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REVIEW

Sustainability of biofloc technology in enhancing the productivity of aquatic organisms in aquaponic systems: a review

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Abstract Aquaponics, a sustainable farming practice that integrates the cultivation of aquatic organisms with plant farming, aims to minimize waste while maximizing productivity. However, certain conventional aquaponic systems present health risks to aquatic species due to issues such as nutrient imbalances and the reliance on mechanical and biological filtration systems. An emerging alternative to traditional aquaponics is the integration of Biofloc Technology (BFT) with hydroponics. Biofloc-based aquaponics utilizes a microbial co-culture, which promotes efficient nutrient cycling, reduces feed input, and minimizes the need for complex filtration systems. This hybrid approach offers significant technical advantages, including reduced operational costs and increased sustainability compared to conventional intensive aquaculture systems. Despite its promise, the adoption of BFT in aquaponics is still in its nascent stages, hindered by inconsistencies in experimental design and system configuration. This review explores the application of BFT in aquaponics, focusing on the cultivation of both aquatic animal and plant species. We critically analyze the current state of BFT research, identify key challenges, and propose recommendations for future studies aimed at enhancing the economic viability and sustainability of this integrated aquaculture technique.

Keywords Aquaponics . Biofloc technology . Aquatic plants . Aquatic animals . Aquaculture sustainability

Introduction

Aquaculture is a rapidly expanding global industry, playing a crucial role in food security and economic development (Gao et al. 2020; Gururani et al. 2022). Given the rising global demand for food and the pressing need to mitigate the environmental impacts associated with conventional aquaculture systems, there is an urgent need to pursue the sustainable intensification of aquaculture production (Khatoon et al. 2021). In response, numerous studies have investigated innovative production systems designed to enhance the sustainability of aquaculture. One promising approach is aquaponics, which integrates hydroponic plant cultivation with the farming of fish and crustaceans in a recirculating water system, thereby promoting efficient resource use and minimizing environmental waste (Chandramenon et al. 2024).

Aquaponics is an integrated food production system that combines the simultaneous cultivation of aquatic animals and terrestrial plants, enabling the efficient sharing of water and nutrients among the different species (Chandramenon et al. 2024). In intensive aquaculture systems, the accumulation of waste nutrients occurs due to the partial assimilation of feed by aquatic animals, with only a fraction being metabolized (Hou et al. 2024; Raza et al. 2024b). These waste products, however, can serve as a valuable nutrient source for plants, thereby reducing or completely eliminating the need for supplemental nutrient solutions

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typically required in traditional hydroponic systems (Gebauer et al. 2023; Flores-Aguilar et al. 2024). This symbiotic relationship not only enhances system productivity through the diversification of outputs but also mitigates the overall environmental impact. Furthermore, by utilizing a water supply originally designated for plant cultivation, aquaponics facilitates the dual-purpose use of water for both plant and aquatic animal production, optimizing resource efficiency (Lennard and Goddek 2019).

Biofloc Technology (BFT) has proven to be an effective approach for integrating aquaculture with aquaponics. This method facilitates the conversion of toxic nitrogenous wastes, generated by aquatic organisms, into less harmful compounds like nitrates through microbial activity. Moreover, the system also promotes the cultivation of bacterial biomass, enhancing waste management and nutrient recycling within the system (Khanjani et al. 2024b; Raza et al. 2025b). Unlike conventional systems that rely on water exchange or recirculating aquaculture systems dependent on external biofilters, BFT utilizes microbial processes, such as immobilization and nitrification, to facilitate this conversion (Saseendran et al. 2021). The bioflocs, which consist of a combination of organic matter and microorganisms, remain suspended in the water and serve as an additional food source for the cultured organisms (Khanjani et al. 2020; Raza et al. 2024a). This process enhances the microbial loop, converting nutritional waste from aquatic animals into biomass. Furthermore, BFT improves biosecurity within the system, thereby reducing the need for continuous water sourcing from external natural resources (Chu and Brown 2020).

Aquaponic systems that incorporate Biofloc Technology (BFT) have been shown to achieve high productivity for both aquatic species and plants, while simultaneously providing significant ecological advantages. These benefits include enhanced nutrient recycling, the elimination of pesticides, and the efficient use of both water and space (Pinho et al. 2022). Recent studies have highlighted the potential of combining hydroponic techniques with BFT to improve the production of marine shrimp (Custódio et al. 2021) and tilapia (Abdel-Rahim et al. 2019). An emerging variation of traditional aquaponics, termed FLOCponics, utilizes BFT within the aquaculture subsystem, replacing the conventional recirculating aquaculture systems (RAS) that typically rely on external biofiltration (Pinho et al. 2021a; Pinho et al. 2021b). BFT fundamentally relies on the growth of specific microbial communities that function as biological filters, facilitating nutrient cycling within the system. The integration of BFT with aquaponics, referred to as FLOCponics, has garnered increasing interest due to its advantages, including reduced fish feed requirements, continuous nutrient cycling, and the elimination of the need for complex filtration systems typically associated with recirculating aquaculture systems (RAS) (Custódio et al. 2021; Pinho et al. 2022). However, despite the theoretical benefits, recent studies have raised concerns about the practical viability of FLOCponics. Pinho et al. (2021a) reported that 63% of the plants cultivated using water from a mature biofloc-based fish system exhibited undesirable visual characteristics, rendering them less marketable. These findings highlight potential challenges regarding the economic feasibility of FLOCponics systems (Chu and Brown, 2020). As with any emerging technology, it is essential to assess the financial viability of such systems before large-scale implementation (Pinho et al. 2021a; Pinho et al. 2021b).

The diversification and long-term sustainability of aquaculture production through emerging technologies such as FLOCponics necessitate economic profitability for producers (Barbosa et al. 2022). Accordingly, it is essential to evaluate the financial viability of integrating BFT with hydroponic plant cultivation, as well as to assess the influence of plant visual quality on the marketability and overall performance of FLOCponics systems (Silva et al. 2022; Mahari et al. 2024). This review presents a comprehensive analysis of the co-cultivation of aquatic animals and plants within aquaponic systems employing BFT. The study critically examines the current state of BFT development in aquaponics and identifies key challenges and opportunities. By synthesizing recent findings, this review aims to guide future research toward improving the economic feasibility of BFT-based aquaponics and advancing sustainable aquaculture practices.

History and basics of aquaponics system

The term "aquaponics" was coined in the late 1970s and early 1980s by Mark McMurtry and researchers at the New Alchemy Institute and North Carolina State University in the United States. This system, known as the "Integrated Aqua-Vegeculture System" (IAVS), combines aquaculture and hydroponics. The origins of aquaponics may be traced back to ancient civilizations such as the Aztec Chinampas, Egypt, Babylon, and Far Eastern countries like China and Thailand. These societies used a combination of fish and vegetable growing (Shumet 2021). According to Shabeer et al. (2016) William McLarney, Nancy Todd, and John Todd recreated the Aztec aquaponics system prototype in 1969, leading to the creation of the first commercially effective aquaponics system. In 1981, Dr. James Rakocy and his colleagues at the University of the Virgin Islands pioneered modern commercial-scale aquaponics. Most of the research on aquaponics began in the early 1970s (Okomoda et al. 2023).

Aquaponics is a kind of farming that combines the production of aquatic creatures in tanks with hydroponics. This technology utilizes microbial processes to convert nutrient-rich wastewater from aquaculture into valuable resources for plant nourishment and irrigation (Baganz et al. 2022). Aquaponics systems utilize resource reutilization and recycling to produce healthy food while minimizing or eliminating the need for chemicals such as fertilizers, pesticides, and antimicrobials (Schoor et al. 2024). Consequently, compared to traditional aquaculture and hydroponics systems, aquaponics offers several advantages and has been designed to serve as a more sustainable and cyclical method of food production (Lennard and Goddek 2019; Mahari et al. 2024).

