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*Review Article*

# Could Biofloc Technology (BFT) Pave the Way Toward a More Sustainable Aquaculture in Line With the Circular Economy?

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Aquaculture is a growing industry, but current practices and raw material utilization must be reviewed to ensure a resilient and sustainable development. In this sense, the transition from a linear economy (take, make, dispose) to a circular one (renew, remake) is accelerating. The biofloc technology (BFT) is a relatively new cultivation system that can be adopted to accomplish more sustainable aquaculture and circularity goals. This document discusses BFT and its association with the circular economy (CE), the current aquaculture challenges, and the role of BFT in overcoming those challenges. This manuscript adopts Cramer's 10 R's and Muscat et al.'s five P's frameworks to understand whether a functioning BFT and its key compartments (i.e., feed, environment, water, system, and microbials) align with CE's core principles. In addition, the present work provides and discusses relevant insights regarding the further (industry and academia) application of CE approaches, especially in a biofloc-based farming context. According to the findings and connections with Cramer's 10 R's and Muscat et al.'s five P's frameworks, BFT encompasses several transitioning steps into circularity and could play a crucial role toward a more sustainable aquaculture in line with the CE.

**Keywords:** aquafeeds; biofloc technology; circularity; environment; sustainability

## 1. Introduction

The exponential increase in the world's population poses many challenges. According to the Food and Agriculture Organization of the United Nations (FAO), the global population will reach 10 billion by 2050 [1]. The current food production processes and nutrition models are inefficient, unsustainable, and may not support a global food demand of this magnitude [2].

Recent data suggest that by 2050, humans may consume 367 Mt of livestock meat and 172 Mt of fish meat. Edible fish provide over 30% of protein consumption worldwide, and more than half are derived from aquaculture and mariculture [3, 4]. The aquaculture industry has taken off rapidly on a global scale and is regarded by some as a vital part of providing nutrition [5, 6]. However, aquaculture's growth is hindered by the availability of suitable and cost-effective feeds [7, 8], water shortages, the decreasing availability of water resources [9, 10], the pollution caused by effluents from cultivation farms [11, 12], the lack of the use of genetic improved populations [13], the excessive dependence on finite marine resources for aquafeeds, and the prevalence of microbial and parasitic diseases [14, 15]. As such, key objectives should be considered to increase sustainable aquaculture production, for example, (i) adoption of genetically improved population [16]; (ii) expansion without significantly increasing the use of natural resources (e.g., water and land) [9]; (iii) development of sustainable production systems that do not affect or have a minimal impact on the surrounding environment and animal welfare [17–19]; and (iv) provide community economic and social support for a resilient aquaculture production [9, 16, 20]. New techniques and technologies, such as recirculating aquaculture systems (RASs) and biofloc technology (BFT), are essential to achieving important goals of sustainable aquaculture [20, 21]. For instance, optimizing stocking density and system management with reduced water exchange, improved feed conversion ratio (FCR), and reduced feed costs are a few deliverable examples once BFT is implemented and functioning [16, 22, 23]. This technique also has comparable bioremediation efficiency and normally represents less investment costs than other bioremediation systems (such as RAS) [24].

In addition, BFT allows feed optimization using low-protein feeds without affecting growth since microbial biomass complement the protein requirement and other high-value nutrients [25–27]. Also, BFT is used to treat aquaculture waste (either organic or inorganic) in bioreactors [28] and prevent disease through the in situ microbial communities formed, including bacteria, algae, and protozoa [29]. For a proper functioning BFT, a symbiotic process is carried out among the culture aquatic animals, heterotrophic/chemoautotrophic bacteria, and other living microbes in the water [9]. In this context, BFT has been considered a promising alternative for eco-friendly and sustainable aquaculture [30–32].

The current linear economy "take-make-dispose" leads to waste, depletion of limited natural resources, and environmental degradation. Circular economy (CE) is one of the ways to deal with these trends. In a CE, production and consumption are decoupled from the environmental pressure to overcome the current "linear" model based on continuous growth and increasing resource demand [33, 34]. CE appears to be the focus on economic prosperity, followed by environmental quality, and social dimensions of sustainability [35]. Currently, several frameworks have been developed according to different industries scenarios and needs. Broadly, CE is also known as the "reduce, reuse, recycle, and recovery" industry framework, reducing resource consumption, preserving natural resources, and recovering the resource as energy [35, 36]. A broader and pioneer approach was developed by Cramer [37] suggesting 10 R's levels of circularity. In this framework, also known as "ladder of circularity," the highest priority (1–10) is refusing the use of raw materials ("prevention"), followed by reducing the use of raw materials per unit of product, and so on. Another key one was suggested by Muscat et al. [38] where five ecological principles were selected to guide biomass use toward a circular bioeconomy. This approach is (agro) ecosystems driven and suggests a more in-depth transformation of current economic system, including holistic changes to technologies, organizations, social behavior, and markets, as well as to policies.

In this context, aquaculture needs to rethink some of the common farming practices to improve the sustainability of operations, and one way is to embrace a "circular aquaculture bio-economy" [36]. If widely adopted by the industry, this new behavior could be an essential element for the long-term resilience of the aquaculture sector, enhancing food-wasting–recycling process, reducing the environmental impact [39], and in some cases generating coproducts [40] and potentially higher profitability.

The present manuscript analyzes BFT as a suitable technology contributing to the CE in the aquaculture sector, bringing a perspective of moving from a linear model of production to a circular bioeconomy. There is no intent to develop a new framework or explore/compare a range of sustainability indicators (e.g., life cycle assessment [LCA], emergy accounting, among others), but instead simply breakdown key BFT principles and help to understand the connections with two established approaches [37, 38]. The completion of such exercise may help (i) the thinking process for farmers, technicians, retailers, distributers, and policy makers; and for (ii) future framework development with data-driven recommendations to optimize raw materials utilization and enhance the management practices in aquaculture operations, especially BFT.

## 2. What Is the CE and Why Is This Important to the Aquaculture Industry?

There are more than 100 definitions of CE [4, 41–45]. The Ellen MacArthur Foundation (EMAF) has defined a CE as "an economic system designed to be regenerative and restorative" [46]. Through the EMAF's circular economic model, it is aimed to generate financial, natural, and social capital based on three fundamental principles. Herein, to create a sustainable system, we must (i) design out waste and pollution, (ii) reuse products and materials, and (iii) restore natural systems to create an industrial system that is both restorative and regenerative. Instead of the current linear model, a CE model emphasizes economic growth and activities that are independent of finite resources and minimize system waste, thus creating positive societal benefits [47]. Within a CE, value chains are closed loops in which materials initially intended for disposal are reused, recycled, or reprocessed [46].

Currently, several frameworks have been developed according to different industries, scenarios, and needs. Cramer [37] proposed a 10 R's framework to add value to the economy, well-being, and the environment. Although focused on industrial and metropolitan purposes, this approach could easily be tailored to other industries, including aquaculture. This approach considers 10 R's levels of circularity, that is, (i) refuse: prevent raw materials use, (ii) reduce: decrease raw materials use, (iii) renew: redesign product in view of circularity, (iv) reuse: use product again, (v) repair: maintain and repair product, (vi) refurbish: revive product, (vii) remanufacture: make new product from second hand, (viii) repurpose: reuse product but with other function; (ix) recycle: salvage material streams with highest possible value; and (x) recover: incinerate waste with energy recovery. In general, it seems to be more focused on economic prosperity, followed by environmental quality, and social dimensions.

