to reach 9.6 billion by 2050 [2], the demand for food is escalating amidst limited natural resources such as water and land required for the continuous production of food. Nevertheless, aquaculture production is projected to rise from 40 million tons by 2008 to 82 million tons in 2050 [3]. This is probably due to the gradual adoption of semi-intensive and intensive aquacultural practices for the production of economically important aquatic species. However, intensive aquacultural practices are of great environmental concern due to the discharge of nutrient-rich wastewater into the environment. With all these constraints in mind, the development of sustainable aquaculture systems should focus more on system designs that permit not only the efficient use of fewer resources such as water, energy, land, and capital but also minimizing environmental pollution and maximizing production and profitability. This would, in the long run, lead to the fulfillment of the Sustainable Development Goals (SDGs), notably SDG 1 (end poverty), SDG 2 (zero hunger, achieve food security, improve nutrition, and promote sustainable agriculture), SDG 8 (promoting inclusive and sustainable economic growth, decent work for all), and SDG 14 (conservation and sustainable use of water bodies for sustainable development) [1].

Biofloc technology (BFT) is one of the most exciting food production alternatives that has attracted the attention of the scientific community and producers for sustainable aquaculture due to (i) zero water exchange, thus permitting efficient use of limited water resources and preventing the discharge of nutrient-rich wastewater into the environment; (ii) reduced artificial feed input (fishmeal), which reduces the costs of production while permitting the inclusion of alternatively cheaper and highly nutritious protein sources, and (iii) natural establishment of microbial biomass that not only purifies water but also enhances the growth, growth performance, and immunity of aquatic species reared in the system. The use of this system in farming practices for the production of crustaceans and some finfish species has been extensively studied [4][5][6][7][8][9][10][11][12]. The aim of this review, therefore, is to (i) give a brief overview of BFT systems, including operational parameters that affect their efficiency; (ii) review studies that have been conducted on the application of BFT systems for the sustainable production of economically important aquatic species; (iii) highlight the economic aspects of BFT systems, as well as their drawbacks and limitations, and recommend management aspects of BFT systems for sustainable aquaculture.

1.1. Biofloc Technology

According to the National Agricultural Library Glossary (United States Department of Agriculture, North Bend, WA, USA), BFT is defined as 'the use of aggregates of bacteria, algae or protozoa, held together in a matrix along with particulate organic matter to improve water quality, waste treatment and disease prevention in intensive aquaculture systems' [2]. In other words, BFT relies on the principle of nitrogenous waste recycling by several microbial species (bioflocs) in the system while improving water quality and the growth performance of the reared aquatic species. Heterotrophic bacteria within the system take up ammonium as a nitrogen (N) source for their biomass, thus resulting in a decrease in ammonium/ammonia in the water to non-toxic levels. This process is, however, faster than the nitrification process carried out by autotrophic nitrifying bacteria due to the faster growth rate of heterotrophic bacteria. **Figure 1** shows a general overview of the BFT system. Certain factors that affect floc formation (mixture of microorganisms) and water quality in BFT systems are discussed below.