Nitrifying bacteria in aquaponics systems convert aquaculture effluents into plant-available nutrients, allowing plants to grow and use their feed to its maximum potential (Khanjani et al. 2020; Silva et al. 2022). To maintain a stable operation of the aquaponics system, it is necessary to establish a nitrogen cycle. Ammonia is discharged and transformed into nitrite by ammonia-oxidizing bacteria during the process of fish breeding. Nitrite is subsequently converted into nitrate by oxidation by nitrite-oxidizing bacteria, mainly *Nitrospira* sp. and *Nitrobacter* sp. (Abakari et al. 2022; Gao et al. 2022).

The nitrates produced in aquaculture systems serve as essential nutrients for plants, facilitating their growth (Nair et al. 2025). Optimal nutrient cycling is achieved when there is a balanced equilibrium between the nitrate production by aquatic organisms and the plant biomass within the system (Shreejana et al. 2022). Furthermore, unlike conventional aquaponics systems, integrated systems offer the benefit of fulfilling plant's nutritional requirements without the use of fertilizers. This is achieved by supplying plants with a diverse range of nutrients (such as phosphorus, nitrogen, potassium, calcium, Sulphur, iron, magnesium, copper, manganese, zinc, molybdenum, boron, and aluminum) through the utilization of food and excrement from cultured organisms (Lee et al. 2019). Aquaponics reduces the need for fertilizer in hydroponics and minimizes water treatment in RAS systems, leading to nutrient recovery and increased profitability by allowing the simultaneous production of two cash crops within the same system (Pinho et al. 2022).

Decoupled aquaponic system

The primary obstacle to the profitability of conventional aquaponics is its capacity to provide an ideal environment for the development of both fish and plants (Baganz et al. 2022). To address this issue, a decoupled aquaponic system was created. This system separates the hydroponic components and aquaculture and allows for the adjustment or adaptation of the environmental conditions of each component to meet the individual needs of the fish and plants (Aslanidou et al. 2024). To maximize the growth efficacy of the system, the compromise between pH, temperature, and nutrient needs must be minimized (Aslanidou et al. 2023). The decoupled aquaponic system consisted of two independent loops, one for the RAS and another for the hydroponic components (Zhu et al. 2024). This arrangement enabled the recirculation of process water within each component, allowing for better control of the system tailored to the specific needs of the species involved (Aslanidou et al. 2023; Aslanidou et al. 2024).

The mineralization loop utilizes microorganisms to break down sludge, enhancing the availability of dissolved nutrients for plants (Danner et al. 2019). Additionally, the acidification process lowers the pH, producing an ideal environment for plant development (Monsees et al. 2017). The demineralization loop is used in hydroponics to separate the nutrients and dissolved salts from the process water. The process water is then returned to the hydroponic unit, while the demineralized water is circulated back to the RAS (Palm et al. 2024). This helps to improve control over nutrient concentration in the respective subsystem of Dynamic Aquaponics System (Goddek and Korner 2019). Decoupled aquaponics involves a reduction in the strength of interconnections between subsystems, resulting in the autonomous construction of the system in accordance with the nutritional needs of plants (Baganz et al. 2022; Aslanidou et al. 2023). This results in a one-way flow where fish do not receive any benefits from the plants. Nevertheless, a connection is being established between the two subsystems, and the remineralization unit and other loops work together to maintain water quality (Tetreault et al. 2023). This creates a virtuous cycle wherein fish, bacteria, plants, retained water, and fish all benefit from each other (Baganz et al. 2022). The phrase "decoupled" refers to the process of restructuring software systems by breaking down a huge monolithic system into smaller, independent pieces (Palm et al. 2024). The DAPS design enables independent control of water recirculation in aquaculture and hydroponic systems, ensuring optimal water quality for promoting healthy growth of both plants and fish (Blanchard et al. 2020).

In contrast to a traditional aquaponic system, Blanchard et al. (2020) asserted that the enhanced production of the hydroponic component was a result of the decoupled system's superior control over water quality. African catfish and basil exhibited satisfactory growth in the decoupled aquaponic system when the feeding rate was reduced by 30% of the fish's actual feeding rate (Pasch et al. 2021). In a decoupled aquaponic system, increased plant production was the result of higher fertilizer concentrations in hydroponics, whereas enhanced water quality for fish was the consequence of lower nutrient levels in RAS. When comparing DAPS to traditional aquaponics, Monsees et al. (2017) found that improved pH and fertilizer control led to a 36% increase in tomato fruit output. Compared to hydroponics, the DAPS achieved the same yield while using 100% less freshwater and 62.8% fewer mineral nutrients for production (Monsees et al. 2017).

The decoupled system's net present value (NPV) was shown to be higher than that of traditional aquaponics in the cost-benefit analysis (Blanchard et al. 2020). Contrarily, Monsees et al. (2017) proposed using the decoupled system for large-scale production and using conventional aquaponics to cultivate plants with lower nutrient requirements and fruiting vegetables with higher nutrient requirements. While DAPS offers improved sub-system control and increased productivity, it is much more sophisticated than connected aquaponics and hydroponic systems, requiring a far larger initial investment (Pasch et al. 2021). Additionally, the extra loops lessen the system's economic viability for small-scale entrepreneurs; instead, they are appropriate for commercial production systems operating on a large scale or in regions with access to energy sources. Therefore, to expand DAPS, or on-demand coupled aquaponic systems, on a commercial scale, substantial research should be adopted (Blanchard et al. 2020; Baganz et al. 2022).

Ecological prospectives of aquaponics

Due to the growing global population, limited resources, and advancements in production technology, aquaponics is seen as a promising ecological solution to the global food crisis and its environmental impacts (Kotzen et al. 2019; Ghamkhar et al. 2020). Aquaponics possesses the capacity to significantly augment ecological and sustainable intensification in agriculture through the following mechanisms: reduction of resource consumption (e.g., water and land), optimization of wastewater and nutrient reuse efficiency, generation of zero waste, attainment of high productivity, and obviation of chemical fertilizer requirements. Because of this, it contributes significantly to climate-smart agriculture and the circular economy (Milliken and Stander 2019; Chen et al. 2020).

Aquaponics use 90% less water than soil-based systems, with water consumption amounting to only 1% of that used in pond aquaculture. Extensive claims about the sustainability of aquaponics and its potential to reduce environmental costs have raised questions, leading to increased interest in evaluating the validity of these assertions (Chen et al. 2020). Life cycle assessment has become a comprehensive method for evaluating the sustainability of aquaponics and measuring the direct and indirect environmental effects of processes or products over their entire life cycle, from inception to disposal (Ghamkhar et al. 2020; Chen et al. 2020).

One possible way to describe aquaponics' environmental performance is to use life cycle assessment to explicitly evaluate midway and endpoint impacts (Pinheiro et al. 2020). Endpoint impact analysis focuses on assessing the impact of a particular activity on quality, ecosystem resources, and human welfare (Silva et al. 2022). In contrast, midpoint evaluation does not consider the environmental costs that occur earlier in the cause-effect chain, such as eutrophication, acidification, depletion of abiotic resources, and global warming potential. Compared to hydroponics, the midpoint impact of aquaponics is 1.7 times lower, and the endpoint impact is 50% lower (Chen et al. 2020). Conversely, RAS incurs the highest environmental costs in terms of operation and infrastructure, primarily due to their high energy consumption and the technical infrastructure needed for water recycling. This significantly contributes to the exacerbation of global warming (Zhu et al. 2024). The environmental impact of aquaponics is considerably reduced in comparison to that of conventional hydroponics and aquaculture systems. The overall negative impacts on fish culture are mitigated by the coexistence of plant and fish production, which is achieved through climatic control, efficient use of water and resources, and plant biofiltration (Pinheiro et al. 2020).

