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Article *in* Journal of Agriculture and Food Research · March 2025

DOI: 10.1016/j.jafr.2025.101675

8 authors, including:

Benedict Terkula Iber
University of Agriculture

Hidayah Manan
Institute of Tropical Aquaculture and Fisheries (AKUATROP) Universiti Malaysia Te…

Nor Azman Kasan
University of Malaysia, Terengganu

Journal of Agriculture and Food Research 19 (2025) 101675

Contents lists available at ScienceDirect

Journal of Agriculture and Food Research

journal homepage: www.sciencedirect.com/journal/journal-of-agriculture-and-food-research

Application of Biofloc technology in shrimp aquaculture: A review on current practices, challenges, and future perspectives

Benedict Terkula Iber [a,b], Benjamin Chiaaondo Ikyo [d], Mohd Nazli Mohd Nor [a], Siti Rozaimah Sheik Abdullah [e], Muhammad Shukri Bin Shafie [c], Hidaya Manan [a], MHD. Ikhwanudin Abdullah [a], Nor Azman Kasan [a,*]

[a] Higher Institution Centre of Excellence (HICoE), Institute of Tropical Aquaculture and Fisheries (AKUATROP), Universiti Malaysia Terengganu, Kuala Nerus, 21030, Terengganu, Malaysia
[b] Department of Fisheries and Aquaculture, Joseph Sarwuan Tarka University (Formerly, Federal University of Agriculture Makurdi), P.M.B.2373, Makurdi, Benue State, Nigeria
[c] Serandu Aquaponic System SDN. BHD, Malaysia
[d] Nigerian Stored Products Research Institute, Portharcourt, Nigeria
[e] Department of Chemical and Process Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, UKM Bangi, 43600, Selangor Darul Ehsan, Malaysia

ARTICLE INFO

Keywords:
Disease control
Environmental impact
Microbial ecology
Nutrient cycling
Shrimp producing countries
Water quality

ABSTRACT

There are growing concerns on the dangerous footprints of shrimp aquaculture with stringent global regulatory policies on its operation eminent. Traditional aquaculture pays no attention to environmental degradation, water pollution, and overexploitation of natural resources. Biofloc technology (BFT) is a self-sustaining system that improves shrimp production while addressing challenges of the conventional systems. The technology creates a self-sustaining ecosystem, using microbial communities to transform waste into biofloc. This activity maintains water quality while the nutrient-rich biofloc serves as natural food source for shrimp, thereby decreasing dependence on external feed inputs. Maintenance of carbon-to-nitrogen (C: N) ratio for growth and proliferation of heterotrophic bacteria forms the hallmark of the operational principle of the system. Many studies have shown improved growth rate, feed conversion ratio (FCR), feed conversion efficiency (FCE) overall health of shrimp reared under BFT. The zero water exchange advantage of the system makes it bio-secured with reduced incidence of disease. Nevertheless, challenges like high initial costs, alternative carbon sources, market acceptability, system standardization and the complexity of managing microbial communities stands in the way of its widescale adoption. Ongoing research aim to optimize BFT systems via advanced monitoring technologies, exploration of low-cost alternative carbon sources and integration with alternative protein sources and probiotics. In this direction, China, Turkey, Brazil, India and Israel have featured prominently in advancing these technologies. This review synthesizes current practices, challenges, and future perspectives of BFT in shrimp aquaculture, highlighting its potential to enhance sustainability and align with global food security goals.

1. Introduction

BFT has expressed itself as an innovative tool for shrimp aquaculture. The rapid expansion of aquaculture industry is also accompanied with sustainability challenges which BFT tends to address [1,2]. Some of the reoccurring challenges faced by traditional aquaculture practitioners include environmental degradation, water pollution as well as overexploitation of natural feedstocks for use in feed production [97]. These challenges are worrisome especially as global seafood demands escalates. BFT is a system that is self-sustaining; an ecosystem that leverages on microbial associations to form biofloc from organic waste in a culture system. In shrimp production, the biofloc is utilized as natural food for cultured shrimps. The feed supplementation provided by the biofloc minimizes dependence on external feed inputs thereby reducing impacts on environment in addition to economic benefits [1–4,4,6].

As at today, the study and application of BFT is conducted in many regions of the world. However, the comprehension of C:N ratio and its role in water quality improvement as well as microbial stability which

* Corresponding author.
E-mail address: norazman@umt.edu.my (N.A. Kasan).

https://doi.org/10.1016/j.jafr.2025.101675
Received 22 September 2024; Received in revised form 3 January 2025; Accepted 20 January 2025
Available online 22 January 2025

was pioneered by Avnimelech [7] is hard to miss. In the early 2011, the effect of biofloc on the early stage of post larval pink shrimp (*Farfantepenaeus paulensis*) with respect to growth performance, floc composition and salinity stress tolerance was studies. In this research, the dynamism of microbial interaction vi-a-vis nutrient cycling within Biofloc became fully understood [8]. These studies laid the foundation to further comprehending the main principle behind BFT and its broad applicability. Nevertheless, the none uniformity in the global adoption of BFT has seen regions East Asia, Egypt and South America recording tremendous progress while those of India, China, Turkey and Iran are often overlooked. This variation is often associated with challenges peculiar to certain regions that may not be experienced in others. For instance, water management challenges, presence of cost-effective carbon sources and species-specific adaptation are among the issues hindering regional and wide scale adoption of BFT.

The basic principle behind successful operation of BFT lies in optimal carbon-to-nitrogen (C/N) maintenance. This is usually achieved by carbon source addition to encourage proliferation of heterotrophic bacteria [1,2,4,4,6]. These bacteria are known for their ability to remove nitrogenous waste products from the culture system. While this waste reduction leads to water quality improvement, the high-quality microbial protein is further utilized by shrimp for healthy growth [9,10]. Studies have shown that BFT has the ability to improve shrimp growth, FCR, FCE and general biomass production. This has further portrayed the technology as economically viable and more sustainable compared to traditional aquaculture practices [11].According to Raza et al. [10], BFT has demonstrated capacity in reducing environmental impacts arising from aquaculture operations. The environmental impact mitigation is achieved by water resource conservation through reduced water exchange and low effluent discharge. Moreso, incorporation of BFT in shrimp aquaculture improves biosecurity due to low risk of pathogen introduction via water exchange [12,13]. Ekasari et al. [14] reported that BFT could improve the immune response of shrimp, thereby increasing disease resistance and reducing the need for antibiotics as compare to those reared in clear water. Notwithstanding its numerous benefits, BFT implementation in shrimp aquaculture is faced with quite daunting challenges. Issues like high-cost initial setup, energy demands, and the management of microbial communities can deter widespread adoption of the technology [6,12,15,16]. Furthermore, the risk of disease outbreaks from opportunistic pathogens has warranted careful management of stocking densities and Biofloc composition [14]. In this direction, Khanjani et al. [6] suggested inclusion of advanced monitoring technologies and automation systems to improve BFT management precision. In addition, Chakrapani et al. [15] demonstrated the potential of combining with alternative protein sources and probiotics, to decrease costs and improve system resilience.

This review aims to synthesize current practices in the application of BFT in shrimp aquaculture. To critically explore the challenges faced by shrimp farmers and future perspectives for improving the efficacy and technology adoption. By integrating recent scientific findings and industry insights, this paper provides a comprehensive understanding of the role of BFT in enhancing sustainable aquaculture practices that align with global food security goals.

2. Fundamentals of Biofloc technology

2.1. Definition and principles of BFT

BFT is an innovative and environmentally friendly aquaculture system that utilizes the natural growth of microbial communities to improve water quality while making available nutritional benefits to cultured aquatic organisms [10]. This technology is a holistic approach to sustainable aquaculture that addresses critical issues related to conventional aquaculture practices like excessive feed costs, water pollution, and reliance on finite natural resources. BFT takes advantage of the microbial-rich environment within the culture system to recycle excess nutrient and create a self-sustaining feed resource. This leads to a reduction in the need for external feed inputs and environmental impacts typically known in conventional aquaculture [17–19,19].

The core operating principle lies in the conversion of nitrogenous compounds like ammonia, nitrites, and nitrates, into microbial biomass by heterotrophic bacteria [2] Click or tap here to enter text. These bacteria utilize carbon sources to convert nitrogenous wastes into microbial protein. The resulting biofloc is made up of aggregated microorganisms, organic matter, and detritus becomes a nutrient-rich food source for cultured species. Consumption of this composite material improves their growth performance, health, and survival rates. Therefore, the system supports a balanced ecosystem within the aquaculture environment and significantly decreases the dependency on commercial feed. Apart from reduced environmental burden, decreased commercial feed dependency has economic benefits due to lower production cost [21,22].

In order to optimize microbial growth and activity, BFT maintains a balanced C: N ration [21]. Previous studies have reported that C:N ratio of10:1 to 15:1 is suitable for efficient microbial protein synthesis and effective assimilation of nitrogenous waste products [97]. To keep the ratio constant, organic substances like molasses, sugar or any other carbohydrate base material are added as carbon sources to encourage proliferation of heterotrophic bacteria [23,24]. To maintain microbial community health and productivity, good C: N management is critical. This also keeps at bay nitrogenous compounds accumulation in the water that would have impacted the living condition of culture species.

BFT systems are characterized by high stocking density, continuous aeration and reduced water exchange which differs from the conventional aquaculture practices [25]. The microbial interactions in the system encourages nutrient cycling and waste management to neutralize the effect of high stocking density. This arrangement is useful for effective management of space and resources [26]. The essence of continuous aeration is to keep at optimum the DO level which is required for microbial activities. Optimum microbial activities and interaction keeps in check the creation of anaerobic layers that could form deleterious by-products like hydrogen sulphide [27]. One outstanding advantage of BFT is the reduced environmental footprint through minimal or zero water exchange. The system emphasizes minimal discharge of nutrient-rich effluent to the environment that would have negatively impacted surrounding ecosystems [26,28]. Mansour et al. [29], Mansour et al. [29] reported that BFT was able to significantly lower FCR in Tilapia, leading to reduced cost of feeding and higher return on investment of the farm operation. Similarly, Xu et al. [31] demonstrated that shrimp cultured in BFT systems showed higher growth rates, better feed efficiency, and higher disease resistance as opposed to traditional system. These findings further demonstrate the potential of BFT to improving sustainability and profitability of aquaculture operations.