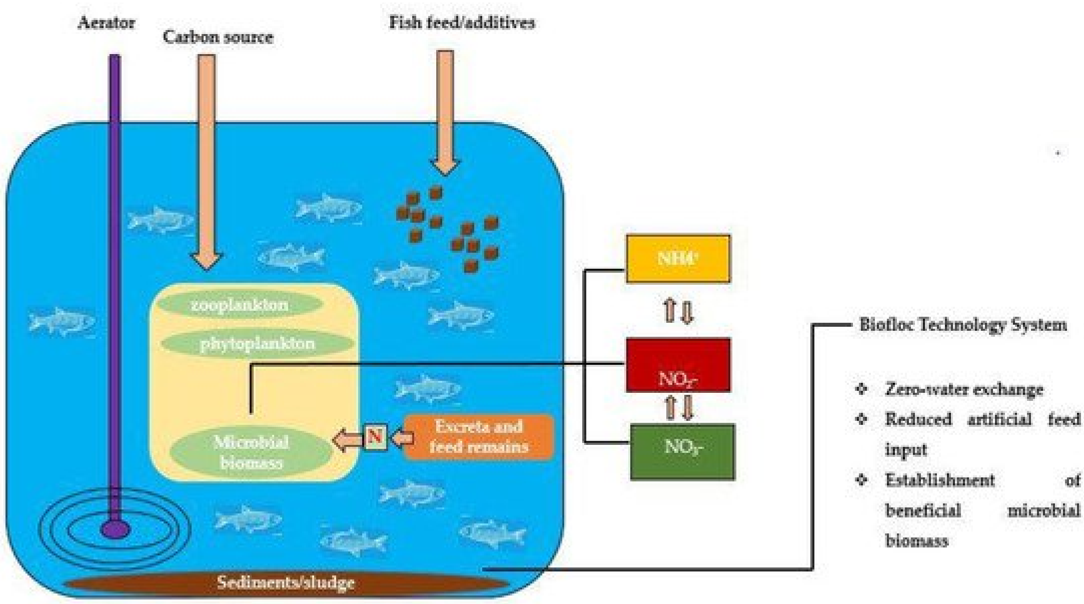

Figure 1. Schematic diagram of a biofloc technology system.

1.1.1. Carbon–Nitrogen Ratio

In the aquatic environment, the carbon–nitrogen ratio (C/N) plays a vital role in the immobilization of toxic inorganic N compounds into useful microbial biomass that might act as a direct source of food for the reared aquatic species. Immobilization of inorganic N occurs at a C/N ratio of organic matter above 10 and, hence, any alteration in this ratio within the BFT system might result in a shift in microbial diversity, which might further affect the water quality. For example, De Schryver et al. [13] observed that a high C/N ratio favors the proliferation of heterotrophic bacteria, which leads to significant changes in water quality and biofloc composition. As such, manipulation of the C/N ratio can be achieved through modification of the carbohydrate content in the feed or the addition of an external carbon source in the rearing water so that microbes can assimilate waste ammonium for microbial biomass production. This will, in turn, decrease the concentrations of ammonium/ammonia to less toxic levels, thus making water exchange unnecessary [14]. Total suspended solids (TSS) is another important water quality parameter whose concentration in aquatic ecosystems depends on the C/N ratio. Xu et al. [15] observed that a high C/N ratio (15:1 and 18:1) rapidly increased the TSS concentrations in water, which negatively affected the growth performance of *L. vannamei*. Moreover, the authors anticipated that production costs would be reduced under the C/N ratio of 12:1 compared to 15:1 and 18:1 due to reduced utilization of organic carbon, saving approximately 20,000 L of molasses per hectare of shrimp production at the same stocking density. Pérez-Fuentes et al. [16] also found that, under high-density cultivation of *O. niloticus* in a BFT system, C/N ratios exceeding 15:1 promoted the production of dissolved salts and settled biomass, which affected the growth performance of fish. The authors recommended a C/N ratio of 10:1 as the optimum condition for the production of *O. niloticus* reared under similar conditions. In another study, Silva et al. [17] also observed poor water quality (high TSS, turbidity, alkalinity, and settleable solids) at a C/N ratio of 20:1, which affected the growth performance of *O. niloticus*. Similar results have been reported in *Clarias gariepinus* [18][19]. However, Yu et al. [20], Haghparast et al. [21], and Wang et al. [22] reported better growth performance and immune stimulation in carp at high C/N ratios (20:1 and/or 25:1) reared in BFT. The discrepancy in results could be attributed to the difference in species and the source of organic carbon.

1.1.2. Source of Organic Carbon

Different carbon sources, such as molasses, glucose, cassava starch, cornmeal, wheat flour, sorghum meal, sugar bagasse, sugar, rice bran, ground bread crumb, glycerol, and anhydrous glucose, are used to enhance nutrient dynamics through an altered C/N ratio as well as improving the production of crustaceans and certain finfish species [20][23][24][25][26][27][28][29]. The efficient establishment of flocs by different carbon sources mainly depends on their carbon content and speed of degradation, hence indicating that certain carbon sources are more efficient in promoting floc formation than others. Generally, simple sugars such as molasses are degraded faster than complex sugars such as cassava starch, leading to improved water quality, as indicated by lower concentrations of ammonia and a higher growth rate of beneficial microbial biomass [2]. Molasses are the most widely used carbon sources in BFT systems during larval, nursery, and grow-out phases due to their efficiency in improving water quality for the sustainable production of aquatic species [2][30].

One of the most elegant flexibilities of BFT systems is the capability of reusing water-containing flocs for the production of certain detritivorous species under intensive cultivation. This practice aims to prevent the discharge of nutrient-rich wastewater into the environment, which might result in pollution. Liu et al. [31] conducted a 56-day experiment to elucidate the effect of no carbohydrate addition applied to control water quality in water-reusing BFT systems for tilapia (GIFT *Oreochromis niloticus*, 99.62 ± 7.34 g). Results indicated no significant difference in growth performance between fish culture in tanks with or without carbohydrate (glucose) addition, hence indicating the feasibility of no carbohydrate addition in water-reusing BFT systems for tilapia. Similar results have been obtained in *L. vannamei* juveniles (3.5 g) reared in a BFT system for 30 days [32].