These variables help mitigate harm to the ecosystem and conserve resources (Greenfeld et al. 2021). A recent advancement in aquaponics research involves the development of customized aquafeeds tailored to different species. To achieve this, it is essential to modify the diet to meet the nutritional requirements of both the plants and fish within the system (Robaina et al. 2019). The primary goal was to reduce reliance on fishmeal and fish oil as protein sources and to identify viable alternatives. This approach aims to alleviate pressure on overexploited marine capture fisheries, decrease carbon emissions, protect biodiversity, and mitigate the environmental impacts of this sustainable production system, all within the framework of a circular economy (Ghamkhar et al. 2020).

From both socioeconomic and environmental perspectives, aquaponics encompasses a range of factors. This method recycles nutrients and wastewater, reduces pollution from aquaculture discharge, and supports economic development and food security. Additionally, it contributes to the reduction of greenhouse gas emissions (Pinheiro et al. 2020). Moreover, as a tool for combating climate change, this climate-resilient system shows great promise. It can adapt to various environments by employing a method that meticulously controls abiotic factors (Pinho et al. 2022). When managed effectively, it becomes less susceptible to environmental fluctuations and climate change, leading to improved disease management, increased production, and reduced resource use (Vasdravanidis et al. 2022).

Use of biofloc technology in aquaponics for culturing aquatic animals

The application of biofloc technology to aquaponic systems is a relatively recent phenomenon (Barbosa et al. 2022). Microorganisms constitute vital constituents within BFT systems (Martinez-Cordova et al. 2020; Khanjani et al. 2024a). To maintain water quality, the bacterial population is managed to restrict the growth of autotrophic microorganisms. This is achieved by maintaining a high carbon-to-nitrogen ratio, as heterotrophic bacteria can efficiently consume nitrogenous by-products (Raza et al. 2024a). At the beginning of the culture cycles, a high carbon-to-nitrogen ratio is essential to promote optimal development of heterotrophic bacteria (Pinho et al. 2022). This energy is utilized by the bacteria for their maintenance and growth. Additionally, various species of microorganisms are crucial components of biofloc technology (BFT) systems. The population of chemoautotrophic bacteria, specifically nitrifying bacteria, stabilizes after approximately 20 to 40 days (Khanjani et al. 2024a; Raza et al. 2024a).

Approximately two-thirds of the ammonia absorption in the system may be attributed to these bacteria (Emerenciano et al. 2017). Therefore, it is important to reduce the amount of external carbon added, while replenishing the alkalinity consumed by the microbes with alternative carbonate and bicarbonate sources (Khanjani et al. 2024b). The dynamic interaction of diverse populations of naturally occurring species, including fungi, bacteria, nematodes, microalgae, rotifers, and protozoans determines the stability of zero or minimal water exchange (Martinez-Cordova et al. 2020). Bioflocs, which are aggregates consisting of proteins and lipids, serve as a natural food supply. These bioflocs are available throughout the day because of the intricate interplay between physical substrate, organic matter, and a diverse array of microbes (Raza et al. 2024a).

The production of microorganisms in tanks, raceways, or lined ponds serves three primary purposes: first, it helps maintain water quality by reducing nitrogen compounds and generating in-situ microbial protein. Second, it provides nutrition, which lowers feed costs and enhances the feasibility of the culture. Third, it helps combat harmful microbes (Martinez-Cordova et al. 2020). In BFT, key concerns regarding water quality for cultured organisms include excess particulate organic matter, harmful nitrogen compounds, and oxygen levels, among other factors (Souza et al. 2019). There are three ways that ammonia nitrogen is removed in this environment: first, photoautotrophic removal by algae; second, heterotrophic bacteria turn ammonia nitrogen into microbial biomass; and third, autotrophic bacteria turn ammonia into nitrate (Martinez-Cordova et al. 2020). Plants grown in aquaponic systems can utilize nitrates and other nutrients, both macronutrients and micronutrients, that accumulate throughout the growth cycle as substrates (Pinho et al. 2017). In summary, the findings indicate that BFT is beneficial for shrimp and fish growth. BFT enhances fish yields and improves water quality compared to traditional aquaculture systems (Panigrahi et al. 2020). This improvement may be attributed to increased microbial activity, which enhances nutrient availability (Khanjani et al. 2020).

Biofloc serves as a high-quality food source for cultured organisms, resulting in significant cost reductions in aquaculture, where feed accounts for 40–60% of operational expenses (Khanjani et al. 2024a; Raza et al. 2025a). Utilizing biofloc as a food source can improve feed efficiency by reducing protein requirements and increasing nitrogen utilization. Biofloc consists of various components, including proteins, lipids, carbohydrates, essential amino acids, essential fatty acids, antioxidants, and vitamins (Raza et al. 2024a). These elements contribute to positive outcomes such as enhanced growth, improved immunity, increased survival rates, and better reproductive performance in cultured organisms (Walker et al. 2020). Additionally, the beneficial microorganisms present in the BFT play a crucial role in supporting aquaculture species. They compete with pathogenic bacteria in the environment, leading to a significant reduction in both the abundance and virulence of these harmful bacteria (Soares et al. 2022). BFT eliminates the need for water exchange by utilizing microorganisms to naturally filter the water. This zero-water-exchange system enhances biological security by preventing the spread of pathogenic microorganisms that can occur during water exchange (Emerenciano et al. 2021). Additionally, this technology is vital for preventing pollution and ensuring biosecurity by stopping the transmission of diseases from aquaculture wastewater into the natural environment (Khanjani et al. 2024b). This system effectively prevents the escape of aquaculture organisms while maintaining optimal temperatures for aquaculture, all while minimizing energy consumption. This suggests that stable production of aquatic products is achievable through BFT (Raza et al. 2024a).

FLOCponics: Combination of biofloc technology and aquaponics

Aquaponics and aquaculture based on BFT are considered environmentally friendly methods of food production. Both are intensive aquaculture systems that prioritize water conservation and nutrient recycling (Boyd et al. 2020). FLOCponics shares similar characteristics (Figure 1). By integrating the principles of aquaponics and bioflocs, FLOCponics has the potential to serve as an additional tool in addressing the challenges of the global sustainable food supply (Pinho et al. 2022). Hydroponics and BFT are combined in FLOCponics, an integrated biofloc-based food production system (Hwang et al. 2023). Based on the same ideas of maximizing and recycling nutrients, water, energy, and land, it is a subset of aquaponics (Emerenciano et al. 2021). Plants grown in water can utilize the nutrients present to their advantage, which is why hydroponic loops are being integrated into biofloc-based farms (Baganz et al. 2022). This integration helps diversify production and provides aquaculture growers with additional products to sell (Deswati et al. 2021). Microbial interactions in BFT can enhance nutrient recycling and promote greater fish development, making it a viable alternative to RAS for aquaculture producers (Pinho et al. 2021b; Khanjani et al. 2024b). In addition to the advantages already mentioned, the use of bioflocs in shrimp and fish production may result in more efficient and sustainable use of water and nutrients (Baganz et al. 2022).