Furthermore, studies by Mansour et al. [29], Mansour et al. [29] revealed that BFT cultured shrimps showed better immune response and disease resistance. This is attributed to the Biofloc consumed which contained essential nutrients, probiotics, and immunostimulants that helped to enhance the overall health and resilience of the shrimp [32,98]. Nevertheless, other studies have reported that management of microbial community, optimal water quality parameters maintenance, and regulation of floc aggregation to prevent overaccumulation are important for careful monitoring and technical expertise in BFT [33]. In addition, continuous aeration comes with extra energy demand. This in addition to initial start-up cost has constantly stood in the way for widespread adoption of BFT, especially by small scale farmers [34,35].

These hurdles in BFT adoption could be handled by direction research efforts on optimizing the system for diverse culture species and environments. Also, improvement of automated monitoring systems, exploring alternative carbon sources as well as incorporation of the system with other sustainable operations like integrated multi-trophic aquaculture (IMTA) should be stepped up to enhance the efficiency and scalability [31,36]. According to Kumar et al. [36], locally available and low-cost carbon sources can be explored to minimize operational cost of BFT operations. Also, the effectiveness of incorporation of BFT with IMTA has been encouraged and believed to provide a more resilient and sustainable culture system [34].

2.2. Mechanisms of Biofloc formation and its role in nutrient cycling

The formation of biofloc is intricate, dynamic and specifically made possible by the interaction between organic matter, physical substrates, and different array of microorganisms. These include bacteria, phytoplankton, protozoa, and small invertebrates [32]. At the onset of the process, there is aggregation of organic waste containing unconsumed feed, faecal matter and other detritus in the system. The continuous build-up of the waste leads to leads to proliferation of heterotrophic bacteria [1,2,6]; Mansour et al. [29], Mansour et al. [29,37]. This bacterium consumes the organic carbon in the waste which is fuel needed for nitrogenous waste assimilation. During this process toxic ammonia and nitrite are digested into a nutrient-rich microbial biomass [38]. In most cases, there is need for inclusion of external carbon source like molasses, starch, or sugar, to optimize the C:N ratio to enhance bacteria growth [39]. The resultant nutrient-rich biomass (biofloc) often serves as alternative feed source for shrimps. The diversity and complex nature of Biofloc comprises bacteria, algae, protozoa, and other microorganisms which together form an aggregate of organic matter and extracellular polymeric substances (EPS). These aggregate forms the core component of the system and responsible water quality regulation while serving as nutrient source [40,41].

2.2.1. Nutritional role of Biofloc

Over the years, many studies have been conducted to establish the significant nutritional benefits of Biofloc to culture organisms [32]. It has so far shown excellence in improving the overall nutritional profile of the aquaculture environment. Biofloc contains protein that is high in essential amino acids that are critical for shrimp growth and development. Furthermore, studies have also demonstrated the presence of various vitamins, fatty acids, and other micronutrients that are vital for shrimp health and wellbeing [42]. To further establish the nutritional capacity of Biofloc in shrimp culture, numerous researches have been conducted where in most cases superior growth performance, better FCR, and better overall health compared to traditional aquaculture systems were reported. Xu et al. [31] reported significant higher growth rates and feed efficiency in Pacific white shrimp (*Litopenaeus vannamei*) cultured in biofloc systems as compared to clear water system. Similarly, Kumar et al. [36] noted that tilapia culture under biofloc exhibited improved growth performance and survival rates. These were a clear demonstration of the potential of biofloc as a sustainable feed alternative.

2.2.2. Role of Biofloc in nutrient cycling and water quality management

The benefits of biofloc system extends beyond nutritional boundaries to include nutrient cycling and water quality management [32,99]. The complex interaction of microorganisms assimilates and transform toxic nitrogenous wastes into safer forms. For instance, ammonia and nitrite are effectively neutralized and made less harmful to culture species [43]. In specific terms, ammonia is first assimilated by heterotrophic bacteria within the biofloc and later converted to microbial proteins [44]. Furthermore, during nitrification by autotrophic bacteria, ammonia is oxidized into nitrite and further to nitrate. The nitrate formed due to the activities of Nitrosomonas and Nitrobacter (autotrophs) is known to be less toxic to culture animals and can be better managed [45,46].

Therefore, biofloc helps to enhance a stable culture system due to its capacity to regulate ammonia and nitrite levels. Regulation of the build-up of toxic ammonia and nitrite in the system leads to less need for regular culture water exchange. This does not only conserve water resource but also reduces environmental impact of aquaculture operations [4]. Conservation of water resource is especially crucial in regions where water scarcity is a concern. In addition, biofloc also provides a pH stable system through microbial activities. The stable pH helps in decreasing build-up of harmful substances like hydrogen sulphide which pose as by-products of organic matter decomposition. These by-products are capable of creating anaerobic layers in the system if not kept in checks. Anaerobic zones are also prevented by continuous aeration of the system.

2.2.3. Previous studies supporting the role of Biofloc in aquaculture

Due to the numerous benefits of BFT, researchers in related fields have undertaken several studies to assess its potential in diverse aquaculture operations. In this direction, the effectiveness of BFT in sustainable shrimp culture was examined by Ahmad et al. [28] who agreed that the system successfully kept water quality parameters in check while enhancing shrimp growth rate and survival. The authors further emphasized that keeping the C:N ratio optimal by supplementation of system with molasses as external carbon source was crucial for biofloc formation. In tilapia culture, Gallardo-Collí et al. [26] reported that BFT contributed to significant improvement in feed efficiency and nutrient utilization, thereby leading to a reduction in feed cost. A decrease in feed cost makes the system a sustainable alternative to traditional feed practices especially to low-income farmers. Ray et al. [34] experimented on the prospects of combining BFT with IMTA and reported better nutrient cycling and decreased environmental footprint of aquaculture operations.

2.3. Comparison of BFT with traditional aquaculture systems

Aquaculture operations using BFT and traditional practices vary in their operational methodologies, environmental impacts, and economic viability as summarized in Table 1. The distinctions emphasize the potential of BFT as a sustainable approach within the aquaculture industry with a poise to changing the tide of the numerous challenges affecting the conventional systems.

Table 1
Major difference between traditional and biofloc aquaculture systems.

Parameter	Conventional Aquaculture Systems	BFT Systems
Water Exchange	High (50–100 % of tank volume per day)	A closed loop system with minimal to no water exchange
Water Usage	High water usage, leads to freshwater depletion	Low water usage, freshwater resources are conserved
Waste Management	Filtration and/or high-water exchange are to dilute waste	Organic wastes are recycled into biofloc, less need for water exchange
FCR	1.5–2.0 reported (depends on species and system)	1.2–1.5 reported in shrimp (due to biofloc consumption)
Stocking Density	Usually lower (5–10 shrimp/m^2 depending on species)	Higher density of up to 400 shrimp/m^2 with good system management
Environmental Impact	Eutrophication from high nutrient discharge	Low risk of eutrophication due to minimal waste discharge
Energy Use	Varies with system but significant pumping and aeration may apply	Higher energy demand for aeration
Economic Viability	Higher feed and water costs leads to lower productivity	biofloc supplementation reduced feed costs, improved production efficiency
Space	Require large space (especially in large scale operations)	Higher productivity with relatively space requirement
Species diversity	Many species have so far been tried	Still evolving, only a few species have shown success
Technicality and sophistication	Though output may be low, it is relatively simple to practice	Requires training and requisite knowledge to manage

[1,5,7,8,82–84]

2.3.1. Operational practices

Conventional aquaculture farming mostly relies on high water exchange rates to contend with the toxic effects of ammonia and nitrite, and to ultimately keep water quality parameters within acceptable limits [14]. The continuous input of fresh water into the system is intended to dilute the toxic effects of waste and keep culture animals healthy. The major disadvantage of this practice is the gross depletion of natural water resources and constant pouring of nutrient-rich effluent into adjacent environment with significant impacts on the ecosystems thereof [12,15]. Eutrophication is usually the major environmental issue associated with the continuous discharge of wastewater rich nutrient, uneaten feed and other organic pollutants. This situation creates favourable environment for harmful algal blooms to flourish, leading to aquatic habitat degradation. On the other hand, BFT provides a system that recycle these excess nutrients in effluent (a closed-loop system). The conversion of accumulated waste into biofloc through the interaction of diverse microbial communities makes the system to self-regulate water quality other than depend on external fresh water exchange [11,16]. The resultant biofloc serves a dual purpose of water quality maintenance and nutritional benefits as well as health [9].

2.3.2. Environmental impacts of BFT

Biofloc technology has demonstrated high potential in taming the dangerous environmental footprints of aquaculture from conventional practices. Introduction of aquaculture effluent into the environment has the potential of altering the habitats of such ecosystems where succeeding species may not be beneficial [47]. Algal blooms from excess nutrients create dead zones in receiving water bodies and may lead to fish die-offs. These and many other challenges have put to question the sustainability of traditional aquaculture practices. According to Abakari et al. [45] BFT system has the capacity to minimize nutrient loading because at least 90 % of the accumulated waste are assimilated. Therefore, the system contributes in preserving the ecological balance of adjacent natural ecosystems rather than degrade them. The provision of a more stable culture system by BFT helps to keep water quality parameters in check such that the little percentage water that may escape does not have significant alterations on the chemistry of the receiving water bodies [48,49]. Furthermore, the stable system prevents proliferation of pathogenic diseases. This does not only improve productivity but also makes the culture water safe for the environment. The ability of BFT to maintain a disease-free culture system was examined by Ahmad et al. [28] who reported reduced incidence of disease in shrimp cultured under biofloc as compared to clear water. This result was attributed to the combined effect of better water quality and probiotic effects produced by microorganisms in the biofloc.

2.3.3. Economic viability of BFT

The numerous advantages of biofloc have placed it in an economically vantage position for sustainable aquaculture operations. The major economic advantage comes from reduced feed cost which is the major component of the cost of production. Reduction in feed cost by application of BFT is made possible due to its dual purpose as waste management and feed supplement [9]. Studies have shown that the high nutrient levels in microbial protein are capable of replacing commercial feed which are often expensive and beyond the reach of low-income farmers ([10,10], Kuhn et al. [25] partially replaced commercial feed with biofloc in the culture of Litopenaeus vannamei and revealed that higher yields and survival in BFT led to increased return on investment (RIO). The efficiency of BFT in managing water quality and disease has created opportunities for high stocking densities of shrimps, leading to higher sales. With the system, shrimps can be stocked at higher densities without compromising water quality, thus increased biomass production in shrimp aquaculture operation. According to Kuhn et al. [25], tilapia species were stocked up to 50 % higher in biofloc than conventional system and yet higher production volumes and revenues were realized from the formal.