2. Bioflocs as a Nutritious Food Source, for Dietary Protein Reduction, Compensatory Growth, and Productivity of Economically Important Aquatic Species

Bioflocs as a Nutritious Feed Source

One of the major challenges facing aquaculture producers is the high cost of aquaculture feeds. Protein levels and adequate amino acid balance are critical in aquaculture feeds due to their essential role in maintaining the growth and the general wellbeing of aquatic organisms. However, these nutrients are an expensive component of the feeds and hence influence their market price [33]. In tilapia, for example, feeding can account for 50% of the operational costs and could even reach higher levels with high-protein diets and/or inadequate protein [33][34]. However, this could be mitigated by feeding tilapia on alternative feed sources such as phytoplankton, zooplankton, and algae, whose nutritive content would enhance the growth, survival, and production of fish [35]. Avnimelech and Kochba [36] found that tilapia can uptake 240 mg N kg^{-1} of biofloc, which is equivalent to 25% of the protein in fish diets. Moreover, bioflocs can contain 20%–<40% crude protein, <1%–>8% lipids, <1%–>15% fiber, <18–>35% total carbohydrates, and <15%–>60% ash, thus providing an alternative feed source to the reared aquatic species [2].

It is worth noting that the nutritional value of bioflocs is highly dependent on the microbial community that encompasses it and, as mentioned in the previous section, certain factors such as carbon sources and C/N ratio influence the biochemical composition of bioflocs. For example, Moreno-Arias et al. [37] reported that the fatty acid and amino acid composition of both biofloc and shrimp cultivated in BFT systems depends on the composition of the aquaculture feed used. The use of plant-based protein sources in the feed is more favorable for biofloc systems and is considered to be more eco-friendly and sustainable. This is because their use reduces the release of phosphorous and nitrogenous wastes in the aquatic ecosystem as well as the dependency on overexploited marine sources [14][38]. The effect of biofloc feed on the general wellbeing and sustainable production of aquatic species is discussed below.

Emerenciano et al. [39] investigated the influence of BFT as a food source in a limited water exchange nursery system on the growth performance of pink shrimp (*Farfantepenaeus brasiliensis*) post-larvae. The authors reported that rearing post-larvae in the BFT system without commercial food supply did not affect the growth performance of the animals. Moreover, no significant differences in final biomass and weight gain were noted between shrimp reared in BFT with or without commercial diet supplementation. The good growth performance of the larvae was attributed to the diverse microbial community that consisted of protozoa grazers, rotifers, cyanobacteria, and diatoms, which were utilized as a food source. In another study, Emerenciano et al. [40] found no significant differences in the final biomass and survival of early post-larvae pink shrimp (*Farfantepenaeus paulensis*) reared in BFT with or without commercial feed supplementation. Emerenciano et al. [11] also observed no significant difference in spawning performance among females reared in BFT with or without feed supplementation. Zhang et al. [10] found that culturing gibel carp (*C. auratus gibelio* ♀ × *C. carpio* ♂, 6.4 ± 0.5 g) in BFT without feed addition for 30 days did not affect the growth performance (weight gain, specific growth, and survival) of fish. The fish were able to utilize the bioflocs as a feed, with increased digestive enzyme activity of pepsin and amylase noted in fish reared in water containing high TSS (300, 600, 800, and 1000 mg L^{-1} TSS). Furthermore, bioflocs enhanced the fish's innate immunity, as indicated by increased superoxide dismutase (SOD) and total antioxidant capacity (TAOC) activity in the skin and mucus. Upregulated immune-related genes included intelectin (ITLN), dual-specificity phosphatase 1 (DUSP 1), keratin 8 (KRT 8), myeloid-specific-peroxidase (MPO), c-type lysozyme (c-lys), and interleukin-11 (IL-11).