On the other hand, Muscat et al. [38] suggested an agro (ecosystem) approach where five ecological principles were selected to guide biomass use toward a circular bioeconomy: (i) safeguard: safeguard and regenerate ecosystems; (ii) avoid: avoid nonessential products and wasting those that are essential, (iii) prioritize: prioritize biomass streams for basic human needs (e.g., food before feed or energy), (iv) recyle: use and recycle byproducts of agroecosystems (i.e., ecosystems supporting food production systems), and (v) entropy: use renewable energy while minimizing overall energy use. The authors focused more on environmental justifications and implications of a circular (agriculture and livestock) bioeconomy and less on social and economic consequences. Similarly, Chary et al. [48] expand on Muscat et al.[38]'s framework and bring perspective of achieving greater environmental sustainability, with social and economic aspects less developed, but now focused on the aquaculture sector. The authors provided a narrative review to translate the five circularity principles to better understand the future role of aquaculture in circular food systems. Regardless of the approach, the hierarchy of R's and guiding circularity principles (meaning priorities) will depend on and vary according to different industries and segments of the economy, and for the aquaculture, aspects such as consumer's demand, culture species, production system, level of technification and management, are just a few examples. There are clear evidence and opportunity to scaling up the adoption of CE practices within the aquaculture industry; an industry that has been criticized for its negative environmental and social effects [49–52]. For instance, much of the criticism has been directed to the feed formulations, especially marine ingredients-based diets (proteins and oils derived primarily from fisheries), and the discharge of nutrients from farms [19, 53–55].

In some cases, these issues also coincide with the lack of markets for fisheries and aquaculture by-products [56], the need for sustainable ingredients for terrestrial and aquaculture livestock [57], peak phosphorus accumulation [58–60], and the increased pressure on land and water resources [61]. Therefore, the aquaculture industry and the food system are primed to implement new practices, for instance, CE principles, addressing waste management concerns and providing high-quality raw materials. A CE should have a restorative and regenerative purpose, and it is crucial to involve eco-design throughout the aquaculture process from the earliest stages of development.

Especially in large-scale verticalized operations, once the aquaculture facility is constructed, environmental, economic, and social implications are hard to change due to the complexity and costs of subsequent adjustments. Consequently, it is imperative during the design phase to consider and make proper decisions regarding the entire production and processing loop (e.g., feeds, side-stream usage, effluent treatment, and by-products) [62]. In this sense, aquaculture systems will require employing ecological principles shortly, as evidenced by recent advances in systems such as the biofloc system, the integrated multitrophic aquaculture (IMTA) [63], aquaponics [64], aquamimicry [65], and recirculation aquaculture systems [66]. Regarding nutrition and genetics, based on a CE concept aquafeeds should explore creative formulation designs that could offer in the long run the potential to improve profitability and sustainability through the valorization of by-products and side streams [6, 63]. In addition, genetic improved populations could enhance the feed efficiency and better utilization of non-marine resources as dietary ingredients [67].

In the aquaculture space, some examples can be found embracing the CE practices. For instance, tilapia carcass, by-products, and wastes from aquaculture supply chains can be used to produce enriched food for human consumption [68], supplement essential nutrients or as dietary ingredient to other aquatic [69] and terrestrial farming species [70], as well as pets [71]. Moreover, approximately 35% of fish meal used in aquaculture comes from fish processing trimmings, and several by-products and waste streams can be utilized as inputs for new aquafeed ingredients such as insect [72, 73] and bacterial meals, boosting growth [74], survival during pathogen challenging conditions [75]. Other examples include the use of sludge in biogas production, coincineration/energy, or fertilization [6]. The adoption of these approaches are example of how the industry can promote circularity and enhance the green credentials [19].

## 3. What Are the Current Main Aquaculture Challenges? A Brief Outlook

*3.1. Water Scarcity and Effluent Discharges.* There is no doubt that water is essential to the production of energy, food, economic development, and ecosystems. Despite this, 40% of the world's population suffers from water scarcity, and 80% of sewage reaches the ecosystem without being treated or reused [76]. Aquaculture professionals are striving to reduce the amount of water consumed in the process of aquaculture. Approximately 70% of the world's population will experience water scarcity by 2050 [9] and the aquaculture industry must embrace such issue. Some aquaculture systems (such as conventional system) need >20,000 L of water to produce 1 k of fish or shrimp; however, others such as RAS, aquaponics, and BFT can rely on less than 200 L/kg produced [77–80]. Timmons and Losordo [81] described several aquaculture operations and found water utilization values of 21, 64.7, 210, and 20 $m^3$ of water per kilogram produced of tilapia (pond systems, Taiwan), catfish (pond systems, USA), trout (raceways, USA), and shrimp (pond, Americas), respectively.

Aquaculture systems are typically polluted and deteriorated by their food supply. About 30% of the nutrients provided are converted to a product, whereas the rest must be removed and disposed of as effluents. The types of waste produced by aquaculture farms are basically similar, although there are differences in their composition and quantity, which depend on the system and the cultured species [82, 83]. The main types of discharge in laboratories and farms are (a) feces and metabolites, (b) food remains, and (c) residues of disinfectants, antibiotics, and biocides [84]. Furthermore, when discharges from some farms are drained near the water intakes of others, cross-contamination effects are created as nutrients, particulate matter, and microorganisms can move from one farm to another [18, 85].

The environment is negatively affected by waste containing N, P, and dissolved organic carbon compounds [86]. The major source of these particles is unconsumed food, fish waste, and the residual part where unassimilated forms accumulate the most nutrients. Minerals require additional treatment to be utilized effectively [87]. There is evidence that up to 70% of the feed supplied to aquaculture production systems ends up as particulate matter at a daily average of 0.4%–12.3% [84, 88]. Normally, this matter contains approximately 7%–32% nitrogen as well as 30%–84% phosphorous for the development of the cultured organisms. There are two types of particulate fractions in aquaculture; suspended solids and settleable solids [89]. In aquaculture systems, suspended solids are fine particles ranging from 30 to 100 micrometers (m), so they donnot settle and stay suspended in the water, making them hard to collect [90]. Meanwhile, settleable solids are bigger particles (100 >µm) and form sediment more quickly. They can be collected and removed from culture systems more easily than suspended solids [91].

*3.2. Social Conflicts.* Traditional aquaculture uses large amounts of natural resources. In the case of mariculture, the facilities are located in the coastal zone, while in freshwater, they are located near rivers, streams, and lakes. Traditional farms with extensive and semi-intensive systems are characterized by having large areas. These can modify the natural environment, and depending on the location, they can affect other activities and generate conflicts. Social impacts are usually related to competition in land and water use, landscape modification, and interference with other productive activities [92]. Therefore, aquaculture expansion strategies must be accompanied by sustainability studies and the preservation of natural resources [93–95]. In certain regions, aquaculture has negatively impacted marine and artisanal fisheries [96, 97]. These include the obstruction of access to the sea for local fishermen, placement of nets, and other daily activities [96]. In addition, the installation of farms in the coastal zone has generated conflicts with tourism. For several years, the installation of cages and other aquaculture facilities in coastal areas has been incorporated as a negative landscape element [98]. While aquaculture contributes more than 40% of aquatic products, tourism is an activity with significant expansion which has a substantial economic impact; therefore, adequate strategies must be established that allows a coexistence between the two industries [99].