Be that as may, one of the major economic challenges of BFT comes from initial set up and energy requirement. This has constantly stood in the way of wide scale adoption of the system especially in developing regions with scarce infrastructure [3]. For optimum microbial activity, continuous aeration requires expensive equipment and energy, leading to high operational cost [51]. Therefore, it has become necessary to step up research to overcome these barriers to enhance BFT adoption. In this direction, there has been innovations in developing aeration systems that are energy efficient as well as discovery of low-cost alternative carbon sources [52]. In addition, studies have also focused on incorporation of renewable energy like solar and wind in attempt to augment the energy need of the system. This is intended to decrease operating cost and improve economic viability of BFT [10]. Recently, combination of BFT with IMTA has been explored to maximize resource efficiency and sustainability. Optimization of nutrient cycling has been achieved with co-culture of shrimp with seaweed where environmental impact of the system was significantly reduced. According to Kasan et al. [3], integration of BFT with IMTA was more sustainable and profitable where the waste product from species serves as beneficial input to the other.

3. Current practices in Shrimp aquaculture using BFT

Over the years, BFT has been utilized in shrimp aquaculture to achieve high productivity and solve critical environmental challenges across different continents. It is particularly considered a sustainable approach with a conscious balance between yield and environmental impact [22]. In the Eastern part of Asia, China las led in the development of large-scale commercial BFT system. Studies in this region have so far made significant contributions to water quality management and incorporation of rice bran and molasses in BFT as low carbon sources [53–55]. Currently, China has incorporated automated water quality monitoring systems to large-scale shrimp farms in order to cut down cost of labour [56]. Shrimp farming operations using biofloc are designed to encourage self-sustaining ecosystem with microbial communities converting uneaten feed and faecal droppings into biofloc [21,24]. Just like any other culture species, shrimp biofloc contains aggregate of bacteria, algae, protozoa and particulate organic materials. Application of BFT encourages high stocking of shrimp post larval within a small space without consequences of water quality deterioration and disease outbreaks. This decreases s need for continuous water exchange and environmental impacts peculiar to conventional systems.

In India, the Indian Council of Agricultural Research (ICAR), is actively involved in the promotion of BFT. Currently, studies on optimization of tapioca starch and molasses as alternative carbon sources are being undertaken [57–59]. The reason for investment in this line of research by ICAR is to showcase the cost effectiveness of BFT in India, especially to coastal and inland farmers. Furthermore, significant levels of adoption of BFT in shrimp farming has also been witnessed in Brazil, especially in the northeastern part where the local economy is experiencing a boost from shrimp farming. Similar to India and other regions, Brazilian researchers are exploring agricultural waste and biochar as alternative carbon sources [60–63]. As a modern way of efficient resource utilization in BFT, Turkey has stepped forward in the use of IMTA, raising shrimps alongside other fish species in order to maximize nutrient cycling [64–66]. Iran is known for its abundant coastal regions and have recently been utilized for BFT in brackish water systems. As a semi-arid region, the lack of freshwater has further made biofloc a cherished technology with which high shrimp outputs can be obtained with little or no water exchange [67,68]. For instance, *Litopenaeus vannamei* was stocked at high densities in a Mixotrophic biofloc Nursery System for 21 days and evaluated for Water Quality and Growth Performance. Although final body weight, weight gain, weekly growth rate, and specific growth rate were not affected, survival rate in biofloc system stocked at 5000 PL/m^3 was high at the end of culture without water quality issues [69].

3.1. System design and management

Recently, tank design and aeration are considered critical to the success of shrimp aquaculture using BFT [25]. To ensure optimal water circulation and mixing, circular or rectangular tanks are used. In most cases, the use of circular tanks is preferred due to the uniform water movement experienced with them. This prevents creation of dead zones in the system where anaerobic degradation of biofloc may occur. Nevertheless, where rectangular tanks are carefully designed with proper aeration and water movement, they may also be utilized [28]. It is important to keep the system constantly aerated to maintain water quality and to keep the floc in perpetual suspension in the water column. The major reason for keeping floc in suspension is so they may be readily accessible for shrimp consumption. Sufficient system aeration may be achieved in the system through paddlewheels, air diffusers, or a combination of both. Often considered as more effective are the paddlewheels which create horizontal water movement that prevent biofloc settling. On the other hand, air diffusers keep oxygen levels optimal for shrimp and aerobic microbial growth through vertical mixing [33–35].

To enhance shrimp growth and health, tanks are carefully designed, taking into account the high stocking densities associated with BFT systems. Depending on the species and growth stage, the efficient nature of BFT can accommodate 100 to 450 shrimp per cubic meter. High density shrimp stocking systems are susceptible to stress and disease, therefore, effective management of water quality parameters such as dissolved oxygen, ammonia, and nitrite levels must be in place So far many studies have reported that significant increase in shrimp survival and overall system productivity can be achieved through maintenance of optimal water quality through effective aeration and biofloc management [3,23,26,34].

The growth performance and economic fortunes of shrimp farming are directly impacted by stocking density (Kh). Many studies have reported stocking density of over 400 shrimp per square meter Mansour et al. [29], Mansour et al. [29,35,37]. Despite this, improved growth rates and FCR were not affected, making shrimp farming in BFT a profitable venture. Khanjani et ai., (2022) improved water quality indices, growth performance and survival rates in post larvae (PL) of banana shrimp (*Fenneropenaeus merguiensis*) stocked at 1000 shrimps/m^3 and reared for 32 days. It has also been reported that BFT could reduce feed cost of over 33 % during the culture of *Litopenaeus vannamei* by many other related studies [39,41,43] leading to higher income to farmers. It is pertinent to note that, balancing of carbohydrate-to-protein ratio is vital as carbohydrate contributes to stimulating microbial growth and biofloc production. Shrimp feed that are high in carbohydrate could promote proliferation of heterotrophic bacteria that are responsible for conversion of nitrogenous waste into microbial biomass. The continuous elimination of nitrogenous waste and availability of floc for shrimp consumption helps keeps the system healthy [44].

3.2. Composition of Biofloc and their nutritional value

Biofloc is a complex mixture of microorganisms (bacteria, algae, protozoa), and organic matter. Biofloc composition and nutritional make up depends on added external carbon sources and the protein level of shrimp diet [37]. Studies have shown that biofloc also contain high inorganic materials where ash contents after complete combustion ranges between 591.0 and 649.2 g/kg [70]. Whereas, the crude protein levels could extend from 95.9 to 137.3 g/kg. These studies all agreed that carbon sources like sugarcane bagasse or wheat flour as well as the conditions under which the biofloc are produced could influence its variation Mansour et al. [29], Mansour et al. [29]. Biofloc lipid is responsible for its overall energy value and could also be considered as a nutritional component. Over 78.9 % apparent digestibility coefficient of biofloc lipid has been reported (Khanjani et al., 2024). The diverse microbial composition of biofloc provides required trace minerals, vitamins, and other micronutrients vital for shrimp growth and overall health [39]. Moreso, there is significant increase in heterotrophic bacteria count when wheat flour is added as external carbon source. This leads to improved growth performance in shrimp.

3.3. Some successful examples of BFT in Shrimp farms

Adoption of BFT in shrimp aquaculture worldwide to harness its numerous benefits has been reported. This has helps in unravelling the potentials of the system in promoting both productivity and sustainability across different geographical regions.

3.3.1. Egypt

Application of BFT for the culture of *Litopenaeus vannamei* was carried out at the National Institute of Oceanography and Fisheries, Egypt where significant growth performance was recorded. Higher final shrimp weight and biomass were obtained compared to the conventional system [16]. In another development, post larvae of green tiger shrimp (*Penaeus semisulcatus*) was subjected to varying levels of protein level in the presence or absence of biofloc in an on-farm trial. The intensive culture was tested for water quality, shrimp survival and growth rate. It was observed that significant decreases in nitrate, nitrite-N, and total ammonia nitrogen occurred between BFT system and normal culture [71]. Although BFT systems are known for high stocking densities, recent trial on *L. vannamei* showed that higher growth performance and gene expression associated with immune function and stress resistance were recorded at 100 shrimp/m^2 than 300 shrimp/m^2 [72].

3.3.2. Brazil

A review of related literature has revealed that Brazil is among the leading countries in adoption of BFT for shrimp culture. Several related studies have been traced to Brazil with special focus in areas like nitrogen transformation, biofloc microbiology, and immunostimulant properties of biofloc [19]. In addition, the notion that shrimp output in biofloc systems also varies with species has also been examined by Brazilian researchers. In a study carried out at the Federal University of Rio Grande, *Farfantepenaeus brasiliensis* and *Litopenaeus vannamei* were compared where biofloc was administered as supplementary feed to both shrimp species. It was revealed that *L. vannamei* demonstrated better utilization of biofloc thereby showing greater zootechnical performance [73–75]. Furthermore, attempts have also been made in comparing different sources of carbon as external organic source in biofloc system. It was reported that wheat flour enhanced the nutritional value of biofloc, leading to improved growth rates and feed efficiency in Brazilian shrimp farms [19,19,74,75].

3.3.3. Indonesia

As one of the major world producers of shrimp, Indonesia is not left behind in exploring the numerous benefits of BFT with many testimonies affirming increased shrimp survival rates and minimized feed cost. Utilization of biofloc as supplementary feed has lessen dependency on commercial feed, thereby making the technology economically attractive [76]. The culture of white-leg shrimp was carried out on a household-scale using BFT system in Pangkalpinang City, Bangka Belitung Islands Province, Indonesia to determine its economic efficiency. This study reported an average yield per cycle of 1.8 tons and 2.39 [77]. While the study affirmed the feasibility and cost effectiveness of BFT, especially in coastal shrimp farming, it also emphasized that choice of organic carbon is vital in system performance optimization. Relatedly, the impact of different carbon sources on the quality of biofloc and shrimp growth were also examined. The comparison of dextrose, potato starch and α-cellulose revealed that complex carbohydrate like cellulose demonstrated higher ability to improve biofloc performance thereby resulting to decreased TAN and nitrite levels (Fitriani and Kustono, 2020). High biofloc volumes is not always desirable and can cause stress in shrimp as was the case with dextrose as carbon source.