The nutritive content and quality of bioflocs are rich and, as such, bioflocs have been used as a cheaper and sustainable alternative to the highly expensive fishmeal. For example, in shrimp culture, 15% to 30% of conventional protein sources can be replaced by biofloc meal without negatively affecting the general wellbeing of the species [2]. The incorporation of biofloc meal in aquaculture indeed reduces the costs of production whilst permitting an intensive culture of species, hence maximizing profits. Several studies have shown that replacing fishmeal with biofloc meal alone or in combination with certain dietary sources such as lysine, soy protein concentrate, and protein hydrolysate improves the growth performance, survival, digestive enzyme activity, and immunity of the reared aquatic species [41][42][43][44][45][46][47][48].

Currently, more research studies in the field of pro- and prebiotic bioflocs are ongoing. Probiotics are beneficial microbes that are either added or naturally developed in the BFT system to stimulate the immune system for the reared aquatic species against biotic and abiotic stress. Several beneficial microorganisms, such as those from the Bacillaceae family, have been previously identified and isolated from the shrimp culture BFT system [49]. These bacteria have been used in the biocontrol of disease outbreaks caused by pathogenic microbes as well as immunostimulants for enhancing the general wellbeing of aquatic species. **Table 1** shows some of the conducted studies on probiotics in BFT systems included in animal diets or added directly into the rearing water for enhancement of the general wellbeing of the reared aquatic species.

Table 1. Some of the conducted studies on probiotics in BFT systems included in animal diets or added directly into the rearing water for enhancement of the general wellbeing of the reared aquatic species.

Aquatic Species	Probiotic Species	Dosage and Duration of Study	Observation	Reference
Litopenaeus vannamei	Altai™, Providencia, Santiago, Chile (*Bacillus subtilis*, *Bacillus*	10^9 CFU g^{-1}–45 days	↑ Growth and survival. ↓ Severe lesions in shrimp	Aguilera-Rivera et al.

Aquatic Species	Probiotic Species	Dosage and Duration of Study	Observation	Reference
	natto, *Bacillus megaterium*, *Lactobacillus acidophilus*, *Lactobacillus plantarum*, *Lactobacillus brevis*, *Lactobacillus casei*, and *Saccharomyces cerevisiae*)		tissues. ↓ Abundance of pathogenic bacteria.	[50]
Penaeus indicus	*Bacillus* sp.	5.4×10^9 CFU mL^{-1}–90 days	↑ Immunity	Panigrahi et al. [51]
Litopenaeus vannamei	*Bacillus* spp.	1×10^4 CFU mL^{-1}–42 days	↓ Abundance of pathogenic bacteria *Vibrio alginolyticus* (BCCM 2068). ↑ Immunity.	Ferreira et al. [52]
Litopenaeus vannamei	*Bacillus* sp.	1.5×10^8 CFU L^{-1}–95 days	↑ Microbial diversity of beneficial bacteria. ↓ Abundance of pathogenic bacteria.	Hu et al. [53]
Clarias gariepinus	*Bacillus* sp.	5×10^{10} CFU–60 days	↑ Growth performance, survival rate, and feed utilization.	Putra et al. [6]
Clarias gariepinus	*Bacillus cereus*	5 mg L^{-1}–35 days	↑ Growth performance.	Hapsari [54]
Oreochromis niloticus	*Bacillus* sp. *Rhodococcus* sp.	1×10^7 CFU mL^{-1}–60 days	↑ Survival.	Kathia et al. [55]
Oreochromis niloticus	Multi strain probiotics (*B. subtilis*, *L. plantarum*, *L. Rhamnosus*, *L. acidophilus*, *L. delbrueckii*)	10^8 CFU g^{-1}–112 days	↑ Immune response (serum protease, SOD, CAT, AP, MPO, and RBA activities). ↓ Mortality against *Aeromonas hydrophila* infection challenge.	Mohammadi et al. [56]
Oreochromis niloticus	*Bacillus* sp. *L. acidophilus*	10^7 bacteria mL^{-1}–8 weeks	↑ Survival percent and weight in fish fed on *Bacillus* sp. alone or probiotic mixture. ↑ Resistance against pathogenic bacteria.	Aly et al. [57]

Aquatic Species	Probiotic Species	Dosage and Duration of Study	Observation	Reference
Oreochromis niloticus	*Chlorella vulgaris* *Scenedesmus obliquus*	0.014 g L^{-1}–12 days	↔ Growth performance. ↑ Immune response.	Jung et al. [58]
Cyprinus carpio	*B. pumilus* *L. delbrueckii*	12.8 × 10^{8} cells ml^{-1} and 13.5 × 10^{8} cells mL^{-1}–60 days	↑ Development of suspended biomass in the BFT system. ↑ Immunity and disease resistance.	Dash et al. [59]

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