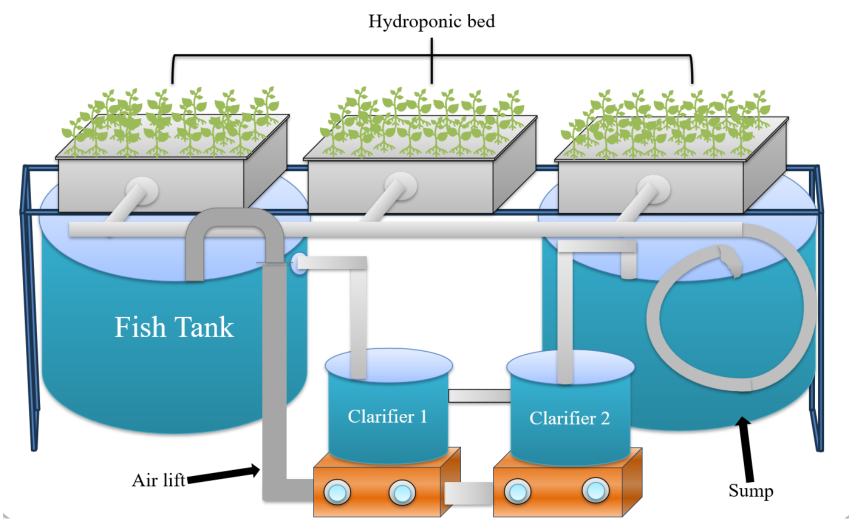

Fig. 1 Schematic design of FLOCponics system

Studies on FLOCponics have predominantly focused on comparing its yield performance with that of other production systems, alongside evaluating its nutritional profile and water quality parameters (Martinez-Cordova et al. 2020; Pinheiro et al. 2020). While these studies have covered a broad spectrum of topics, their primary aim has been to optimize FLOCponics and facilitate its commercialization. FLOCponics has shown significant potential, not only in the production of fish and shrimp and nutrient recovery but also in fulfilling sustainability standards (Pinho et al. 2021b). However, some studies have highlighted operational challenges associated with implementing FLOCponics in a permanently connected system (Pinho et al. 2021a; Pinho et al. 2022). Large-scale farmers tend to favor FLOCponics for educational and social purposes, in contrast to recirculating aquaculture systems (RAS), which are mainly used for commercial objectives (Rono et al. 2024). A notable drawback of FLOCponics is the high cost of infrastructure required to maintain biofloc bacteria and ensure system functionality, which poses challenges for its adoption in social initiatives (Mahkeswaran et al. 2024). In terms of real-world applications, FLOCponics remains in the early stages of development. The private sector generally refrains from sharing data, resulting in limited information on its commercial use (Pinho et al. 2021b). However, there have been documented cases of biofloc technology (BFT) farmers incorporating hydroponic subsystems into their units for small-scale FLOCponics experiments (Pinheiro et al. 2020). The optimal design of the system, the target species for cultivation, and the overall economic feasibility are influenced by environmental factors, production objectives, scale, and management practices (Pinho et al. 2017; Pinho et al. 2022). FLOCponics typically operates in a closed-loop system, requiring minimal land and water to produce nutrient-rich food, which provides it with a distinct advantage over traditional aquaponics and BFT systems (Pinho et al. 2021b).

Aquatic animal species cultured in FLOCponics

Park et al. (2024) revealed that among 256 aquaponic participants, 70% utilized tilapia (*Oreochromis niloticus*) (Abdel-Rahim et al. 2019), while 27% employed catfish (*Siluriformes*) (Oladimeji et al. 2020) in their commercial operations. Other fish species commonly used in commercial aquaponics include rainbow trout (*Oncorhynchus mykiss*) (Bordignon et al. 2022), common carp (*Cyprinus carpio*) (Luo et al. 2025), large-mouth bass (*Micropterus salmoides*) (Fischer et al. 2021), barramundi (*Lates calcarifer*) (Fotedar 2016), pacu (*Piaractus mesopotamicus*) (Pinho et al. 2021b), and Murray cod (*Maccullochella peelii*) (Lennard 2021). A critical factor for the successful cultivation of aquatic organisms in aquaponics is their ability to tolerate high population densities, as well as elevated concentrations of total suspended solids, phosphorus, nitrogen, and potassium (Fischer et al. 2021). It is generally not recommended to exceed a fish stocking density of 0.07 kg/L; however, species that can thrive at this density are well-suited for aquaponic systems (Bordignon et al. 2022; Gao et al. 2024). Moreover, these species should be suitable for cultivation in highly intensive culture systems (Figure 2) (Fischer et al. 2021).

Nile tilapia is the most commonly used and arguably the most successful fish species in aquaponics, followed by carp and African catfish (Abdel-Rahim et al. 2019). A literature review revealed that 44% of published studies identified tilapia as the primary aquatic organism in aquaponic systems (Pinho et al. 2017; Zappernick et al. 2022). Tilapia's success in aquaponic environments is attributed to its remarkable resilience to suboptimal water conditions (Zappernick et al. 2022). This species is known for its rapid growth, resistance to stress and disease, tolerance to a wide range of environmental conditions, and its ability to consume food from lower trophic levels (Pinho et al. 2017; Abdel-Rahim et al. 2019).

Tilapia is a microphagous, low-trophic omnivore that primarily feeds on phytoplankton and other minute organic particles (Zappernick et al. 2022). Due to its low dissolved oxygen requirements and relatively small space needs for growth, tilapia is ideally suited for aquaponic systems that aim to fulfill plant nutrient demands (Abdel-Rahim et al. 2019; Zappernick et al. 2022). However, the impact of excretion from various species on nutrient concentrations in the aquaponic solution and its subsequent effect on plant production remains an unresolved issue in current aquaponic research (Pinho et al. 2017). For instance, water effluent from Nile tilapia, African catfish, and common carp has been found to contain nitrate levels ranging from 18 to 41.6 mg/L, and phosphorus levels between 9.5 and 19 mg/L (Oladimeji et al. 2020).

Knaus and Palm (2017) found that the use of wastewater from common carp resulted in higher cucumber yields compared to tilapia effluent. However, the tilapia effluent led to greater tomato yields. Although tilapia have higher metabolic feeding activity than carp, the underlying reasons for the enhanced growth of tomatoes with tilapia effluent are still not well understood (Knaus and Palm 2017; Nadia et al. 2023). This suggests that tilapia may excrete a higher volume of feces into the water compared to carp. The authors also proposed that utilizing various species could offer advantages in achieving a more balanced nutrient profile in the water (Abdel-Rahim et al. 2019). Several shrimp species, such as Litopenaeus vannamei (Pinheiro et al. 2020; Alarcón-Silvas et al. 2021) and *Penaeus monodon* (Li et al. 2021), have been incorporated into aquaponics systems. However, the potential benefits of polyculture, which involves the use of different aquatic species to enhance plant development, have yet to be thoroughly investigated (Pinho et al. 2022).

Plant species cultured in FLOCponics

Traditionally, leafy vegetables have been cultivated in aquaponic systems due to their short growing seasons, low nutrient requirements, tolerance for nitrogen-rich environments, and high global demand (Barbosa et al. 2022). However, despite their higher economic value compared to leafy greens, cultivating flowering crops in aquaponic systems poses greater challenges. These challenges stem from their increased demand for phosphate and potassium fertilizers, greater susceptibility to pests and diseases, and slower growth cycles (Chu and Brown 2020). Furthermore, the same study found that profit does not always correlate with crop value. According to their research, Bibb (Boston) lettuce generated higher revenue per week per m^2 ($8.50–9.50 USD) than basil ($4.90–5.90 USD), despite basil having the greatest value per kg ($8.50–10.03 USD) (Sousa et al. 2024). This was due to improved planting density and yield. The majority of aquaponic economic studies concluded that the system was lucrative by including green vegetables. Muñoz-Euán et al. (2024) found that an aquaponics farm producing barramundi and lettuce generated an annual economic return that was $22,850 higher than that of the two independent systems. Over the course of a year, the aquaponic farm saved $1,315 on phosphate and nitrogen fertilizers, $1,270 on wastewater disposal, and $3,390 on all variable expenditures (Muñoz-Euán et al. 2024).