3.3.4. India

In India, the focus on incorporating probiotics with BFT has yielded favourable results in the improvement of water quality and shrimp growth performance [78]. In this direction, molasses and maize flour were utilized as external carbon sources to combine with probiotics of *Bacillus licheniformis* and *Lactobacillus rhamnosus.* As expected, there was improved water quality, shrimp growth and general productivity. Specifically, the system was able to keep DO levels within 6.25–6.75 mg/L and 27–28 °C temperature which were considered conducive for shrimp growth [19]. Although BFT is quite effective for high stocking density shrimp farming, studies have consistently demonstrated that lower stocking densities make the system to function most efficiently. Different stocking densities of *Macrobrachium rosenbergii* were tested in biofloc system conducted in Ramayapatnam, Prakasam District of Andhra Pradesh, India. Prawns were stocked at 50, 70 and 90 prawns/m^2 and reared for 180 days. Highest growth performance, weight gain, FCR, and survival rates were obtained from the lowest stocking density (Reddy and Sharma, 2020).

4. Challenges in the application of Biofloc technology

The general and widespread adoption of BFT across various regions of the world if faced with challenges which are often categorised into technical, biological, and economic aspects. Each of these presents unique hurdles that must be addressed via research, innovation, and targeted management strategies.

4.1. Technical challenges

4.1.1. High energy requirements and operational costs

Many studies on the technical challenges hindering adoption of BFT have often converged on the high energy demand of the system-to-system conditions optimal [79–81]. The high energy is needed to suspend floc and maintain oxygen levels for shrimp health and biofloc formation. This makes up a significant part of the operational cost. According to Lima et al. [24], energy demand in BFT can account for over 30 % of the cost of production thereby making the practice unsustainable especially in countries struggling with high electricity tariffs. Furthermore, technological infrastructures like automated systems used for monitoring water quality parameters and microbial analysis are lacking in countries like India and Iran. Recently, the development of automated systems to monitor important water quality parameters like pH, DO and ammonia by Chinese researchers has been considered a major breakthrough. These discoveries were made possible due the advancements in Internet of Things (IoT) technologies and machine learning (Li et al., 2023).

4.1.2. Management of water quality and microbial dynamics

The growth and proliferation of beneficial heterotrophic bacteria in biofloc system is important to maintain water quality parameters and shrimp health. Imbalances in microbial community would lead to build up of toxic nitrogenous waste that could lead to stress, disease and poor growth [82,83]. Studies have shown that maintaining C:N ratio is vital and has direct impact on the biofloc quality which in turn influences microbial dynamics. Poor biofloc quality leads to flourishing of rather harmful pathogens with disease implications. Microbial dynamism and water quality in BFT complement each other and many researchers have made several attempts to balance the two. Bacterial inoculums comprising *Bacillus subtilis*, *Pseudomonas* species, and *Saccharomyces cerevisiae* was applied in the culture of *Heteropneustes fossilis* under BFT condition. Results showed great improvement in water quality, biofloc microbiota and gut health of the species. It was revealed that the inoculum functioned specifically in growth improvement, better gut histomorphology and enzymatic activities like amylase, protease and lipase. In addition, further investigation showed a favourable boost in immune gene expression and antioxidative responses as well as enhancement of specific and non-specific immune responses [83].

It has been reported that beneficial microorganisms like *Bacillus* sp., *Lecane* sp., and *Pseudomonas* sp., are specifically involved in breakdown of waste and nutrient cycling that helps in maintaining water quality parameters and also stabilizes culture systems. On the other hand, *Bacillus* sp., *Lecane* sp., and *Pseudomonas* sp., are pathogenic in nature and their development and proliferation is associated with sub-optimal water quality conditions [84]. In a study where BFT system was compared with traditional continuous flow system for culture of *Anguilla japonica*, biofloc system showed a greater diversity of microbiota. This directly impacted pH, total ammonia and nitrite concentrations. In addition, the system showed a more diverse and stable microbial community that significantly reduced sulphur compounds oxidation and chitinolysis [14,85].

4.2. Biological challenges

4.2.1. Risks of disease outbreaks and pathogen management

BFT is widely associated with high stocking density which makes the system prone to incidence of disease attack from pathogenic bacteria. It is worthy of notes that BFT systems are not exclusive to beneficial bacteria, the nutrient-rich system is also home to opportunistic bacteria like *Vibrio species* [84]. These bacteria also compete for the nutrient to proliferate, posing a significant health threat to the culture shrimp. BFT is a closed system that keeps shrimps on close proximity. This arrangement favours rapid spread of disease when occurred (Khanjani et al., 2024. Recent studies have suggested use of probiotics and improved biosecurity as some of the majors to control disease outbreaks in BFT systems. Nevertheless, management efforts are often frustrated due to the fact that microbial population growth and proliferation in BFT is highly variable and unpredictable. This has made consistent and effective pathogen control strategies impossible. Further studies are recommended to comprehend microbial ecology of BFT system in order to come up with targeted intervention strategies [33,86]. Kaya et al. (2020) studied biofloc technology in recirculating aquaculture system as a culture model for *Penaeus semisulcatus* where effects of different feeding rates and stocking densities were evaluated. The research revealed that shrimp species respond differently to BFT systems. The authors observed that *Penaeus vannamei* is the most widely studies shrimp species where most of the information on shrimp farming under biofloc system can be traced to. Furthermore, shrimp species like *Penaeus japonicus* and *Macrobrachium rosenbergii* have different management approach. Research is therefore in the direction of adapting BFT to different species of shrimp especially in regions where many species are cultivated. It is also important to understand the factors responsible for the variation in the adaptability of biofloc system by different shrimp species.

4.2.2. Variability in Biofloc quality and its impact on Shrimp health

Biofloc quality is often measured in terms of its nutrient levels and mostly affected by C:N ratio balance, source of external alternative carbon and system management [36]. Biofloc inconsistency impact not only shrimp growth performance but also health and efficiency of the production. The variation in the nutritional profile of biofloc due to changes in carbon inputs were tested by [19,19]. This led to differences in microbial composition and subsequent impact on the growth and health of shrimps. This study showed that to achieve better shrimp growth performance, careful attention must be paid on nutritional profile optimization of biofloc systems. As at today, obtaining a consistent floc quality still remains a major problem in large-scale operations with widely varied environmental conditions.

4.3. Economic challenges

4.3.1. Initial investment costs and economic viability

In small-scale shrimp farming operations, initial set up cost of BFT is usually a major setback since most of the farmers may lack the requisite knowledge or collateral to obtain and manage loans [62,73,77,87]. BFT infrastructure and equipment are expensive especially when ventured into on a large scale. Consequently, the viability of the system is often criticized in terms profitability as compared to the conventional approach. Hargreaves et al. (2024) reported that start-up cost, energy requirement and labour could take back a greater portion of the supposed profit, leading to a low ROI. Recent studies have shown that the potential for long-term cost saving, achieved by decreased feed cost and higher shrimp growth rates notwithstanding, the lack of affordable capital makes setting up and maintaining BFT a far distant dream. Therefore, research towards developing cost-effective systems and operation processes like energy-efficient aerators and low-cost monitoring equipment have been encouraged [3,39].

Furthermore, developing countries are continuously faced with the challenge of finding cost-effective sources of carbon for application in BFT. Although molasses and rice bran have become common in regions like China and India, other sources such as agricultural waste and algae-based products are also being explored [57,59]. Nevertheless, the economic viability of these alternatives carbon sources as well as arriving at region-specific effective sources still remains a major challenge today. In Brazil, agricultural by-products such as sugarcane molasses and coconut husk have utilized in recent times in attempt finding low-cost effectives carbon sources. Although these by-products showed promising outcomes, they have not been optimized for different shrimp species.

4.3.2. *Market acceptance and consumer perception of BFT Shrimp*

Shrimps produced under BFT faces another problem of market and consumer acceptance due to poor awareness thereby posing significant economic challenge [87,88]. Often time, BFT produced shrimps experience low demand and market pricing duet to scepticism by consumers as to the quality and safety of such products. In a recent survey carried out in Vietnam, Nguyen et al. (2023) reported low consumer awareness of BFT produced shrimp and suggested the need for educating them. In this direction, market acceptance and improved market demand can be achieved through deliberate effort at educating the population on the environmental gains and potential nutritional benefits of BFT shrimp. Such programs should emphasize the decreased environmental impacts, sustainability and proved shrimp growth that could lead to high ROI. This trust when built would help in the long-term success of BFT in the world market.

Generally, studies on consumer preference of BFT cultured shrimps in different parts of the world are few since most related studies are rather too general. Recently, consumer behaviour toward prawn consumption was evaluated in Bangladesh were majority preferred fresh, large-sized prawns. In addition, the purchasing decision was divided into high-income and low-income with the formal going for premium products while the later revealed to be more price sensitive. Also, of significant influence on consumer choice and preferences were size, freshness, taste, price, and market availability of the product [88]. This goes to say that the choice of BFT shrimp may not really pose a challenge in most markets provided many of the other factors influencing consumer behaviour are met. In Brazil, production of new ready-to-bake seafood meal was achieved using Pacific white shrimp. The production process followed a mixture of sweet-sour sauce and cream cheese, then vacuum-packed and frozen. Having achieved Brazilian safety standard, consumer acceptability was 8.72 on a 10-point scale rating with 82 % intent to buy [89]. It was interesting to observe that none of the customers with strong purchasing desire cared more on the present condition of the shrimp rather than where it was obtained. This means that, though consumer acceptance of BFT shrimp may be a challenge, it does not pose a headache as much as other technical and biological hinderances. This knowledge should guide researchers on which area of the technology requires more efforts. In the southeastern United States, consumer preferences for shrimp characteristics were determined using a conjoint analysis [87]. Again, strong preferences were recorded for large, fresh, whole shrimp, where the shrimp price was the most determinant factor. Further demographic analysis showed remarked differences with African American and Hispanic consumers preferring price more than Caucasians.

5. Future perspectives on Biofloc technology

The increasing global demand for seafood has further given credence to BFT as a transformative and sustainable aquaculture operation with promise to addressing environmental issues. Nevertheless, the future success of the technology still hangs in the balance with concerted efforts still needed tackle challenges related to technological innovation, policy development, and education [28]. In this direction, some key areas are being explored to fashion the trajectory of BFT in years to come.

5.1. *Innovations and research directions*

Innovations in the development of monitoring tools to optimize system performance in order to improve output and save cost are underway. IoT technologies being integrated with the system ensures real-time water quality monitoring [90,91]. While machine learning assists in the system optimization to predict and control microbial population in BFT. Durán et al. [92] reported that combination of IoT and machine learning were highly effective in improving shrimp survival and decreased chance of disease outbreaks. In China, the future of BFT is further brightened with the advent of automated feeding technologies and water quality monitoring systems [55,91,93]. This has been shown to improve operational efficiency and feed cost reduction. Going forward, studies may focus on inventing smart BFT systems where C:N ratio, oxygen levels and feed inputs can be adjusted automatically thereby keeping optimal operating conditions for shrimp growth.