The conversion and abandonment of agricultural land for aquaculture development is a phenomenon that has been registered in some countries such as China and Malaysia. Some farms have been established on land that was previously used to cultivate rice and other vegetables that are of great importance to meet the growing demand for food in the world [100]. In addition, the threat of climate change requires taking efficient mitigation and protection actions. Environments such as mangroves, coral reefs, beaches, and brackish marshes must be adequately conserved and protected due to the critical role they play in the biotic and abiotic processes of the coastal zone [101, 102], for which economic activities, including aquaculture, must be developed in a sustainable way considering the future scenario.

*3.3. Presence of Diseases.* Disease outbreaks pose a latent risk for aquaculture regardless of the cultivated species. Infectious diseases may lead to catastrophic losses in aquaculture, causing entire aquaculture parks to give up their operations and start over. Infectious diseases can be caused by bacteria, viruses, fungus, and parasites; however, diseases that might not typically affect wild species can become problematic in aquaculture [103]. Some important diseases caused by pathogenic bacteria are mycobacteriosis pathoge *Mycobacterium fortuitum* [104], streptococcosis pathoge *Streptococcus agalactiae* [105], vibriosis pathoge *Vibrio harveyi* [106], aeromoniasis pathoge *Aeromonas hydrophila* [107], edwardsiellosis pathoge *Edwardsiella tarda* [108], and pseudomonasis pathoge *Pseudomonas anguilliseptica* [109].

During the past decades, recommendations for preventing opportunistic diseases included suitable water source and quality, moderating stocking density, and using pesticides and antibiotics [103]. However, the current aquaculture requires to be intensified to cope with the food demand; simultaneously, antibiotics are restricted or banned in some countries due to antibiotic resistance to pathogens, and threats to human health [110]. Therefore, the current challenge is to produce aquatic protein in intensive but biosecured environment. One of the latent risks in fish farming is the appearance of diseases that are not detected until the infection process is in the advanced stages. For example, granulomatous diseases caused by bacteria can remain encapsulated by the same fish for weeks and eventually break into the body leading the host to a precarious health status [111, 112]. Under this scenario, the use of antibiotics becomes necessary; however, early detection methods, including molecular tests, can provide a wide margin of action; also, the establishment of prophylactic measures and the implementation of closed systems prevent the spread of pathogens. In this sense, modern aquaculture requires systems that do not necessarily need to be connected to bodies of water, while at the same time maximizing/reusing its use and avoiding the spread of pathogens to the environment and, finally, to other farms [113].

*3.4. Antibiotic Use.* Antibiotics are used worldwide, especially in salmon and shrimp aquaculture [114, 115]. There is a wide variety of bactericidal compounds, and their use depends on availability, price, and the type of infectious agent to be eradicated. The continuous use of antibiotics creates resistance and affects the composition of the natural bacterial flora [116, 117]. A change in the structure of the bacterial community in the sediments and the water affects the decomposition process of organic matter and interferes with the biogeochemical cycle of some nutrients [118]. In this sense, Chen et al. [119] suggested that, due to the risks involved in antibiotics, it is necessary to promote strict management measures and environmental monitoring in water bodies that receive aquaculture effluents. Tetracycline, amoxicillin, flumequine, oxytetracycline, sulfamerazine, thiamphenicol, and erythromycin are among the most commonly used antibiotics in aquaculture [120]. Antibiotic contaminants are new environmental pollutants that may change the balance of aquatic ecosystems [115]. The overuse of antibiotics can have negative effects like changing the population of environmental bacteria [121], changing the population of host digestive microflora [122], and changing fish responses to stress [123].

The persistence of antibiotics in fish and the consumption of fish by humans can cause bacterial infections in humans and weaken of immune system [115, 120, 124], problems related to allergy and poisoning of workers [125], changing the natural flora of the environment, plankton, microbiota [110, 126], and changing the ecological balance of the environment [127, 128].

*3.5. Wild-Caught Fishmeal Replacement.* In 2018, 88% (156 million tons) of world fishery production was used for direct human consumption, while the remaining 12% (22 million tons) for nonfood purposes, highlighting the production of fishmeal and fish oil, with 18 million tons [129]. Although this amount has remained stable since 2010, it is still high, and it is necessary to continue exploring the use of alternative sources to produce aquafeeds.

The substitution of fish protein for the elaboration of aquaculture feeds has had important advances. In its beginnings, the most critical challenges for replacement were related to the content of essential amino acids, digestibility, and the presence of antinutritional compounds in alternative sources [130]. However, recent studies indicate that different animal processing by-products (e.g., poultry waste meal) and insect meal have a suitable amino acid profile and digestibility, so they can be included in diets in satisfactory percentages without affecting the productive response of shrimp, tilapia, and some other species [131–133]. Additionally, there are promising sources such as biomass-derived from bioethanol fermentation, microbial protein, cereal flours, cereal glutens, legume meals, etc. [74, 134, 135].

## 4. BFT: Origin and Basic Concept

The BFT was first developed at the French Institute of Exploitation of the Sea (IFREMER) in the early 1970s with *Penaeus monodon*, *P. merguiensis*, *P. vannamei*, and *P. stylirostris* [136, 137]. Due to the commercial application of BFT, in 1988 in Tahiti, SOPOMER farm using 1000-$m^2$ concrete tanks and limited water exchange recorded world production of 20–25 tons/ha with two crops per year [137]. Biofloc was also applied for tilapia and whiteleg shrimp by the US Marine Aquaculture Institute in the 1980s and early 1990s. Several research and academic organizations are currently pursuing various studies on BFT, with an emphasis on applications of the technology in key areas, such as growth management, nutrition, reproduction, microbial ecology, biotechnology, and economics. With the proper management of this technology (adjusting the carbon-to-nitrogen ratio, limited water changes, engineering and suitable aeration systems, etc.), the bacteria population can be used effectively [20, 138, 139]. For example, in some periods during the production cycle, the carbon-to-nitrogen ratio must be adjusted above 10 for heterotrophic bacteria to assimilate nutrients efficiently [140, 141]. In parallel, chemoautotrophic (e.g., nitrifying) bacteria play a key role in nitrogen cycling and water quality maintenance, especially in controlling toxic nitrogen–compounds [142]. These authors highlighted that other biofloc-based approaches such as chemoautotrophic and mature (inoculum) systems can efficiently control nitrogen–compounds, without increasing suspended solids loads.

Regardless the approach, zero or minimal water exchange systems must be employed to maximize biosecurity and minimize the farm's environmental impact [9, 143]. Proper aeration design and engineering are used to supply oxygen to the pond/tank, create water circulation, suspend organic particles, and develop proper microbial communities; while sustaining high fish–shrimp–microbial biomasses [9]. In summary, the main functions of bioflocs are (i) to maintain water quality by absorbing/transforming nitrogen compounds in the pond/tanks and producing microbial protein, (ii) to serve as a natural complementary food source, reducing FCR and decreasing feed costs [144, 145] as well as boosting reproductive outcomes [27], and (iii) pathogen competition once a proper microbial population in the water is achieved. In addition, other benefits include less hormone utilization and less hormone residues during masculinization of tilapia in BFT [146, 147], boosted animals health and immune system [148], as well as coproduction of several high-value species [149], including fish with vegetables, fish with shrimp, shrimp with microalgae, oysters, and seaweed, with increased [150–154].