Integrating a lettuce and basil NFT system with trout farm producing 20,680 kg annually would yield a return of 13.8% and increased profit due to lower water remediation costs and higher plant production revenue (Sousa et al. 2024). This might be the reason why leafy greens and herbs are the main crops grown in commercial aquaponic systems. Basil (81%) (Knaus et al. 2024), salad greens (77%) (Sousa et al. 2024), *Solanum lycopersicum* (Tomatoes) (66%) (Nadia et al. 2023), *Lactuca sativa* (69%) (Khater et al. 2024), *Brassica oleracea* (56%) (Piñero et al. 2024), *Beta vulgaris* (53%) (Munekata et al. 2021), *Capsicum annuum* (pepper) (48%) (Romano et al. 2023), and *Cucumis sativus* (Cucumbers) (47%) (Blanchard et al. 2020) were the most grown crops by commercial aquaponic growers. In addition, aquaponic systems have been developed to cultivate plants that are capable of flourishing in saline environments (Gao et al. 2020). *Salicornia persica* is a significant plant species suitable for cultivation in aquaponics systems that use salt or brackish water (Pinheiro et al. 2020). *Salicornia* is a halophyte that demonstrates tolerance to high salinity levels and efficiently absorbs significant amounts of phosphate and nitrate (Castilla-Gavilán et al. 2024). The advancement of aquaponics has also broadened the range of plant species that can be successfully cultivated (Nadia et al. 2023). However, there is a lack of scholarly studies specifically addressing the use of aquaponics for cultivating flowering plants (Sousa et al. 2024). Further research should investigate the

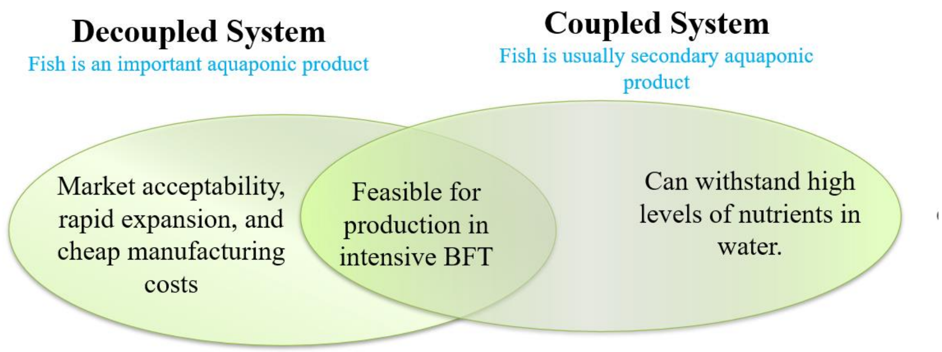

Fig. 2 The general qualities that fish species need in both coupled and decoupled aquaponics systems to be productive.

effectiveness of aquaponics in the floriculture sector (Knaus et al. 2024).

Water quality and nutrient recycling

The ability of BFT microbes to efficiently recycle nutrients and maintain optimal water quality for cultured species is a critical component of BFT systems (Emerenciano et al. 2017). Phytoplankton, nitrifying bacteria, and heterotrophic bacteria collectively participate in the ammonia-nitrogen cycle (Khanjani et al. 2024a). These microorganisms convert harmful ammonia-nitrogen into nitrate or incorporate it into bacterial biomass. Various forms of nitrogen conversion generally occur simultaneously, with the dominance of each form depending on the nutrient management practices of the system (Arbour et al. 2024). Additionally, the physicochemical properties of the water must meet the specific requirements of the microbes. In particular, high levels of dissolved oxygen and alkalinity, along with an optimal carbon-to-nitrogen ratio, are essential for effective microbial activity (Blanchard et al. 2020; Hou et al. 2024). Further research is required to define the precise water quality parameters necessary for the growth of BFT microorganisms, as well as the recommended values for water conditions that must be maintained in fish or shrimp tanks within BFT systems (Khanjani et al. 2024a; Raza et al. 2025b).

Most physicochemical water quality indicators remain within acceptable limits for fish or shrimp production according to studies conducted on FLOCponics systems focused on animal production (Pinho et al. 2022). However, the total volume of suspended solids (bioflocs) was an anomaly, falling below the acceptable threshold. For example, the average biofloc volume in tilapia culture typically ranges from 2.5 to 4.8 ml/L, 0.4 ml/L, and 0.4 to 0.9 ml/L, which are significantly lower than the recommended minimum of 6 ml/L (Pinho et al. 2021a). Despite these low levels, there is no indication that they have impaired the microorganisms' ability to recycle nitrogen or maintain water quality (Pinho et al. 2022). This suggests that the relationship between microbial activity and biofloc volume in both BFT monocultures and FLOCponics remains unclear and is highly variable (Pinheiro et al. 2020). Certain chemical and physical properties of water, particularly those related to pH and suspended particle concentrations in interconnected FLOCponics systems, do not always appear to support optimal plant growth (Pinho et al. 2022; Park et al. 2024). Hydroponic systems generally recommend a pH range of 5.5 to 7 to ensure optimal nutrient availability for plant uptake (Vasdravanidis et al. 2022). However, most documented FLOCponics systems typically operate within a relatively neutral pH range (Blanchard et al. 2020).

There is no necessity to regulate the pH of FLOCponics systems, as pH variations do not significantly affect plant growth (Blanchard et al. 2020). In hydroponic subsystems, it is crucial to maintain a low concentration of suspended solids to prevent the accumulation of bioflocs on plant roots, as this can hinder plant respiration and nutrient uptake (Chandramenon et al. 2024). In contrast, FLOCponics systems are characterized by higher solid concentrations in their hydroponic tanks (Kotzen et al. 2019). One of the key challenges in connected FLOCponics systems is balancing the maintenance of low solid concentrations in hydroponic subsystems while ensuring that biofloc levels in fish tanks remain optimal for animal production (Pinho et al. 2022). All subsystems require optimal water quality, which depends on the inflow of nutrients and their transformation by microbial processes (Khanjani et al. 2022). In traditional aquaponics, the majority of plant nutrients are believed to originate from the effluent of recirculating aquaculture systems (RAS), and this is similarly expected for FLOCponics (Palm et al. 2024).

Feed typically serves as the primary source of nutrients in the aquaculture subsystem of recirculating aquaculture systems (RAS). In contrast, FLOCponics may provide a higher concentration of nutrients by integrating both organic and inorganic carbon sources (Emerenciano et al. 2021). According to Emerenciano et al. (2017), both processes are often necessary to promote the proliferation of BFT bacteria. However, due to limited knowledge regarding the specific characteristics of the nutrient supply in FLOCponics systems, it is challenging to accurately estimate the quantity of nutrients available for plant growth (Pinheiro et al. 2020). Moreover, the precise rates of nutrient recycling and nutrient uptake by BFT bacteria remain uncertain, creating significant challenges in making accurate projections. Investigating the nutritional composition of plant biomass can help identify the nutrients delivered in the smallest amounts (Doncato and Costa 2021).