In addition, exploration of suitable alternative carbon sources on a regional bases to improve biofloc nutritional quality will go a long way to ensuring the success of BFT in the coming days. Alternative carbon sources like organic byproducts or agricultural waste are currently in focus. It is believed that exploration of sources like microalgae, biochar and wastewater sludge would greatly reduce feed cost and improve nutrient cycling. In Israel, application of algae-based carbon greatly enhanced biofloc system performance (Shani et al., 2021). The study added that microalgae inclusion in biofloc has accompanying benefits such as improved oxygen level, carbon dioxide removal and supplemental feed for shrimps. In China today, Wei et al. [18] reported improved biofloc stability, protein level and higher shrimp growth performance when using biochar as a carbon source. Furthermore, manipulation of microbial community through genetic engineering and metagenomics would ensure dominance of beneficial microorganisms in the system as against opportunistic bacteria. These technologies can isolate and identify specific microbial strains with ability to degrade and improve shrimp immunity. With this knowledge, probiotics can be developed for specific BFT management strategies. Although studies by Raza et al. [10] have provided insight on the metagenomic analysis of biofloc communities, more is still needed to unravel the specific functional roles of the microbial taxa. When fully understood, this will pave the way for more targeted and efficient BFT management strategies.

5.2. *Policy and regulatory considerations*

5.2.1. *Need for supportive policies to promote BFT adoption*

The enormous benefits of BFT can only be fully harnessed when deliberate regulatory policy frameworks are crafted in the line of sustainable aquaculture practices. Provision of incentives to encourage BFT adoption by government and regulatory bodies of various regions can be a strategy in the right direction. These incentives could be in form of subsidies for initial capital investment to tackle the issue of start-up cost, tax breaks and/or grants to support BFT research [4,13,41]. These strategies if fully implement will make the technology attractive to small scale farmers thereby leading to a peaceful transition from traditional shrimp aquaculture to more sustainable operations. In addition, promoting research and innovations by government bodies in regions that the technology is just evolving would encourage indigenisation of the knowledge, improve its efficiency and effectiveness. In Indonesia, implementation of national BFT research and development program has led to significant progress in the technology practices and improved adoption among shrimp farmers (Pratiwi et al. [94].

5.2.2. Environmental regulations and sustainability certifications

Today, aquaculture is being wildly criticized by many environmental bodies due largely to its impact to the general ecosystems. The ability of BFT to address many of these aquaculture challenges has placed it in a better position to align with emerging sustainability standards and certifications [45]. Considering the current trajectory of world environmental challenges including water pollution and carbon emissions, global regulations on aquaculture operations are bound to become more enforced. However, BFT systems, given their sustainability and eco-friendliness is better positioned to fit into these regulatory demands. To better position BFT to be acknowledged as viable sustainable alternative, it is imperative to develop clear operating guidelines and standard operating procedures. These guidelines could be in form of certification schemes for products produced through BFT. Standards could be established making references to existing organic or eco-label certifications. For instance, BFT shrimp certification will help to build market acceptance and consumer trust ([10,10]; Fernández et al., 2023).

5.3. Education and training

5.3.1. Importance of training programs for farmers and stakeholders

The success of any venture begins and, in most cases, relies on adequate knowledge of the operational conditions thereof. Therefore, education and training of shrimp farmers and stakeholders alike is crucial to the success of shrimp aquaculture vis-à-vis BFT [44]. Shrimp famers could be made to undertake training to obtain basic knowledge on the principles of BFT operation, system management and water quality monitoring skills before being handed incentives to start the business. Furthermore, the knowledge so acquired by the farmer will help them overcome challenges like management of floc stability and quality, disease outbreaks and optimization of feeding strategies [52]. Just recently in Vietnam, the Food and Agriculture Organization (FAO) came up with BFT farmer training program in conjunction with other local universities. Reports showed that the well-designed training program significantly improved farmer confidence and competence in managing BFT systems with 20 % rise in shrimp survival rates and a 15 % reduction in feed costs (Khanjani et al., 2024). It is suggested that global collaboration and knowledge sharing within the community of researchers, practitioners and policymakers is important to increasing global BFT adoption. So far, the technology has been successfully implemented in regions like China, India, Brazil and Turkey. Therefore, the success stories and achievements of these countries can be drawn in developing training programs for other countries to adopt best practices and prevent common pitfalls. Also, to make up for the technology gaps among regions, networking and partnerships are encouraged, especially in developing countries.

5.3.2. Role of research institutions in disseminating knowledge about BFT

Research institutions are centre for innovations through groundbreaking investigations and serves to bridge the gap between scientific research and practical application. The institutions help to foster spread of best practices and latest technologies in BFT by synergising with industry stakeholders, government agencies, and farmer cooperatives [11]. As a key stakeholder, research institutions keep farmers abreast of cutting-edge research findings by organising workshops, seminars, and extension services. For instance, the biofloc Research and Extension Program at Universiti Malaysia Terengganu (UMT), Malaysia showcased the effectiveness of the effectiveness of the technology in the culture of L. vannamei has been instrumental in promoting BFT adoption in Southeast Asia [3]. Incorporation of workshops and field demonstrations with participants drawn from researchers, farmers, and industry representatives is vital in attaining the goals of such exercise. There is no gain saying that the prospects of BFT in aquaculture are promising. When the current challenges are sufficiently addressed through technological advancements, supportive policies, and comprehensive education, widespread adoption is certain. It is expected that the evolving technology will continue to provide more tools and knowledge to shrimp farmers with which aquaculture industry can be reshaped to meet global seafood demand while accounting for environmental impacts.

6. Conclusion

Shrimp aquaculture is poised to witness more sustainable operations in the wake of biofloc technology. BFT has repeatedly demonstrated ability to address environmental degradation, high feed cost which often leads to increased production cost and water pollution that affect conventional shrimp aquaculture. The core principle of the technology is to convert waste into nutrient-rich biofloc due to interaction of beneficial microorganisms. While the floc serves as nutritious food for shrimp, the activity helps to maintain water quality in the system. In addition, maintenance of C:N ratio promotes growth and multiplication of beneficial heterotopic bacteria involved in assimilation of toxic nitrogenous waste and maintaining water quality. Due to the high nutrient content of the biofloc, reports have shown that shrimp fed with biofloc experienced improved growth rates, superior health and disease resilience from improved immune system compared to traditional cultured shrimps.

This review also re-echoed the challenges hindering widescale adoption of BFT to include high initial setup costs, lack alternative carbon sources which affect floc stability and quality, lack of modern technology infrastructure in some regions, absence of awareness leading to poor market and consumer acceptance and the need for careful management of microbial communities. Nevertheless, recent research advancement in countries like China, Turkey, Brazil and Israel have led to development of advanced monitoring technologies, exploration of alternative carbon sources like sugarcane molasses, agricultural by-products, microalgae, biochar and integration with other sustainable practices have further brighten the prospects of BFT. More efforts are still desired to finding suitable carbon sources per region bases, knowing that agricultural products vary in variety and composition with climate and weather conditions. It is important for government bodies and educational institutions to sustain research and training efforts to educate shrimp farmers on the sustainability and profitability of the technology. Further research to enhance system optimization of operational conditions will surely promote successful implementation of BFT across the aquaculture industry.

CRediT authorship contribution statement

Benedict Terkula Iber: Writing – review & editing, Writing – original draft, Conceptualization. **Benjamin Chiaaondo Ikyo:** Writing – review & editing, Validation, Resources. **Mohd Nazli Mohd Nor:** Writing – review & editing, Formal analysis, Data curation. **Siti Rozaimah Sheik Abdullah:** Writing – review & editing, Visualization, Supervision. **Muhammad Shukri Bin Shafie:** Visualization, Supervision, Resources. **Hidaya Manan:** Writing – review & editing, Visualization, Validation, Investigation. **MHD. Ikhwanudin Abdullah:** Writing – review & editing, Supervision, Project administration, Investigation. **Nor Azman Kasan:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

Acknowledgement

All authors appreciate the Institute of Tropical Aquaculture and Fisheries (AKUATROP), Universiti Malaysia Terengganu (UMT), Malaysia which provides facilities for this research. This project was fully funded by the Ministry of Higher Education, Malaysia through the Translational Research Program entitled Program Translational Sektor Makanan Laut Malaysia untuk Kelestarian Pengeluaran Udang Marin dan Penjanaan Pendapatan-Tinggi: Aplikasi Teknologi "Rapid Biofloc" (UMT/PPIJIM/2-2/68/Trans-KPT (Vot. No: 58932).

Data availability

No data was used for the research described in the article.

References

[1] M.H. Khanjani, A. Mohammadi, M.G.C. Emerenciano, Water quality in biofloc technology (BFT): an applied review for an evolving aquaculture, Aquacult. Int. 32 (7) (2024) 9321–9374, https://doi.org/10.1007/S10499-024-01618-W/METRICS.

[2] M.H. Khanjani, M. Sharifinia, M.G.C. Emerenciano, Biofloc technology (BFT) in aquaculture: what goes right, what goes Wrong? A scientific-based snapshot, Aquacult. Nutr. 2024 (1) (2024) 7496572, https://doi.org/10.1155/2024/7496572.

[3] N.A. Kasan, A.N. Dagang, M.I. Abdullah, Application of biofloc technology (BFT) in shrimp aquaculture industry, IOP Conf. Ser. Earth Environ. Sci. 196 (1) (2018) 012043, https://doi.org/10.1088/1755-1315/196/1/012043.

[4] M.H. Khanjani, M. Sharifinia, Biofloc as a food source for banana shrimp fenneropenaeus merguiensis postlarvae, N. Am. J. Aquacult. 84 (4) (2022) 469–479, https://doi.org/10.1002/NAAQ.10261.

[5] M.H. Khanjani, M. Sharifinia, Biofloc technology with addition molasses as carbon sources applied to Litopenaeus vannamei juvenile production under the effects of different C/N ratios, Aquacult. Int. 30 (1) (2022) 383–397, https://doi.org/10.1007/S10499-021-00803-5/METRICS.