## 5. How Does the BFT Align With the CE and Address Current Aquaculture Challenges?

Figure 1 highlights key "circular" approaches of BFT and suggests the connections between BFT and CE, preventing waste and creating in situ value. From the nutrition perspective (yellow text boxes), key aspects of resources savings, improved nutrient recycling and recovery and less carbon footprint can be observed. The improved feed efficiency and lower FCR, natural food source in the form of "bioflocs," inclusion of biofloc meal, alternative, and local feedstuff in diet formulation (less premium ingredients) and the reduction of dietary protein are examples of improved circularity. With respect to the adoption of new systems variations, for example, IMTA and aquaponics (blue text boxes), gains in terms of nutrient recovery, resources savings, and system optimization can be observed. Similarly, water and land optimization (in situ water treatment, less water requirement, and water reuse), close-to-market farms, opportunities for renewable energy sources and improved animal health and performance (green text boxes) are examples of alignments among BFT and improved circularity. Detailed data review will be explored in Sections 4.1–4.4.

Figure 2 breakdown key BFT principles and help to understand the connections with two established approaches [37, 38]. From the 10 R's of the circularity ladder, more than 90% can be connected and are addressed to some extent by BFT. In addition, most of Muscat et al.'s five ecological principles toward a circular bioeconomy are also covered by BFT.

Considering the current aquaculture challenges, thorough Sections 4.14.2, 4.3 and –4.4, we describe connections with the 10 R's [37], key advantages of BFT, but also limitations (Section 4.5). For instance, in an economic and social perspectives, if properly managed BFT can increase the net profit margin of commercial operations (e.g., intensive shrimp farms) [155], enhancing employment conditions. From an environment perspective, reusing water in fish and shrimp production can be achieve [77, 156], improving the circularity of BFT farms.


FIGURE 1: Illustration highlighting key "circular" approaches of BFT in line with CE creating in situ value. Yellow text boxes bring a nutrition perspective, blue text boxes bring an integrated multisystem "coproduction" perspective, and green text boxes bring a health, performance, and system optimization perspective. *Note:* Illustration is an original figure created by the authors of the manuscript.

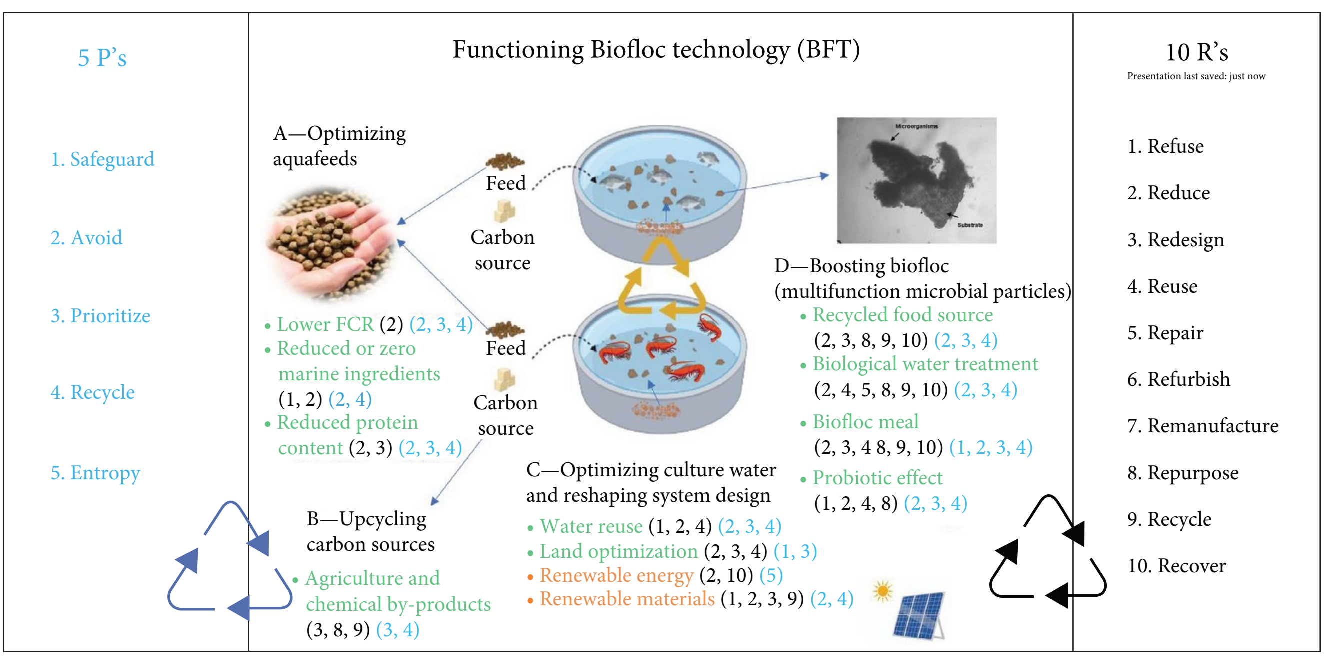


FIGURE 2: Illustration highlighting key "circular" approaches of BFT (A, B, C, and D) and proposed connections and synergies with the 10 R's [37] and 5 P's [38]. Green font: approaches currently embraced by BFT; orange font: approaches under initial adoption. *Note:* Illustration is an original figure created by the authors of the manuscript.

*5.1. BFT to Reduce Effluent, Land, and Water (R's 1, 2, 3, and 4).* Biofloc does not generate significant aquaculture effluents since only a limited quantity of water is exchanged [135]. Conventional (semi-intensive) production of fish (e.g., tilapia) and shrimp (e.g., *Litopenaeus vannamei*) in earthen ponds normally reach ~10 and ~3 tons/ha in ~180 and ~120 days, respectively. Of course, these are just random examples and might change case by case. However, it is clear that production can significantly be improved and the land optimized in BFT systems. For the same hectare of production, values of 60 and

30 tons/ha can be found in tilapia and *L. vannamei* in BFT-based systems [29]. In these senses, there are clear advantages in terms of land optimization and opportunities for controlled large-scale production [157], as well as focused on premium products (e.g., fresh never frozen shrimp) in close-to-market areas [149]. However, BFT systems require higher aeration and present high-power consumption in comparison to conventional pond farming [20]. The high aeration/water turbulence promotes higher evaporation rates, and top-ups of 2%–4% of pond volume per day are often observed [9, 13]. On the other hand, this high demand is translated into an efficient and rapid reduction of ammonium concentrations [158–160], 30% more economical than conventional biofilters [161–163].

In terms of water use, BFT minimizes water consumption since there is limited water exchange during production [9]. Table 1 presents the water consumption in different aquaculture systems. For instance, freshwater consumption has been reported at 6.8 $m^3$/kg of shrimp *Macrobrachium rosenbergii* and at 0.071 $m^3$/kg of Nile tilapia *Oreochromis niloticus* [78, 79]. Comparatively, traditional freshwater aquaculture uses 16.9 $m^3$ of water per kilogram of production. Consequently, it is essential to adopt farming techniques that use natural resources and increase production [173]. In addition, Krummenauer et al. [77] reported that the amount of saltwater needed to produce shrimp (*L. vannamei*) using BFT system varies from 98 to 169 L of water per kilogram of production. Otoshi et al. [21] calculated that 163 L of saltwater is required to produce 1 kg of *L. vannamei* using biofloc-based super-intensive systems. Krummenauer et al. [174] documented a similar low water use of 169 L/kg of shrimp produced in 35-$m^3$ raceways. Further, Samocha et al. [175] reported that only 98 L of water was required to produce 1 kg of shrimp in an experimental zero-exchange super-intensive system.