FLOCponics water generally contains lower concentrations of fertilizers compared to hydroponic solutions (Pickens et al. 2020). However, unlike traditional aquaponics systems utilizing recirculating aquaculture systems (RAS), the addition of external carbon sources in FLOCponics leads to elevated levels of potassium (K), phosphorus (P), sulfur (S), calcium (Ca), and iron (Fe) (Pinho et al. 2021b). The process of converting RAS sludge into minerals using bioreactors and effectively utilizing the resulting liquid as fertilizer in multi-loop aquaponics has also been explored (Tetreault et al. 2023). Despite this, there is limited documentation on the use of mineralized solids as a nutrient source for plants in FLOCponics (Pickens et al. 2020). Research on FLOCponics has largely focused on using plants as filters to remove excess nutrients from water as part of nutrient recycling strategies. These studies have primarily concentrated on recovering nitrogen and phosphorus and converting them into plant biomass (Emerenciano et al. 2021). Pinheiro et al. (2020) investigated the extraction of nitrogen and phosphorus from BFT effluent using halophyte plants. Their findings indicated that combining shrimp and plant production could eliminate between 24.2% and 39.4% of nitrogen (N) and between 14.6% and 19.5% of phosphorus from the system's input. It is important to note that both nitrogen and phosphorus often accumulate in BFT water (Luo et al. 2020), and when present in high concentrations, these compounds can be harmful to aquaculture species. Furthermore, if released into aquatic ecosystems, they can contribute to eutrophication (Raza et al. 2024a).

Productive results of aquatic animals cultivated in FLOCponics

Most of the research utilized Pacific white shrimp (*Litopenaeus vannamei*) or Nile tilapia (*Oreochromis niloticus*), except for Castro-Castellón et al. (2020) who cultivated South American catfish (*Rhamdia quelen*). According to Emerenciano et al. (2017) pacific white shrimp and tilapia are the predominant species in biofloc-based cultures. Both species exhibit a notable resilience to adverse environmental circumstances, including elevated levels of suspended particles and nitrogenous chemicals in water. This is the primary factor contributing to their ability to thrive in such environments. In addition, their morphological modifications allow them to efficiently exploit bioflocs as an extra food source (Walker et al. 2020).

The most used species for the nursery period was tilapia, with an initial weight ranging from 0.4 to 4.2 g (Abdel-Rahim et al. 2019). Nevertheless, in the context of shrimp farming, the growth-out phase involved the production of shrimp, starting from an initial weight of 1.6 g until they reached an approximate weight of 13 g (Alarcón-Silvas et al. 2021). Research on the efficacy of FLOCponics for aquatic creature development has examined a wide range of factors. Some examples of treatments include: (i) adjusting the trophic levels of the BFT or the carbon source to evaluate alternative nutrient inputs (Castro-Castellón et al. 2020), (ii) varying levels of salt in the water (Pinheiro et al. 2020), (iii) the impact of using BFT in conjunction with hydroponics (Poli et al. 2019), (iv) how shrimp performance is affected by plant production-specific management (Fimbres-Acedo et al. 2020) and (v) how classical aquaponics utilizing RAS (Pinho et al. 2021a), compares to FLOCponics systems in terms of plant and fish development.

Fimbres-Acedo et al. (2020) described that tilapia fed with a feed containing 40% protein and no fertilizer addition performed better than those fed with a food containing greater protein content and fertilizer supplement in the FLOCponics system (Abdel-Rahim et al. 2019). Using bioflocs from an ex-situ BFT led to better tilapia output and feed conversion ratio (Martinez-Cordova et al. 2020). A comparative study between traditional aquaponics and FLOCponics systems was conducted to assess the production of tilapia juveniles. The results showed that the FLOCponics system yielded a higher growth rate, greater final weight, and a lower FCR compared to the traditional aquaponics system (Pinho et al. 2021a). The authors noted that the average volume of bioflocs in the tank was below the required level for BFT cultivation. A large supply of natural food in the tank could have improved the performance of the fish. Rocha et al. (2017) also discovered a similar pattern of low biofloc volume and its effect on fish development in their study, which involved the use of linked systems. The authors of this study did not see any significant statistical differences in *Rhamdia quelen* production between aquaponics and FLOCponics. Both experiments indicated that enhancing system design might optimize the interaction of BFT with hydroponics.

The reported density of tilapia by Fimbres-Acedo et al. (2020) which is 23 kgm^{-3}, is considerably lower than the maximum density of 50 kgm^{-3} seen in BFT or the density of 70 kgm^{-3} achievable in the growth-out phase of commercial aquaponics with RAS (Emerenciano et al. 2021). The nursery phase values, ranging from 6.9 to 8.8 kgm^{-3}, are within the expected range of 7 to 9 kgm^{-3} in BFT systems. Commencing the growth-out phase with a stocking density of 260 to 520 juveniles per cubic meter in shrimp production can lead to the development of marketable shrimp weighing more than 20 grams and achieving yields of 6 to

8 kg/m^3 (Custódio et al. 2021). The FLOCponics shrimp studies employed comparable stocking densities, resulting in lower yields ranging from 2.2 to 2.9 kg/m^3 (Pinheiro et al. 2020). Connecting a hydroponics system to biofloc tanks affects solids and bioflocs, as discussed earlier. With reduced biofloc, there is less natural food available, which may alter microbial activity. This is likely the reason for FLOCponics' lower yields compared to monocultures reliant on biofloc (Pinho et al. 2022). The findings indicate that improving the system's design and carrying capacity may be able to address issues with yield performance and solids management. This would make FLOCponics work better and get it closer to commercial aquaponics with RAS (Pinheiro et al. 2020; Pinho et al. 2022).

Productive results of plant cultivated in FLOCponics

One of the main components of FLOCponics systems is the use of nutrient rich BFT effluents to feed hydroponic plants. Nevertheless, there is disagreement among researchers over whether FLOCponics increases or decreases plant yields (Pinheiro et al. 2020). Plant growth in this system should be compared with crops in hydroponics, conventional aquaponics utilizing RAS obtain definitive conclusions on the influence of BFT waste on plant productivity (Chandramenon et al. 2024). Standardizing the nutritional input composition across all systems may also be accomplished concurrently with this comparison. There were several reviews that contrasted FLOCponics with hydroponics or conventional aquaponics, but none that did so with soil-based techniques (Blanchard et al. 2020).

The quantity and type of nutrients supplied to the hydroponics subsystem varied among the treatments and systems in experiments comparing FLOCponics with other approaches. Most studies on FLOCponics have focused on the output of lettuce or salicornia. Leafy plants like lettuce are often used in conventional aquaponics systems due to their rapid growth cycle and low nutritional requirements (Chandramenon et al. 2024). Among the studies comparing lettuce grown in FLOCponics to lettuce cultivated in other systems, 19% found that FLOCponics performed better, 13% indicated that traditional aquaponics was more effective, 25% reported better results with hydroponics, and 44% found no significant differences between the systems (Hwang et al. 2023). The researchers evaluated the production of lettuce using BFT effluents, either treated with filtering devices or left untreated, but neither scenario showed any modifications in plant development. Solids and bioflocs were observed on plant roots, particularly in the absence of filtration systems; therefore, the scientists proposed the development of effective mechanical filters to prevent the accumulation of solids (Blanchard et al. 2020). They evaluated the effects of supplementing the hydroponics subsystems of the FLOCponics treatments with fertilizer on lettuce growth within the same experiment. The authors found that, due to the added fertilizer, the lettuce grew similarly in both the hydroponics and FLOCponics systems (Blanchard et al. 2020). Halophyte salicornia is a very valuable commodity. Researchers in these experiments failed to evaluate FLOCponics in comparison to other methods of crop production. Most of them emphasized how salicornia production and BFT may work together for the better (Table 1) (Pinheiro et al. 2020).