[6] M.H. Khanjani, A. Mohammadi, M.G.C. Emerenciano, Water quality in biofloc technology (BFT): an applied review for an evolving aquaculture, Aquacult. Int. (2024) 1–54, https://doi.org/10.1007/S10499-024-01618-W, 2024.

[7] Y. Avnimelech, Feeding with microbial flocs by tilapia in minimal discharge bio-flocs technology ponds, Aquaculture 264 (1–4) (2007) 140–147, https://doi.org/10.1016/J.AQUACULTURE.2006.11.025.

[8] M. Emerenciano, E.L.C. Ballester, R.O. Cavalli, W. Wasielesky, Effect of biofloc technology (BFT) on the early postlarval stage of pink shrimp Farfantepenaeus paulensis: growth performance, floc composition and salinity stress tolerance, Aquacult. Int. 19 (5) (2011) 891–901, https://doi.org/10.1007/S10499-010-9408-6/METRICS.

[9] M. Deng, J. Chen, J. Gou, J. Hou, D. Li, X. He, The effect of different carbon sources on water quality, microbial community and structure of biofloc systems, Aquaculture 482 (2018) 103–110, https://doi.org/10.1016/J.AQUACULTURE.2017.09.030.

[10] B. Raza, Z. Zheng, W. Yang, A review on biofloc system technology, history, types, and future economical perceptions in aquaculture, Animals 14 (10) (2024) 1489, https://doi.org/10.3390/ANI14101489, 2024, Vol. 14, Page 1489.

[11] A.F.M. El-Sayed, Use of biofloc technology in shrimp aquaculture: a comprehensive review, with emphasis on the last decade, Rev. Aquacult. 13 (1) (2021) 676–705, https://doi.org/10.1111/RAQ.12494.

[12] A.B. Dauda, Biofloc technology: a review on the microbial interactions, operational parameters and implications to disease and health management of cultured aquatic animals, Rev. Aquacult. 12 (2) (2020) 1193–1210, https://doi.org/10.1111/RAQ.12379.

[13] M.A. Zafar, M.M. Rana, Biofloc technology: an eco-friendly "green approach" to boost up aquaculture production, Aquacult. Int. 30 (1) (2022) 51–72, https://doi.org/10.1007/S10499-021-00781-8/METRICS.

[14] J. Ekasari, U.A. Nugroho, N. Fatimah, D. Angela, Y.P. Hastuti, G.S.J. Pande, F.M. I. Natrah, Improvement of biofloc quality and growth of Macrobrachium rosenbergii in biofloc systems by Chlorella addition, Aquacult. Int. 29 (5) (2021) 2305–2317, https://doi.org/10.1007/S10499-021-00750-1.

[15] S. Chakrapani, A. Panigrahi, J. Sundaresan, S. Mani, E. Palanichamy, V. S. Rameshbabu, A. Krishna, Utilization of complex carbon sources on biofloc system and its influence on the microbial composition, growth, digestive enzyme activity of pacific white shrimp, Penaeus vannamei culture, Turk. J. Fish. Aquat. Sci. 22 (4) (2021), https://doi.org/10.4194/TRJFAS18813.

[16] W. Jiang, W. Ren, L. Li, S. Dong, X. Tian, Light and carbon sources addition alter microbial community in biofloc-based Litopenaeus vannamei culture systems, Aquaculture 515 (2020), https://doi.org/10.1016/J.AQUACULTURE.2019.734572.

[17] M.T. Nguyen, N.T.A. Pham, L.T. Vo, D.V. Truong, H.V. Nguyen, T.D.Q. Nguyen, P. N. Nguyen, P. Bossier, Integrated mariculture of co-cultured whiteleg shrimp (Litopenaeus vannamei) and grey mullet (Mugil cephalus) in sequence with red tilapia (Oreochromis spp.) in a closed biofloc-based system, Aquaculture 566 (2023) 739200, https://doi.org/10.1016/J.AQUACULTURE.2022.739200.

[18] X.F. Wei, S.T. Meng, Y.T. Wang, L. Li, R. Zhu, D.L. Li, S.Y. Liu, L.F. Wu, Effects of replacing fish meal with biofloc meal on growth performance, nutrients metabolism, immune response and intestinal microbiota of common carp (Cyprinus carpio), Aquaculture 591 (2024) 741124, https://doi.org/10.1016/J.AQUACULTURE.2024.741124.

[19] W. Xu, F. Huang, Y. Zhao, H. Su, X. Hu, Y. Xu, G. Wen, Y. Cao, Carbohydrate addition strategy affects nitrogen dynamics, budget and utilization, and its microbial mechanisms in biofloc-based Penaeus vannamei culture, Aquaculture 589 (2024) 740907, https://doi.org/10.1016/J.AQUACULTURE.2024.740907.

[21] S. McCusker, M.B. Warberg, S.J. Davies, C. de S. Valente, M.P. Johnson, R. Cooney, A.H.L. Wan, Biofloc technology as part of a sustainable aquaculture system: a review on the status and innovations for its expansion, Aquacult., Fish Fish. 3 (4) (2023) 331–352, https://doi.org/10.1002/AFF2.108.

[22] U. Nisar, D. Peng, Y. Mu, Y. Sun, A solution for sustainable utilization of aquaculture waste: a comprehensive review of biofloc technology and aquamimicry, Front. Nutr. 8 (2022) 791738, https://doi.org/10.3389/FNUT.2021.791738/BIBTEX.

[23] M.S. Kim, E.Y. Min, J.H. Kim, J.K. Koo, J.C. Kang, Growth performance and immunological and antioxidant status of Chinese shrimp, Fennerpenaeus chinensis reared in bio-floc culture system using probiotics, Fish Shellfish Immunol. 47 (1) (2015) 141–146, https://doi.org/10.1016/J.FSI.2015.08.027.

[24] P.C.M. Lima, A.E.M. Silva, D.A. Silva, S.M.B.C. Silva, L.O. Brito, A.O. Gálvez, Effect of stocking density of Crassostrea sp. in a multitrophic biofloc system with Litopenaeus vannamei in nursery, Aquaculture 530 (2021) 735913, https://doi.org/10.1016/J.AQUACULTURE.2020.735913.

[25] D.D. Kuhn, A.L. Lawrence, J. Crockett, Dietary toxicity of manganese to shrimp and its accumulation in bioflocs, Aquacult. Nutr. 23 (5) (2017) 1121–1127, https://doi.org/10.1111/ANU.12480.

[26] A. Gallardo-Collí, C.I. Pérez-Rostro, M.P. Hernández-Vergara, L.A. Ortega-Clemente, I.R. Huerta-Mora, Effect of three biofloc meal production methods on its chemical composition, Aquacult. Int. 32 (4) (2024) 5017–5028, https://doi.org/10.1007/S10499-024-01413-7/METRICS.

[27] T.M. Samocha, D.I. Prangnell, T.R. Hanson, G.D. Treece, T.C. Morris, L.F. Castro, N. Staresinic, Design and operation of high-density, biofloc-dominated production systems of pacific white shrimp, Penaeus vannamei, Vannamei Shrimp Farming (2020) 14–36, https://doi.org/10.1201/9781003083276-3.

[28] I. Ahmad, A.M. Babitha Rani, A.K. Verma, M. Maqsood, Biofloc technology: an emerging avenue in aquatic animal healthcare and nutrition, Aquacult. Int. 25 (3) (2017) 1215–1226, https://doi.org/10.1007/S10499-016-0108-8/METRICS.

[29] A.T. Mansour, O.A. Ashry, M. Ashour, A.S. Alsaqufi, K.M.A. Ramadan, Z. Z. Sharawy, The optimization of dietary protein level and carbon sources on biofloc nutritive values, bacterial abundance, and growth performances of whiteleg shrimp (Litopenaeus vannamei) juveniles, Life 12 (6) (2022), https://doi.org/10.3390/LIFE12060888.

[31] W.J. Xu, T.C. Morris, T.M. Samocha, Effects of C/N ratio on biofloc development, water quality, and performance of Litopenaeus vannamei juveniles in a biofloc-based, high-density, zero-exchange, outdoor tank system, Aquaculture 453 (2016) 169–175, https://doi.org/10.1016/J.AQUACULTURE.2015.11.021.

[32] M.H. Khanjani, M. Sharifinia, S. Hajirezaee, Biofloc: a sustainable alternative for improving the production of farmed cyprinid species, Aquacult. Reports 33 (2023) 101748, https://doi.org/10.1016/J.AQREP.2023.101748.

[33] M.G.C. Emerenciano, K. Fitzsimmons, A. Nishioka Rombenso, A. Miranda-Baeza, G. Bernardes Martins, R. Lazzari, Y. Elizabeth Fimbres-Acedo, S. Mello Pinho, Biofloc technology (BFT) in Tilapia culture, Biol. Aquacult. Tilapia (2021) 258–293, https://doi.org/10.1201/9781003004134-14.

[34] A.J. Ray, J.W. Leffler, C.L. Browdy, The effects of a conventional feed versus a fish-free feed and biofloc management on the nutritional and human sensory characteristics of shrimp (Litopenaeus vannamei), Aquacult. Int. 27 (1) (2019) 261–277, https://doi.org/10.1007/S10499-018-0321-8/METRICS.

[35] V. Santhana Kumar, P.K. Pandey, T. Anand, G.R. Bhuvaneswari, A. Dhinakaran, S. Kumar, Biofloc improves water, effluent quality and growth parameters of Penaeus vannamei in an intensive culture system, J. Environ. Manag. 215 (2018) 206–215, https://doi.org/10.1016/J.JENVMAN.2018.03.015.

[36] V. Kumar, S. Roy, B.K. Behera, H.S. Swain, B.K. Das, Biofloc microbiome with bioremediation and health benefits, Front. Microbiol. 12 (2021) 741164, https://doi.org/10.3389/FMICB.2021.741164/BIBTEX.

[37] U. Uawisetwathana, M.L. Situmorang, S. Arayamethakorn, Haniswita, G. Suantika, A. Panya, N. Karoonuthaisiri, W. Rungrassamee, Supplementation of ex-situ biofloc to improve growth performance and enhance nutritional values of the pacific white shrimp rearing at low salinity conditions, Appl. Sci. 11 (10) (2021) 4598, https://doi.org/10.3390/APP11104598, 2021, Vol. 11, Page 4598.

[38] M.H. Khanjani, A. Mohammadi, M.G.C. Emerenciano, Microorganisms in biofloc aquaculture system, Aquacult. Reports 26 (2022) 101300, https://doi.org/10.1016/J.AQREP.2022.101300.