Not only reduction, but also reusing this limited resource has been documented in BFT. Krummenauer et al. [77] observed advantages in terms of survival, growth, and feed conversion rates of *L. vannamei* cultured in reuse water. For tilapia, Malpartida Pasco et al. [176] established a biofloc culture using 50% biofloc-rich water as inoculum and found no adverse effects caused by the water source on survival and productivity. Other advantages such as comparable proximal composition, superior gonad maturity, and healthy status were found when water from BFT systems as recycled for tilapia cultivation [156, 177].

*5.2. Biofloc as an In Situ Food Source and Ingredient in Aquafeeds (R's 1, 2, and 3).* In BFT farming systems, bioflocs act as an in situ food source, available continuously providing complementary nutrients for aquatic species within the rearing media [178].

Some studies on biofloc's use in cultured aquatic diets can be found in Table 2. Aquatic species with adequate morphological structure (e.g., shrimp, tilapia, and bivalves) have advantages enabling them to graze/filter/capture the microbial aggregates properly [188–190]. As a result, a decrease in FCR and improved growth rates have been reported for shrimp, freshwater prawns, and fish [79, 191, 192].

In *L. vannamei*, over 29% of shrimp's diet can be replaced by bioflocs in open pond conditions [193]. Wasielesky et al. [192] demonstrated that by consuming flocs, the *L. vannamei* FCR can be reduced from 1.39 to 1.03, and the growth rate is increased from 0.39 to 1.25 g/week. By reducing FCR and increasing feed efficiency, biofloc can be used to replace approximately 30% of *L. vannamei* feed without affecting their growth [194]. Azim and Little [195] reported reduced FCR and improved growth in tilapia juveniles raised in BFT in comparison to clear-water conditions. Pérez-Fuentes et al. [79] found similar outcomes, but now for *M. rosenbergii* reared in ponds, in which BFT outperformed the traditional water-exchange method.

Biofloc systems can reduce the dietary protein requirement [196]; however, it is not always the case [192, 197]. Tilapia, crustaceans, and carp can use in situ microbial proteins instead of dietary feed-based protein reducing its content in formulations [26, 27, 196–201]. In some cases, for example tilapia, bioflocs may contribute about 50% of fish's protein requirement [9]. Mansour and Esteban [198] demonstrated that tilapia fed with 20% crude protein (CP) diet in biofloc performed significantly better than those fed a 30% CP diet in clear-water conditions. Growth performance, humoral and cellular immune parameters, and superoxide dismutase and catalase activity were significantly improved in biofloc treatments. Besides the reduction of dietary CP, BFT system also allowed the inclusion of alternative feed ingredients [202]. Some examples in tilapia culture include (i) inclusion of insect meal-based diets [203] and (ii) food waste pizzeria by-product [204]; increasing the circularity and reducing the carbon footprint of the diets. Olier et al. [205] suggested that the addition of a vertical substrate enabled savings on dietary protein (reduction of 35% to 30% CP content) without losses on growth performance and chemical aspects in *L. vannamei* biofloc-based culture. Silva et al. [196] observed in biofloc-based tilapia juveniles culture (10–60 and 60–230 g) fish can be fed on diets with 28% of CP (26% of digestible protein) and 22% CP (20% of digestible protein), respectively, without compromising performance. Interestingly, Ekasari et al. [189] showed that biofloc consumption by shrimp, red tilapia, and mussels occurs irrespective of floc size but that floc size can play an important role in the quality of biofloc in terms of nutritional composition and nitrogen retention by the animals.

As ingredient in aquafeeds, BFT is emerging as a sustainable way to produce high-value "biofloc meal" used in commercial aquafeeds [134]. Nitrogen transformation/recycling process and low-cost agricultural by-products can be used as substrates for microbial growth in controlled environment [28]. Similarly, other microbial-derivate ingredients (e.g., Novacq) have shown positive results in *L. vannamei*, *P. monodon*, and tilapia, improving growth, feed efficiency, and resilience during pathogen challenges [74, 75, 206].

Ex situ biofloc is normally produced in especially designed units, for example, sequencing batch reactor (SBR), which works independently [28, 190, 207, 208]. Using a small diameter mesh (e.g., 10 μm), biofloc biomass can be collected, decanted or filtered, centrifuged, dried/freeze-dried, and converted

Table 1: Water utilization in biofloc and other different aquaculture systems.

| Rearing system | Reared species | IW (g) | RP (day) | Water consumption | Highlights | Reference |
|---|---|---|---|---|---|---|
| Biofloc | *O. niloticus* | 1.17 | 42 | 52.48–101.54 L/kg | In the BFT, the amount of water consumption increases with the increase in stocking density | Lima et al. [164] |
| Biofloc<br>Clear water | Gibel carp | 19.09 | 60 | 300 L/kg<br>31,700 L/kg | The water consumption in the BFT was about 100 times lower than that of the CW | Cang et al. [165] |
| Biofloc<br>Clear water | *O. niloticus* | 30 | 140 | 108 L/kg<br>1,166 L/kg | The water consumption in the BFT was about 10 times lower than that of the CW | Hwihy et al. [166] |
| Clear water<br>Aquaponic | *Clarias gariepinus* | 7–8 g | 70 | Water exchange: 20% every morning and evening<br>water circulation: 1500 L/h | The water consumption in the aquaponic system was negligible, and the water is circulated | Diatin et al. [167] |
| Clear water<br>Biofloc | *L. vannamei* | 2.56 | 35 | Water exchange: daily 35%–50% of the volume of rearing water<br>Zero-exchange water | Daily water consumption in the CW system was 35%–50% higher than the BFT | Khanjani et al. [168] |
| Biofloc<br>Clear water | *O. niloticus* | 1.79 | 35 | 61.47 L/kg<br>2777.64 L/kg | Water consumption was 45 times lower in the BFT than in the CW | Khanjani and Alizadeh [169] |
| Biofloc | *L. vannamei* | | 360 | Zero water exchange | Water consumption in the BFT system was lower | Almeida et al. [170] |
| Biofloc<br>Clear water | Indian major carp | Rohu = 26.33<br>Catla = 17.3<br>Mrigal = 28.1 | 90 | 1050 L/TWR<br>1750 L/TWR | Water requirement in BFT was ~37.8% less as compared to CW | Deb et al. [170] |
| Biofloc<br>Clear water | Rohu, *L. rohita* | 50 | 90 | 133.7 L/kg<br>200.5 | The needed number of water exchanges was more in treatments with higher stocking densities and less in biofloc treatments | Mahanand et al. [171] |
| Biofloc<br>Clear water | *L. vannamei* | 0.085 mg | 7 | 6.49–6.89 L/thousand PL<br>56.22 L/thousand PL | Treatment with dextrose or molasses required ~12% of the water used by the CW group | de Lorenzo et al. [172] |

*Note:* Indian major carp, Rohu (*Labeo rohita*), Catla (*Catla catla*), Mrigal (*Cirrhinus mrigala*).
Abbreviations: CW, clear water; Gibel carp, *Carassius auratus gibelio* ♀ × *C. carpio* ♂; IW, initial weight; PL, postlarvae; RP, rearing period; TWR, total water requirement.