The trophic level in BFT can influence the performance of various plant species, including spinach, lettuce, pak-choi, rocket, and basil. Their findings underscore the importance of evaluating the suitability of specific species for a given production system. Pickens et al. (2020) conducted a comparative study on tomato growth in FLOCponics and hydroponic systems, both before and after fish harvest. Following the harvest, the researchers observed that the FLOCponics system yielded fewer tomatoes than the hydroponic system. This discrepancy was attributed to a nutrient deficiency in the water, which impeded the growth of the remaining tomatoes. While nitrogen levels in the BFT effluent were deemed low, the elemental composition of cucumber leaves remained within acceptable thresholds (Fimbres-Acedo et al. 2020).

Further studies about FLOCponics have yielded promising results, focusing on visual attributes, nutritional content, and stress indicators (Pinheiro et al. 2017; Pickens et al. 2020; Pinho et al. 2021a; Soares et al. 2022). Their findings suggested that the growing conditions in FLOCponics did not induce excessive plant stress. Some studies reported that Biofloc Technology (BFT) positively influenced the visual quality of plants, while others found no observable signs of nutritional deficiencies (Pinho et al. 2017; Pickens et al. 2020). Research on FLOCponics often associates the presence of particulates or bioflocs on plant roots, as well as elevated water pH levels (above 7), with poor visual characteristics and suboptimal plant growth.

These factors can limit nutrient availability in forms that are readily absorbed by plants (Soares et al. 2022). Additionally, nutritional imbalances and the consumption of nutrients by BFT microbes further contribute to these challenges (Pickens et al. 2020). However, the precise role of these bacteria in nutrient recycling and elimination remains poorly understood (Pinheiro et al. 2017). Furthermore, inadequate waste management practices and the failure to optimize nutrient use by reusing or demineralizing sediments and bioflocs exacerbate these issues (Pinho et al. 2021a).

Economic sustainability aspects of FLOCponics

Researchers have developed emerging technologies to promote the transition of aquaculture toward more environmentally sustainable practices. Sustainability in aquaculture encompasses the need for systems to be both technically feasible and economically viable. The objective is to provide safe and nutritious food to meet the needs of current and future generations (Boyd et al. 2020). Conducting economic evaluations of different aquaculture operations can yield valuable information for implementing managing techniques that enhance the business's resilience and longevity (Pickens et al. 2020; Soares et al. 2022). Sustainability assessments are essential for developing a comprehensive understanding of the social and ecological impacts of a new production system, considering its interconnectedness. This understanding is crucial for

Table 1 An overview of productive results of aquatic organisms and plant species cultivation in FLOCponics.

Plant	Animal	Results	Reference
Lettuce (*Lactuca sativa L.*)	Tilapia (*Oreochromis niloticus*)	Lettuce cultivated in FLOCponics showed noticeably poorer growth performance and visual quality compared to lettuce grown in traditional aquaponics. In contrast, juvenile tilapia demonstrated significantly enhanced zootechnical performance in the FLOCponics system.	Pinho et al. (2021a)
Cucumber (*Cucumis sativus L.*)	Tilapia (*Oreochromis niloticus*	Variations in pH influenced the availability of macro and micronutrients. However, they did not significantly affect the growth rate of cucumbers. Both cucumbers and tilapia showed significant growth rate in BFT supported aquaponics.	Blanchard et al. (2020)
Cherry tomato (*Solanum lycopersicum var. cerasiforme)*	African cichlid (*Melanochromis* sp.)	Tomatoes and fish grown in FLOCponics water exhibited a remarkable 20% increase in growth rate compared to those cultivated in a traditional hydroponics system. This demonstrates the enhanced efficacy of the FLOCponics approach in promoting growth for both crops and aquatic species.	Castro-Castellón et al. (2020)
Jalapeño pepper (*Capsicum annum*)	Tilapia (*Oreochromis niloticus*)	Tilapia demonstrated enhanced productivity in tanks employing BFT. However, there were no significant differences in plant productivity among the assessed systems for the pepper plants.	Martinez-Cordova et al. (2020)
Tomato (*Lycopersicon esculentum*)	Tilapia (*Oreochromis niloticus*)	The growth performance of tomatoes was not enhanced in BFT supported aquaponics. In contrast, the growth and survival rates of tilapia showed significant improvement.	Nadia et al. (2023)
Cherry tomato (*Solanum lycopersicum var. cerasiforme)*	Tilapia (*Oreochromis niloticus*)	The cherry tomato 'Favorita' yielded similarly in FLOCponics and hydroponics before fish harvest, whereas the tomato 'Goldita' yielded more in hydroponics. Both cultivars grew better in hydroponics after the fish harvest.	Pickens et al. (2020)
Perennial glasswort (*Sarcocornia ambigua*)	Pacific white shrimp (*Litopenaeus vannamei*)	The combined production of *L. vannamei* and *S. ambigua* in FLOCponics was recommended at 16–24 psu since the shrimp performed well and the plants grew and removed nitrogen and phosphate compounds.	Pinheiro et al. (2020)
Perennial glasswort *(Sarcocornia ambigua)*	Tilapia (*Oreochromis niloticus*) and pacific white shrimp (*Litopenaeus vannamei*)	Compared to BFT, the FLOCponics system's IMTA produced a better yield. The presence of *S. ambigua* did not affect the consumption of phosphorus or nitrogen, despite the reduction in nitrate levels.	Poli et al. (2019)
Asparagus (*Sarcocornia ambigua*)	Pacific white shrimp (*Litopenaeus vannamei*)	The growth performance of *Litopenaeus vannamei* and *Sarcocornia ambigua* cultivated together in FLOCponics was significantly enhanced.	Soares et al. (2022)
lettuce (*Lactuca sativa L.*)	Tilapia (*Oreochromis niloticus*)	Growing lettuce in freshwater FLOCponics resulted in a greater harvest than in brackish water.	Zappernick et al. (2022)
Lettuce (*Lactuca sativa L.*)	Silver catfish (*Rhamdia quelen*)	Compared to traditional aquaponics, FLOCponics methods utilizing silver catfish wastewater as fertilizer significantly enhanced lettuce growth.	Rocha et al. (2017)
lettuce (*Lactuca sativa L.*)	Tilapia (*Oreochromis niloticus*)	Lettuce grown using BFT effluent demonstrated greater productivity compared to that cultivated in conventional aquaponics. Among the various types of lettuce examined, butter lettuce exhibited the most favorable growth characteristics, highlighting its suitability for BFT systems.	Pinho et al. (2017)
Perennial glasswort (*Sarcocornia ambigua*)	Pacific white shrimp (*Litopenaeus vannamei*)	*S. ambigua* absorebed maximum nutrients from shrimp waste and improved the growth rate. While shrimp growth was not improved by the combination of *S. ambigua* with shrimp production, while using BFT in aquaponics.	Pinheiro et al. (2017)

establishing effective public strategies that promote the sustainable growth of the industry. It encompasses biological, technical, and economic considerations (David et al. 2018). Research utilizing Life Cycle Assessment has shown that the primary environmental impacts of aquaponics production are associated with infrastructure, energy consumption, and feed (Maucieri et al. 2018; Francisco et al. 2024).