[39] Y. Bin Yu, J.H. Choi, J.H. Lee, A.H. Jo, K.M. Lee, J.H. Kim, Biofloc technology in fish aquaculture: a review, Antioxidants 12 (2) (2023) 398, https://doi.org/10.3390/ANTIOX12020398, 2023, Vol. 12, Page 398.

[40] G. Abakari, G. Luo, H. Meng, Z. Yang, G. Owusu-Afriyie, E.O. Kombat, E. H. Alhassan, The use of biochar in the production of tilapia (Oreochromis niloticus)

in a biofloc technology system - BFT, Aquacult. Eng. 91 (2020), https://doi.org/10.1016/J.AQUAENG.2020.102123.
[41] M.T. Jamal, M. Broom, B.A. AL-Mur, M. AL Harbi, M. Ghandourah, A. AL Otaibi, M.F. Haque, Biofloc technology: emerging microbial biotechnology for the improvement of aquaculture productivity, Pol. J. Microbiol. 69 (4) (2020) 401, https://doi.org/10.33073/PJM-2020-049.
[42] E.G. Durigon, R. Lazzari, J. Uczay, D.L. de A. Lopes, G.T. Jerônimo, T. Sgnaulin, M. G.C. Emerenciano, Biofloc technology (BFT): adjusting the levels of digestible protein and digestible energy in diets of Nile tilapia juveniles raised in brackish water, Aquacult. Fish. 5 (1) (2020) 42–51, https://doi.org/10.1016/J.AAF.2019.07.001.
[43] J.L. Arias-Moscoso, L.G. Espinoza-Barrón, A. Miranda-Baeza, M.E. Rivas-Vega, M. Nieves-Soto, Effect of commercial probiotics addition in a biofloc shrimp farm during the nursery phase in zero water exchange, Aquacult. Reports 11 (2018) 47–52, https://doi.org/10.1016/J.AQREP.2018.06.001.
[44] S. Deb, M.T. Noori, P.S. Rao, Application of biofloc technology for Indian major carp culture (polyculture) along with water quality management, Aquacult. Eng. 91 (2020), https://doi.org/10.1016/J.AQUAENG.2020.102106.
[45] G. Abakari, G. Luo, E.O. Kombat, Dynamics of nitrogenous compounds and their control in biofloc technology (BFT) systems: a review, Aquacult. Fish. 6 (5) (2021) 441–447, https://doi.org/10.1016/J.AAF.2020.05.005.
[46] M.A.A. Zaki, A.N. Alabssawy, A.E.A.M. Nour, M.F. El Basuini, M.A.O. Dawood, S. Alkahtani, M.M. Abdel-Daim, The impact of stocking density and dietary carbon sources on the growth, oxidative status and stress markers of Nile tilapia (Oreochromis niloticus) reared under biofloc conditions, Aquacult. Reports 16 (2020), https://doi.org/10.1016/J.AQREP.2020.100282.
[47] M.M. Said, Y.A. El-Barbary, O.M. Ahmed, Assessment of performance, microbial community, bacterial food quality, and gene expression of whiteleg shrimp (Litopenaeus vannamei) reared under different density biofloc systems, Aquacult. Nutr. 2022 (1) (2022) 3499061, https://doi.org/10.1155/2022/3499061.
[48] M. Faris Allam, J. Ekasari, I. Fauzi, W. Wiyoto, Characteristics and quality of biofloc in vannamei shrimp culture with different carbon sources, Deleted J. 23 (1) (2024) 92–100, https://doi.org/10.19027/JAI.23.1.92-100.
[49] G. Liu, M. Verdegem, Z. Ye, J. Zhao, J. Xiao, X. Liu, Q. Liang, K. Xiang, S. Zhu, Advancing aquaculture sustainability: a comprehensive review of biofloc technology trends, innovative research approaches, and future prospects, Rev. Aquacult. 17 (1) (2024), https://doi.org/10.1111/RAQ.12970.
[51] Y. Liu, Y. Tang, H. Gao, W. Zhang, Y. Jiang, F. Xin, M. Jiang, Challenges and future perspectives of promising biotechnologies for lignocellulosic biorefinery, Molecules 26 (17) (2021) 5411, https://doi.org/10.3390/MOLECULES26175411, 2021, Vol. 26, Page *5411*.
[52] R.B. dos Santos, J. Izel-Silva, P.A. de Medeiros, M.M.S. Fugimura, T.M. de Freitas, S.U. Gallani, G. da Silva Claudiano, E.A. Ono, E.G. Affonso, Immunophysiology of tambaqui fed with different levels of dietary protein in biofloc and clear water system, Aquacult. Int. 32 (2) (2024) 1067–1079, https://doi.org/10.1007/S10499-023-01205-5/METRICS.
[53] L. Cao, W. Wang, Y. Yang, C. Yang, Z. Yuan, S. Xiong, J. Diana, Aquaculture Pollution in China Subject Area 5.1: microbial studies and technologies supporting waste disposal, management, and remediation of municipal and industrial hazardous wastes Environmental Impact of Aquaculture and Countermeasures to Aquaculture, Environ. Sci. Pollut. Res. Int. 14 (7) (2007) 452–462. http://crsps.net/wp-content/downloads/AquaFish/Inventoried10.29/8-2007-4-47a.pdf.
[54] S. Dong, Y. Li, F. Huang, L. Lin, Z. Li, J. Li, Y. Zhang, Y. Zheng, Enhancing effect of Platymonas addition on water quality, microbial community diversity and shrimp performance in biofloc-based tanks for Penaeus vannamei nursery, Aquaculture 554 (2022) 738057, https://doi.org/10.1016/J.AQUACULTURE.2022.738057.
[55] Q. Wang, Z. Li, J.F. Gui, J. Liu, S. Ye, J. Yuan, S.S. De Silva, Paradigm changes in freshwater aquaculture practices in China: moving towards achieving environmental integrity and sustainability, Ambio 47 (4) (2018) 410–426, https://doi.org/10.1007/s13280-017-0985-8.
[56] H. Choi, J.S. Park, J.A. Hwang, S.K. Kim, Y. Cha, S.Y. Oh, Influence of biofloc technology and continuous flow systems on aquatic microbiota and water quality in Japanese eel aquaculture, Diversity 16 (10) (2024) 601, https://doi.org/10.3390/D16100601, 601.
[57] S. Deb, M.T. Noori, P. Srinivasa Rao, Experimental study to evaluate the efficacy of locally available waste carbon sources on aquaculture water quality management using biofloc technology, Aquacult. Int. 25 (6) (2017) 2149–2159, https://doi.org/10.1007/S10499-017-0180-8/METRICS.
[58] R. Ramasubburayan, S. Prakash, G. Immanuel, D. Mubarakali, G. Rajakumar, D. Thirumurugan, A. Palavesam, The transformative role of prebiotics, probiotics, and microbiomes in biofloc systems for sustainable aquaculture: a comprehensive review, Rev. Aquacult. 17 (1) (2025) e13000, https://doi.org/10.1111/RAQ.13000.
[59] S. Tasleem, B.S. Alotaibi, S. Masud, S.S. Habib, Ü. Acar, S.C. Gualandi, M. Ullah, K. Khan, F. Fazio, K. Khayyam, Biofloc system with different carbon sources improved growth, haematology, nonspecific immunity, and resistivity against the aeromonas hydrophila in common carp, Cyprinus carpio, Aquacult. Res. (2024), https://doi.org/10.1155/2024/7652354, 2024.
[60] S. Deb, M.T. Noori, P. Srinivasa Rao, Experimental study to evaluate the efficacy of locally available waste carbon sources on aquaculture water quality management using biofloc technology, Aquacult. Int. 25 (6) (2017) 2149–2159, https://doi.org/10.1007/S10499-017-0180-8.
[61] M.I.S. Gonzaga, D. C. F. de Souza, J.C. de J. Santos, Use of organic waste biochar as an innovative alternative for increasing agricultural productivity in small rural communities, Soc. Dev. 10 (4) (2021) e8910413848, https://doi.org/10.33448/RSD-V10I4.13848. Research.
[62] J.P. Otoni, S.C.G. Matoso, X.L.O. Pérez, V.B. da Silva, Potential for agronomic and environmental use of biochars derived from different organic waste, J. Clean. Prod. 449 (2024), https://doi.org/10.1016/J.JCLEPRO.2024.141826.
[63] A.B. Speratti, M.S. Johnson, H.M. Sousa, H.J. Dalmagro, E.G. Couto, Biochars from local agricultural waste residues contribute to soil quality and plant growth in a Cerrado region (Brazil) Arenosol, Gcb Bioenergy 10 (4) (2018) 272–286, https://doi.org/10.1111/GCBB.12489.
[64] M.H. Azhar, D. Memiş, Application of the IMTA (integrated multi-trophic aquaculture) system in freshwater, brackish and marine aquaculture, Aquat. Sci. Eng. 38 (2) (2023) 101–121, https://doi.org/10.26650/ASE20231252136.
[65] A.M.A.S. Goda, A.M. Aboseif, M.K.S. Taha, E.Y. Mohammady, N.M. Aboushabana, H.M. Nazmi, M.M. Zaher, H.A. Aly, M.A.S. El-Okaby, N.I. Otazua, M. Ashour, Optimizing nutrient utilization, hydraulic loading rate, and feed conversion ratios through freshwater IMTA-aquaponic and hydroponic systems as an environmentally sustainable aquaculture concept, Dental Sci. Reports 14 (1) (2024), https://doi.org/10.1038/S41598-024-63919-7.
[66] N. Nurfadillah, I. Hasri, M.R. Purnama, A. Damora, S. Mellisa, The application of integrated multi-trophic aquaculture (IMTA) using floating net cages on Tilapia fish with native fish (Peres, Lemeduk, and Depik), Depik 10 (3) (2021) 219–224, https://doi.org/10.13170/DEPIK.10.3.22465.
[67] E. Ajamhasani, R. Akrami, E.H. Najdegerami, H. Chitsaz, M. Shamloofar, Different carbon sources and probiotics in biofloc based common carp (Cyprinus carpio) culture: effects on water quality, growth performance, fish welfare and liver histopathology, J. World Aquacult. Soc. 54 (6) (2023) 1546–1562, https://doi.org/10.1111/JWAS.12993.
[68] K. Minabi, I. Sourinejad, M. Alizadeh, E.R. Ghatrami, M.H. Khanjani, Effects of different carbon to nitrogen ratios in the biofloc system on water quality, growth, and body composition of common carp (Cyprinus carpio L.) fingerlings, Aquacult. Int. 28 (5) (2020) 1883–1898, https://doi.org/10.1007/S10499-020-00564-7, 2020 28:5.
[69] G. Mohammadi, M. Seddiq Mortazavi, M. Hafezieh, Evaluation of high stocking densities on the water quality and growth performance of pacific white shrimp Litopenaeus vannamei reared in a mixotrophic biofloc nursery system, Aquacult. Res. 2023 (1) (2023) 1765366, https://doi.org/10.1155/2023/1765366.
[70] H.S. Neto, S.T. Santaella, A.J.P. Nunes, Bioavailability of crude protein and lipid from biofloc meals produced in an activated sludge system for white shrimp, Litopenaeus vannamei, Rev. Bras. Zootec. 44 (8) (2015) 269–275, https://doi.org/10.1590/S1806-92902015000800001.
[71] A.R. Khafage, S.M. Taha, M.A. Attallah, Presence of tiger shrimp Penaeus monodon Fabricius, 1798 (Penaeidae) in the Egyptian commercial shrimp catch, Alexandria, Egypt, Egypt. J. Aquat. Res. 45 (2) (2019) 183–187, https://doi.org/10.1016/j.ejar.2019.05.002.
[72] M.M. Said, H.G. Abo-Al-Ela, Y.A. El-Barbary, O.M. Ahmed, H.S. Dighiesh, Influence of stocking density on the growth, immune and physiological responses, and cultivation environment of white-leg shrimp (Litopenaeus vannamei) in biofloc systems, Sci. Reports 2024 14 (1) (2024) 1–15, https://doi.org/10.1038/s41598-024-61328-4, 14:1.
[73] D. Krummenauer, A.F. da Silva, M. Xavier, G.K. Foes, L.H. Poersch, A. Cardozo, W. Wasielesky, Comparative analysis of the culture of pink shrimp Farfantepenaeus brasiliensis and pacific white shrimp Litopenaeus vannamei in biofloc system, Aquacult. J. 4 (1) (2024) 1–14, https://doi.org/10.3390/AQUACJ4010001.
[74] A. Panigrahi, R.R. Das, S. Sarkar, R. Aravind, P.N. Rekha, K.P. Sandeep, Biofloc-based farming of Indian white shrimp, Penaeus indicus, in recirculating aquaculture system (RAS) enriched with rotifers as feed supplement, Aquacult. Int. (2022) 1–24, https://doi.org/10.1007/S10499-022-01000-8/FIGURES/6.
[75] A. Panigrahi, P. Esakkiraj, C. Saranya, R.R. Das, M. Sundaram, N.S. Sudheer, I. F. Biju, M. Jayanthi, A biofloc-based aquaculture system bio-augmented with probiotic bacteria Bacillus tequilensis AP BFT3 improves culture environment, production performances, and proteomic changes in Penaeus vannamei, Prob. Antimicrob. Proteins 14 (2) (2022) 277–287, https://doi.org/10.1007/S12602-022-09926-4/METRICS.
[76] S. Dong, Y. Li, F. Huang, L. Lin, Z. Li, J. Li, Y. Zhang, Y. Zheng, Enhancing effect of Platymonas addition on water quality, microbial community diversity and shrimp performance in biofloc-based tanks for Penaeus vannamei nursery, Aquaculture 554 (2022) 738057, https://doi.org/10.1016/J.AQUACULTURE.2022.738057.
[77] E. Bidayani, F.S. Valen, Short Communication: efficiency economic of whiteleg shrimp Litopenaeus vannamei (Boone 1931) cultivation with a household scale biofloc system, Indo Pacif. J. Ocean Life 7 (2) (2023), https://doi.org/10.13057/OCEANLIFE/O070205.
[78] Y. Aparna, S.H. Banafsha, M.S. Reddy, Efficacy of probiotics and biofloc system in maintenance of water quality and growth performance in shrimp Litopenaeus vannamei, Int. J. Fish. Aquat. Stud. 11 (6) (2023) 7–20, https://doi.org/10.22271/FISH.2023.V11.I6A.2873.
[79] L.G.P. Da Silveira, V.T. Rosas, D. Krummenauer, L.H. Poersch, W. Wasielesky, Comparison between horizontal and vertical substrate in shrimp super-intensive culture in biofiocs system, Aquacult. Eng. 96 (2022) 102218, https://doi.org/10.1016/J.AQUAENG.2021.102218.
[80] M.N. Hoang, P.N. Nguyen, P. Bossier, Water quality, animal performance, nutrient budgets and microbial community in the biofloc-based polyculture system of white shrimp, Litopenaeus vannamei and gray mullet, Mugil cephalus, Aquaculture 2020 (2019) 734610, https://doi.org/10.1016/j.aquaculture.2019.734610.
[81] J. Soto-Alcalá, P. Álvarez-Ruiz, J.M. Audelo-Naranjo, H.M. Esparza-Leal, I.E. Luis-Villaseñor, J.A. Estrada-Godínez, A. Luna-González, C. Gámez-Jiménez, G. Diarte-Plata, J. Soto-Alcalá, P. Álvarez-Ruiz, J.M. Audelo-Naranjo, H.M. Esparza-Leal, I. E. Luis-Villaseñor, J.A. Estrada-Godínez, A. Luna-González, C. Gámez-Jiménez, G. Diarte-Plata, Comparing RAS with and without biofloc: transcriptional response