Table 2: Research on using biofloc meal and wet biofloc as feed ingredient and food source in different aquaculture scenarios.

| Reared species | IW (g) | RP (day) | Biofloc source | Substituted amounts in diet | Suitable amount | Highlights | Reference |
|---|---|---|---|---|---|---|---|
| *L. vannamei* | 2.48 | 28 | Microbial floc meal + soy protein | 0%–100% | 100% | Improved shrimp survival rate and growth performance | Bauer et al. [134] |
| *L. vannamei* | 2.56 | 35 | Wet biofloc biomass | 33.3%–100% | 33.3% | Enhanced growth performance | Khanjani et al. [168] |
| *O. niloticus* | 0.57 | 44 | In-situ biofloc | 5% and 10% | 5% and 10% | Increased diversity of the gut's microbial | Deng et al. [179] |
| *L. vannamei* | 0.0057 | 42 | Ex situ biofloc | 5% and 10% | 5% | Improved water quality, growth performance, and survival rate | Uawisetwathana et al. [180] |
| *F. merguiensis* | 0.0045 | 30 | Wet biofloc biomass | 25%–100% | 25%–50% | Improved growth and survival rates | Khanjani and Sharifinia [140] |
| Red hybrid tilapia | 4 | 57 | Dried biofloc | 4% and 16% | 4% | Improved water quality and growth performance | Binalshikh-Abubkr and Mohd Hanafiah [181] |
| *P. monodon* | 16.9 | 42 | Biofloc powder | 0%–100% | 100% | Boosted immunocompetence | Promthale et al. [182] |
| *P. clarkii* | 0.0078 | 63 | Biofoc meal | 33%–100% | 33%–66% | Improved growth performance | Lunda et al. [183] |
| *P. monodon* | 2.90 | 60 | Dried biofloc | 0%–12% | 4%–8% | Improved growth performance | Anand et al. [184] |
| *O. niloticus* | 3.2 | 53 | Wet biofloc biomass | 0%, 15%, 30%, 45%, and 100% | 15% | Improved water quality and growth performance | Sarsangi Aliabad et al. [185] |
| *P. vannamei* | 0.03 | 60 | biofloc meal | 0%–40% | 30% | Biofloc meal incorporation at 30% in shrimp diet would potentially improves the growth performance and physiological responses of shrimp | Nethaji et al. [186] |
| *O. niloticus* | 21.52 | 85 | Synbiotic and biofloc meal | 3 g /kg feed | — | Adding synbiotics and biofloc meal to Nile tilapia diets is an effective strategy that can mitigate the potential adverse effects of salinity on growth and also improve gut microbiota, body composition, and tissue histomorphology | Hersi et al. [187] |

Abbreviations: IW, initial weight; RP, rearing period.

into a fine powder or "meal" [209, 210]. This relatively "new ingredient" can be incorporated into formulated diets and replace premium feedstuff with comparable performance [134, 211, 212]. Shao et al. [212] found that the 15% replacement of fishmeal with biofloc meal did not make negative difference on growth performance and digestive enzymes of shrimps compared with control group. A 28-day study conducted by Bauer et al. [134] investigated the effect of replacing fish meal by soy protein concentrate and biofloc meal on the growth and food intake of *L. vannamei* juveniles and found no adverse effects when replacing it completely. Shyne Anand et al. [213] showed that the addition of 4%–8% biofloc to the diet of *P. monodon* led to immunomodulatory effects and improved physiological condition. In brief, this area of research offers great potential since the nutritional properties of the biofloc can potentially be manipulated. However, production costs (e.g., US$/kg of biofloc meal), especially considering the drying methods and the impact on costs and performance, need further improvement and investigation.

*5.3. BFT: A Natural "Probiotic" Source and Elimination of Antibiotic Use (R's 1, 2, 4, and 8).* The aquaculture industry faces a major problem with diseases outbreaks with increasing intensification and scrutiny regarding antibiotic usage. Despite vaccines being developed and marketed (e.g., fish farming), they cannot be used as a universal tool and cost-effective means of disease control in all farms and regions [214].

In response, new strategies for disease management in aquaculture have been developed. For instance, biofloc can be an effective in situ strategy for managing diseases [215]. There is a "natural probiotic" effect created by the presence of beneficial bacteria in the biofloc, competing with pathogens and improving immunity both internally and externally [20, 216–218]. A probiotic is a beneficial bacterium that plays a key role in maintaining a healthy microbiome and water environment. Studies show that biofloc probiotics tend to mitigate the invasion of pathogenic bacteria, improving fish and shrimp immunity. The biofloc system significantly improves nonspecific immunity of animals cultured with these beneficial bacteria [219, 220].

External microbial blends (known as probiotics) can be added to enhance the microbial function of BFT. The study on external probiotics applied in BFT systems is summarized in Table 3. Table 4 shows that bioflocs have probiotic properties that reduce the activity of pathogenic agents, enhance immunity in farmed aquatic animals, and increase their survival rates. The use antibiotics in biofloc-based farming likely can drastically impact the natural microbial biota, causing disfuction of water quality and health attributes.

*5.4. BFT as a High-Yield System to Boost Productivity and Coproduction (R's 1, 2, 3, 4, 8, 9, and 10).* One of the important goals of farmers is to reduce production costs, improve yields, and profitability. There are several strategies to achieve such goals (e.g., increase or reduce stock densities, single or multiple phases, etc.); however, market prices play a key role on the approach selected [138, 139]. Production costs are primarily determined by growth rate, survival, and FCR. Additional costs such as electricity and labor also play a critical role [175]. In this sense, new technologies must be implemented to achieve greater profits, consistency, and predictability. According to Ray et al. [243], *L. vannamei* production increased by 41% with the biofloc system. Wasielesky et al. [192] reported that bioflocs improve the digestion of shrimp, increase growth by as much as 15%, and reduce the FCR by as much as 40%. Higher growth rates impact on the cycle's duration, translating in lower production costs. Compared to flow-through water-exchange systems, costs for pumping can be more economical in BFT due to reduced water exchange rates and less energy demand [9, 20]. However, aeration to supply proper levels of dissolved oxygen and provide water movement can significantly increase the production costs in BFT depending on the region. In some cases, higher profitability can be achieved using BFT [169], and the improved feed efficiency, yields, and water recycling can be determinant for positive economic outcomes and "green credentials."

Using BFT, a kilogram of green tiger shrimp (*P. semisulcatus*) and tilapia can be produced with 33% and 10% cost reduction, respectively [244].

Compared to traditional clear-water systems, Nile tilapia in biofloc-based conditions increased production by 43% in small-scale tanks [195]. In Table 5, the values of the FCR and production in the BFT and the increased percentage compared to the clear water system are presented. High survival was found in tilapia cultured in greenhouse ponds with BFT, ranging from 80% to 97% [30]. In shrimp pond cultures using biofloc, productivity has been found to be 8%–43% higher than in conventional methods [28, 148, 169, 210]. However, the production management (e.g., water quality and microbial management), species, feed and feeding, carbohydrates source, and biofloc consumption may have a direct impact on those numbers [137, 251].

Combining BFT with other species can improve production, diversity, and profitability, as well as enhancing circularity, water quality, and feed efficiency [153, 160, 252]. Two successful examples at experimental scale are combining BFT with IMTA [40, 63, 252] and with plant production in aquaponics, nowadays called as FLOCponics [153, 253, 254]. Coupling fish (tilapia) production with shrimp (*L. vannamei*) in IMTA-biofloc based decreased the sludge production per kilogram of fish biomass produced, and the recovery of nitrogen and phosphorus increased 27.9% and 223.0%, respectively. Pinheiro et al. [254] evaluated the production of the halophyte *Sarcocornia ambigua* integrated with *L. vannamei* in FLOCponics and observed an increase in nitrogen assimilation efficiency by 25%. In the future, the adoption of BFT combined with other techniques, for example IMTA or aquaponics, certainly will have a massive impact in large-scale operations nutrient optimization and system efficiency.