The positive aspects of aquaponics systems are frequently linked to their low water consumption and their potential to support cultural, recreational, educational, and tourism-related benefits, as well as to enhance the landscape (Castilho-Barros et al. 2018; Junge et al. 2019; Pickens et al. 2020). While the carbon footprint associated with commercial shrimp production, as determined by life cycle assessment, does not significantly impact biofloc-based production, energy consumption does (Boyd et al. 2020). The literature reveals a lack of sustainability assessments for FLOCponics systems. This gap is likely due to the absence of a large and comprehensive database necessary for such analyses (Pinho et al. 2022). Emerenciano et al. (2021) described FLOCponics as a novel technique with the potential to mitigate certain unsustainable aspects of traditional aquaculture, despite the lack of available sustainability assessment data. Replacing the RAS with BFT can enhance the advantages and disadvantages of both biofloc-based systems and conventional aquaponics.

An environmentally friendly food production system, already recognized for its effectiveness, can integrate this substitution (Pinho et al. 2022). Additionally, the key sustainable benefits of FLOCponics systems include the ability to produce a variety of food items close to consumers, in compact urban areas, while minimizing environmental impact and providing social benefits (Pickens et al. 2020). Furthermore, FLOCponics is a highly significant system in food production, as it yields pesticide-free, nutritious products available to consumers in various forms, including fish and vegetables. A speculative commercial-scale FLOCponics system was modeled to incorporate *Litopenaeus vannamei* and *S. ambigua*, a halophyte, with a focus on its profitability (Castilho-Barros et al. 2018). Even in the most pessimistic business projections, the authors assert that the system is financially viable due to the high market value of the species involved. Additionally, they found that FLOCponics requires expensive operational equipment, highly trained personnel, and significant deployment costs. It would be unwise to assume that FLOCponics will be profitable based solely on hypothetical outcomes in specific regions and with products (Emerenciano et al. 2021; Pinho et al. 2022).

It is crucial to recognize that if the productive capacity of FLOCponics is validated, the expenses could be mitigated by increased biomass production, addressing this economic concern (Pickens et al. 2020; Soares et al. 2022). For instance, the cost of electricity per kilogram of food produced in FLOCponics systems is expected to be lower than that in biofloc-based monocultures (Knaus et al. 2024). Incorporating renewable energy sources such as solar, wind, and biogas from biodigesters, along with durable infrastructure and equipment, could further enhance the environmental sustainability of FLOCponics systems (Pinho et al. 2017; Pinho et al. 2022). Food production systems inherently affect the environment. Therefore, we recommend supporting systems that achieve high productivity with minimal negative impacts (David et al. 2020). It is essential to evaluate the trade-offs between the benefits and drawbacks of FLOCponics, as well as to assess the long-term viability of actual systems. To accomplish these goals, we must develop a more comprehensive technical and economic database on FLOCponics, which can then be subjected to sustainability studies (Knaus et al. 2024).

Challenges of using BFT in aquaponics

If the technological challenges are addressed, FLOCponics could serve as a viable alternative for investors looking to establish integrated agri-aquaculture farms. To effectively operate a FLOCponics system and achieve optimal results, a thorough understanding of several key subjects remains essential (Pinheiro et al. 2017; Pinho et al. 2022). Additionally, the selection of the food production system must consider several elements, including market demand, climatic conditions, producer expertise, technical knowledge, input costs, and availability, among other considerations (David et al. 2020). While recognizing the potential benefits of FLOCponics, it is essential to conduct a comprehensive review of the entire production process to select the most suitable method for a given situation (Khater et al. 2024). The design and construction of FLOCponics systems are crucial elements that require alteration. The configuration of this system must be carefully designed to maximize the favorable environmental situations required for the growth of aquatic plants and organisms, as well as the nourishment of BFT bacteria (Pinho et al. 2021b). The primary goal is to maintain optimal levels of suspended particles in the water to support the growth of both fish and plants. As previously mentioned, the high concentration of solids in FLOCponics systems appears to impede plant growth. Efforts to remove solid particles from the hydroponics subsystem have, however, diminished the availability of food and bioflocs for the animals in their natural environment (Pinho et al. 2021a; Khater et al. 2024). A potential strategy to address this issue involves developing mechanical separators that efficiently separate the solid and liquid components of the BFT effluent. This would allow for the transfer of nutrients and water from the bioflocs to the hydroponics subsystem, while reintegrating these elements into the aquaculture subsystem (David et al. 2020). Bag filters with backwash technology, drum filters, and sedimentation containers with meticulously engineered biofloc return flow should be considered for FLOCponics (Pinho et al. 2021b).

Additionally, it is essential to establish the regularity of their operation and control the water discharge rate into these filtration systems. It is important to emphasize that each of these filters can be utilized in interconnected FLOCponics systems (David et al. 2020). However, in all interconnected systems, there will inevitably be a trade-off between the needs of plants and animals (Monsees et al. 2017; Khater et al. 2024). The enhancement of the technical components of FLOCponics systems should effectively mitigate or perhaps resolve these issues, mostly associated with solids management (Pinho et al. 2021a). Furthermore, implementing a decoupled design would enable effective adjustments of pH levels to optimal values for each subsystem and allow for the direct addition of specific minerals to the hydroponics subsystem (Piñero et al. 2024). Unlike commercial hydroponics that rely on completely prepared fertilizers, FLOCponics might potentially lower production costs by using only particular nutrients (Pinheiro et al. 2020). This is feasible because BFT effluent already contains a diverse array of nutrients. To achieve this goal, it is crucial to obtain detailed information about the quantities of nutrients present in the feed and the carbon source (Monsees et al. 2017; Khater et al. 2024). Additionally, it is important to analyze the micronutrient content in the process water of the BFT system, as these micronutrients significantly impact plant physiological processes, such as photosynthesis (Monsees et al. 2017; Piñero et al. 2024). An examination of the differences in the quality and diversity of micronutrients between FLOCponics systems and a properly balanced hydroponic fertilizer will shed light on the possibility of a specific nutrient deficiency (Nadia et al. 2023). This could facilitate the creation of tailored supplementation regimens for each plant species, thereby maximizing both yield and quality of the vegetables (Sousa et al. 2024).

Furthermore, it is essential to conduct this research at high densities to achieve greater yields. Only a limited number of animal species that can be efficiently cultivated in BFT systems, and consequently in FLOCponics systems, possess the necessary traits. However, several studies have identified additional species that may also be viable (Walker et al. 2020). Pacific white shrimp and Nile tilapia are the most widely cultivated species using BFT. Both species are extensively farmed and make significant contributions to the global food supply. Although the limited availability of other high-value species poses a challenge for FLOCponics, focusing on established products while developing innovative technologies is advantageous (Panigrahi et al. 2020).

Conclusions

Aquaponics involves the integrated cultivation of aquatic organisms and plants, where the majority of nutrients required for plant growth are derived from aquaculture effluent. In a conventional aquaponics system, a recirculating aquaculture system (RAS) is coupled with a hydroponic system, facilitating the continuous exchange of water and nutrients. A primary challenge in conventional aquaponics is managing the conversion of ammonia, produced during aquatic animal cultivation, into nitrate, while simultaneously maintaining a balance between concentrations in the aquatic animal tank and the plant growth bed. The integration of Biofloc Technology (BFT) into aquaponics holds promise for addressing this challenge effectively, offering innovative solutions to the issues faced by the aquaculture sector. This combined system, termed FLOCponics, merges BFT with aquaponics and is designed to be environmentally sustainable. The integrated system can enhance economic diversity by generating value-added plant products while mitigating the accumulation of nitrate and phosphorus in the BFT management system. However, further research is needed to evaluate the environmental, social, educational, and economic impacts of implementing FLOCponics in urban environments. Such assessments will facilitate the promotion of sustainable practices within the aquaculture industry.

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