of immune-related genes in Litopenaeus vannamei post-larvae, Rev. Colombiana Ciencias Pecuarias 33 (1) (2020) 32–43, https://doi.org/10.17533/UDEA.RCCP.V33N1A03.

[82] M.H. Khanjani, M. Alizadeh, M. Sharifinia, Effects of different carbon sources on water quality, biofloc quality, and growth performance of Nile tilapia (Oreochromis niloticus) fingerlings in a heterotrophic culture system, Aquacult. Int. 29 (1) (2021) 307–321, https://doi.org/10.1007/S10499-020-00627-9.

[83] V. Kumar, H.S. Swain, P. Vuong, S. Roy, A. Upadhyay, R.C. Malick, K. Bisai, P. Kaur, B.K. Das, Microbial inoculums improve growth and health of Heteropneustes fossilis via biofloc-driven aquaculture, Microb. Cell Factories 22 (1) (2023) 106, https://doi.org/10.1186/S12934-023-02107-0.

[84] E.T. Akange, A.A. Aende, H. Rastegari, O.A. Odeyemi, N.A. Kasan, Swinging between the beneficial and harmful microbial community in biofloc technology: a paradox, Heliyon 10 (3) (2024) e25228, https://doi.org/10.1016/J.HELIYON.2024.E25228.

[85] S.Z. Abbas, Y.C. Yong, M.A. Khan, M.R. Siddiqui, A.A.H. Hakami, S.A. Alshareef, M. Otero, M. Rafatullah, Bioflocculants produced by bacterial strains isolated from palm oil mill effluent for application in the removal of eriochrome black T Dye from Water, Polymers 12 (7) (2020), https://doi.org/10.3390/polym12071545.

[86] M.H. Khanjani, A. Mohammadi, M.G.C. Emerenciano, Microorganisms in biofloc aquaculture system, Aquacult. Reports 26 (2022) 101300, https://doi.org/10.1016/J.AQREP.2022.101300.

[87] F.F. Wirth, Consumers' shrimp purchasing preferences: an application of conjoint analysis, J. Food Prod. Market. 20 (2) (2014) 182–195, https://doi.org/10.1080/10454446.2012.735630.

[88] M.T. Uddin, S. Roy, A.R. Dhar, Consumers' attitudes towards prawn consumption in Bangladesh: an investigation on perceived value and willingness-to-pay, Fishes 9 (11) (2024) 429, https://doi.org/10.3390/FISHES9110429, 429.

[89] S. Meire, L. De Araújo, A.A. Gonçalves, A new ready-to-bake seafood meal based on pacific white shrimp: product development, cost evaluation, consumer acceptability, and shelf life stability, Open Food Sci. J. 11 (1) (2019) 18–24, https://doi.org/10.2174/1874256401911010018.

[90] S. Balakrishnan, S. Sheeba Rani, K.C. Ramya, Design and development of IoT based smart aquaculture system in a cloud environment, Int. J. Oceans Oceanogr. 13 (1) (2019) 121–127. http://www.ripublication.com/ijoo19/ijoov13n1_10.pdf%0A.ripublication.com.

[91] J. Huan, H. Li, F. Wu, W. Cao, Design of water quality monitoring system for aquaculture ponds based on NB-IoT, Aquacult. Eng. 90 (April) (2020) 102088, https://doi.org/10.1016/j.aquaeng.2020.102088.

[92] C. Durán, R. Carrasco, I. Soto, I. Galeas, J. Azócar, V. Peña, S. Lara-Salazar, S. Gutierrez, Quantum algorithms: applications, criteria and metrics, Complex Intell. Syst. 9 (6) (2023) 6373–6392, https://doi.org/10.1007/S40747-023-01073-9/METRICS.

[93] R. Ismail, K. Shafinah, K. Latif, A proposed model of fishpond water quality measurement and monitoring system based on Internet of Things (IoT), IOP Conf. Ser. Earth Environ. Sci. 494 (1) (2020) 012016, https://doi.org/10.1088/1755-1315/494/1/012016.

[94] N.T.M. Pratiwi, B. Widigdo, D.A. Syifa, Water quality and organic content from intensive system of vaname production at coastal area of Sumur, Pandeglang, Banten, IOP Conf. Ser. Earth Environ. Sci. 420 (1) (2020) 012022, https://doi.org/10.1088/1755-1315/420/1/012022.

[97] M.H. Khanjani, L.O.B. da Silva, G.K. Fóes, F. Vieira, N. do, M.A. Poli, M. Santos, M. G.C. Emerenciano, Synbiotics and aquamimicry as alternative microbial-based approaches in intensive shrimp farming and biofloc: Novel disruptive techniques or complementary management tools? A scientific-based overview, Aquaculture 567 (2023) 739273.

[98] M.H. Khanjani, M. Sharifinia, S. Hajirezaee, Biofloc: A sustainable alternative for improving the production of farmed cyprinid species, Aquaculture Reports 33 (2023) 101748.

[99] M.H. Khanjani, M.T. Mozanzadeh, M. Sharifinia, M.G.C. Emerenciano, Biofloc: A sustainable dietary supplement, nutritional value and functional properties, Aquaculture 562 (2023) 738757. https://doi.org/10.1016/J.AQUACULTURE.2022.738757.