*5.5. The BFT Main Challenges.* Despite BFT's many advantages, several factors limit its expansion and further adoption. In the sections above, we discussed how BFT aligns with several environmental sustainability goals. However, there are several challenges to properly and effectively mitigate the negative impacts. Recently, a comprehensive review by Khanjani et al. [20] showcased several negative aspects of BFT farming, and

Table 3: Studies on probiotics utilization (water and feeds) in BFT.

| Reared species | IW (g) | RP (day) | Probiotic species | Highlights | Reference |
|---|---|---|---|---|---|
| *L. vannamei* | 3.03 | 42 | *Bacillus thuringiensis*, *Bacillus licheniformis*, *Bacillus cereus* | Increased immunocompetance, reduced the abundance of Vibrio bacteria | Ferreira et al. [221] |
| *M. rosenbergii* | 0.54 | 90 | *Lactobacillus plantarum* | Improve the gut's associated microflora, growth, feed efficiency, and immune response of shrimp | Dash et al. [222] |
| *P. indicus* | 1 | 45 | *Marinilactibacillus piezotolerans* and *Novosphingobium* sp | Improved growth and survival rates and immune status | Panigrahi et al. [223] |
| *P. vannamei* | 1.4 | 42 | *Lactobacillus fermentum* | improved survival rate and FCR | Jiménez-Ordaz et al. [216] |
| *P. vannamei* | — | 45 | *Bacillus tequilensis* | Enhanced disease resistance | Panigrahi et al. [224] |
| *O. niloticus* | 3.2 | 150 | *Bacillus* spp. | Improved growth and FCR | Phan et al. [225] |
| *Clarias gariepinus* | 12.3 | 49 | Commercial probiotics (prod A, prod B, and prod C) | Improved growth performance and FCR | Hartono and Barades [226] |
| *M. rosenbergii* | 0.1 | 127 | *Lactococcus lactis* | Improved growth and survival rate | Cienfuegos-Martínez et al. [227] |
| *L. vannamei* | — | — | *B. subtilis* | Adding probiotics *B. subtilis* via the aquafeed was suggested, based on the corresponding effects on water quality, intestinal digestive enzyme activity, and nonspecific immune enzymes activities of the shrimp | He et al. [145] |
| *L. vannamei* | 0.06 | 40 | *Bacillus amyloliquefaciens* | The addition of probiotics to the BFT system with *L. vannamei* effectively enhanced the water quality, floc volume, and total bacterial number in the water and the growth performance of the shrimp | Amjad et al. [228] |
| *O. niloticus* | — | — | *Lactobacillus rhamnosus* | Synbiotics containing phytase-producing probiotic *Lactobacillus* in the economic diets of Nile tilapia can greatly boost fish growth by improving feed utilization, blood parameters, and general health | Flefil et al. [229] |
| *P. vannamei* | 0.5 | 28 | *L. plantarum* | Lactic acid bacteria could be incorporated into biofloc formulations to purge the growth of pathogenic vibrios in pond settings, rather than being fed directly to shrimp | Thompson et al. [217] |
| *C. gariepinus* | 1.86 | 60 | Commercial probiotics containing bacteria *Bacillus subtillis*, *B. polymixa*, *B megaterium*, *B. coagulans*, *B. cereus*, *B. alvei*, *B. amyloliquefaciens*, *B. brevis*, *B. circulansfirmus*, *B. circulans*, *B. pumilus* | Adding probiotics increased survival and final weight but decreased the best FCR compared to controls | Agusta et al. [230] |
| *O. niloticus* | 16.72 | 98 | *Bacillus subtilis* and *Lactobacillus acidophilus* | The application of BFT systems could efficiently boost TBC in culture water and gut microbiota either alone or with probiotic enrichment | Haraz et al. [231] |
| *L. vannamei* | — | 63 | *B. subtilis*, *B. cereus* | The addition of different *Bacillus* strains as initial indigenous species to the biofloc system had different effects. *B. cereus* YB3 promoted biofloc formation, and *B. subtilis* NT9 elevated shrimp growth performance. | Huang et al. [219] |

Abbreviations: IW, initial weight; RP, rearing period; TBC, total bacterial count.

Table 4: The natural probiotic effect of biofloc on several pathogens and culture conditions.

| Reared species | Pathogen | Pathogen concentration | The effect of biofloc on the pathogen | SR in BFT | Reference |
|---|---|---|---|---|---|
| *L. rohita* | *A. hydrophila* | At a concentration of $1.8 \times 10^7$ CFU/mL | Indicated the potential role of in situ bioflocs in reducing their susceptibility to bacterial infection | 30%–66% | Ahmad et al. [232] |
| *L. vannamei* | *V. harveyi* | At a concentration of $1.7 \times 10^6$ CFU/mL | Biofloc helps to prevent the development of the infection produced by *V. Harveyi* | 100% | Aguilera-Rivera et al. [233] |
| *O. niloticus* | *A. hydrophila* | At a concentration of $3 \times 10^8$ CFU/mL | In BFT, C:N 20 provides higher resistance to *A. hydrophila* infection | 35%–75% | Elayaraja et al. [234] |
| *C. gariepinus* | *A. hydrophila* | At a concentration of $1 \times 10^6$ CFU/mL | In BFT, higher fish robustness against *A. hydrophila* infection | 42.5%–70% | Fauji et al. [235] |
| *M. rosenbergii* | *A. hydrophila* | At a concentration of $1 \times 10^6$ CFU/mL | In BFT, higher survival of shrimp was recorded during pathogen challenge test | 60%–70% | Miao et al. [236] |
| *C. carpio* | *A. hydrophila* | At a concentration of $1.2 \times 10^7$ CFU/mL | BFT could enhance the resistance of fish against bacterial infection especially in C:N ratio of 25 | 65%–77% | Haghparast et al. [237] |
| *O. niloticus* | *S. agalactiae* | At a concentration of $1 \times 10^6$ CFU/mL | In BFT, higher fish robustness against *S. agalactiae* infection | 81.82% | Doan et al. [238] |
| *O. niloticus* | *S. agalactiae* | At a concentration of $1 \times 10^7$ CFU/mL | — | 37.5%–75% | Doan et al. [239] |
| *O. niloticus* | *S. agalactiae* | At a concentration of $1 \times 10^7$ CFU/mL | — | 53.33%–83.33% | Doan et al. [240] |
| *P. vannamei* | *Vibrio parahaemolyticus* | At a concentration of $1 \times 10^3$, $10^5$, and $10^7$ CFU/mL | The application of biofloc could significantly protect and increase the resistance of Pacific white shrimp against pathogenic *V. parahaemolyticus* infection | — | Gustilatov et al. [241] |
| *L. vannamei* | *V. parahaemolyticus* and white spot syndrome virus | At a concentration of $1 \times 10^6$ CFU/mL | Improved the survival of shrimp after the challenge | — | Vázquez-Euán et al. [242] |

Abbreviations: CFU, colony-forming unit; SR, survival rate.

Table 5: Productivity and food conversion ratio (FCR) of some aquaculture animals reared in BFT system.

| Species | FCR | FCR relative to CW (%) | NP | NP relative to CW (%) | Reference |
|---|---|---|---|---|---|
| *L. vannamei* | 1.41–1.56 | 7–16 | 5 ton/ha | 8 | Ekasari et al. [245] |
| *L. vannamei* | 1.47 | 25 | 7 ton/ha | 34 | Xu and Pan [246] |
| *M. rosenbergii* | 2.27 | 21 | 5 ton/ha | 17 | Pérez-Fuentes et al. [79] |
| *Penaeus semisulcatus* | 1.16 | 63 | 5 ton/ha | 33 | Megahed [244] |
| *P. monodon* | 1.47 | 34 | 0.5 ton/ha | >100 | Kumar et al. [247] |
| *O. niloticus* | 1.2 | 18 | 370 ton/ha | 29 | Luo et al. [248] |
| *O. niloticus* | 3.45 | 30 | 48 ton/ha | 43 | Azim and Little [195] |
| *Marsupenaeus japonicus* | 1.67 | 7 | 13 ton/ha | 31 | Zhao et al. [249] |
| *O. niloticus* | 1 | 41 | 10.5 kg/m$^3$ | 32 | Khanjani et al. [191] |
| *Fenneropenaeus merguiensis* | 1.07 | 10 | 7.5 kg/m$^3$ | 14 | Khanjani et al. [22] |
| *L. vannamei* | 1.27 | 21 | 2 kg/m$^3$ | 20 | Khanjani et al. [194] |
| *L. vannamei* | 1.4 | 15 | 19.78 ton/ha | 20 | Anand et al. [250] |
| *O. niloticus* | 1.6 | 20 | 15.4 kg/m$^3$ | 23.37 | Hwihy et al. [166] |
| *O. niloticus* | 1 | 54 | 6.1 kg/m$^3$ | 10 | Khanjani and Alizadeh [169] |

Abbreviations: CW, clear water; NP, net productivity.

potential ways to overcome those challenges. For instance, this technology is relatively complex and needs deep water quality and microbiology knowledge [9]. Same occurs with other technologies including RASs and IMTA. Skilled staff, and a proper engineering, water quality, and microbial management not only play a key on the success of BFT [9, 149] but also in RAS and IMTA. Similarly, other aspects that can be also associated include (i) high implementation costs (e.g., liner ponds, greenhouses, shade mesh, etc.) and electricity demand for aeration and water circulation, (ii) risks with rapid dissolved oxygen depletion due to higher (microbial, fish-shrimp) respiration, (iii) associate costs with water quality supplements and monitoring, (iv) excess of suspended solid and needs for proper sludge treatment; (v) poor water quality management and high N-toxic compounds may lead to poor performance, health and mortalities issues [29, 141]. In BFT, water consumption can be reduced if the same water were to be reused in multiple cultures [76]. However, it is crucial to examine the potential effects of reusing water on the productivity and nutritional quality of cultivating organisms. In this regard, diseases or parasites may spread or toxins may accumulate in the final product by using water from previous cultures [82]. In addition, salt content in BFT effluents is also considered a key issue, thus a proper management (e.g., dilution and/or concentration + suitable disposal) must be considered [23]. To help overcome some of these challenges, other examples include (i) controlling microbial populations and maintaining a balanced community is essential for the successful operation of BFT. Effective monitoring tools for BFT systems are also necessary to ensure stable and consistent production; (ii) scaling up BFT systems to commercial production levels is another challenge to reduce implementation and running costs. Optimizing system design, management practices, and developing economically viable production models are necessary for the BFT adoption at scale; and (iii) creation of tailored BFT waste management practices (e.g., control and disposal of sludge). From an animal welfare perspective, research has shown that at high stocking densities (e.g., 400 and 500 shrimp/m$^2$), the activities of digestive enzymes are reduced in a biofloc-based shrimp culture, as well as the immune status, leading to mortalities when challenged with *V. harveyi* [255]. Further research to understand the impacts that high-density rearing has on shrimp is needed to develop rearing methodologies that foster improvements in immunological and health outcomes of the shrimp.

## 6. Future Perspectives and Conclusions

BFT and any other aquaculture production system require an environmentally friendly and circular approach to meet the sustainable development goals (SDGs) [256] and the challenges associated with global food production, population growth, endangered or fragile ecosystems, and climate change. CE, circular business models, and other-related approaches will likely contribute to meeting the SDGs and improving the future of upcoming generations. In this sense, it is possible that the SDGs could play an important role in the transition from a linear economy to a circular aquaculture. Circular transition indicators (CTIs) [257, 258], and sustainability indicators using tools such as LCA [259], and emergy synthesis [260], aligned with bioeconomic modellings [261] are powerful tools that need further development, exploration, and adoption by the aquaculture industry. Besides the regular production metrics (e.g., growth, FCR, survival, yields, production costs), the adoption of these metrics and future frameworks would provide a more holistic evaluation toward a more circular system, improving circularity, and resources optimization.

Those metrics could also help to educate consumers and farmers and align both their objectives for sustainable consumption and production. On one side, the framework developed can help farmers to assess their circularity and sustainable goals, helping to improve systems thinking, production economics, footprint, and credentials. On the other hand, these future frameworks could bring awareness by increasing the consumers' perception and understanding of the "true" environmental impact of food production and increasing industry transparency to reward producers for adopting improved or new strategies for sustainable farming. In addition, it could bring data-driven recommendations to farmers and policymakers aiming to optimize raw materials utilization and enhance the management practices.

In recent years, BFT has demonstrated that not only is possible to increase the profitability in large commercial operations [157] but also transform aquaculture wastes into useful products [168, 210, 262]. In this sense, depending on different levels of "circularity" or CTI, enabling positive impact (e.g., biofloc versus traditional systems), data-driven recommendations could support incentives and subsidies toward a more sustainable aquaculture production. By closing the loop of materials and substances, circularity reduces resource consumption and environmental emissions. Adopting BFT, tailored nutrition with alternative feed ingredients and other strategies such as BFT-periphyton system [141, 204, 263], BFT-aquaponic system [152, 153], and BFT-IMTA [40, 63, 252, 264], it is believed that emissions could be minimized, losses prevented, and key resources recovered.

Cramer's [37] and Muscat et al.'s [38] approaches were developed to overcome key urbanization, and livestock and agriculture challenges. In aquaculture, arguably, each individual industry (e.g., salmon, tilapia, whiteleg shrimp) and production technique (RAS, earthen ponds, biofloc) would need to develop tailored frameworks aiming to elucidate how the implementation of the circular bioeconomy actually takes place and evolves over time. According to the findings and connections with Cramer [37]'s 10 R's and Muscat et al. [38]'s five P's frameworks, BFT encompasses several transitioning steps into circularity and could play a crucial role toward a more sustainable aquaculture in line with the CE.

## Data Availability Statement

Data will be available upon request from the authors. The present study is a review study and all data are available.

## Ethics Statement

The authors confirm that all the experiments were conducted in accordance with the relevant guidelines and regulations.

## Conflicts of Interest

The authors declare no conflicts of interest.

## Author Contributions

**Mohammad Hossein Khanjani and Maurício Gustavo Coelho Emerenciano**: conception and design of study. **Maurício Gustavo Coelho Emerenciano, Mohammad Hossein Khanjani, Moslem Sharifinia, and Anselmo Miranda-Baeza**: drafting the manuscript. **Maurício Gustavo Coelho Emerenciano, Mohammad Hossein Khanjani, Moslem Sharifinia, and Anselmo Miranda-Baeza:** revising the manuscript critically for important intellectual content.

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