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REVIEW

REVIEWS IN Aquaculture

FLOCponics: The integration of biofloc technology with plant production

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Abstract

FLOCponics is an alternative type of aquaponics that integrates biofloc technology (BFT) with soilless plant production. The aims of this paper are to present a detailed overview of the FLOCponics system's designs and performance, discuss their sustainability, highlight the current challenges, and give directions for future research. Data sources include papers containing the keywords bioflocs and hydroponics, aquaponics and/or plant production. In view of the small number of publications and the lack of standardization in experimental design and system setup, it was concluded that FLOCponics is still in its initial research stage. With respect to the animal and plant yields in FLOCponics, inconsistent results were found. Some investigations presented better or similar yield results in this system compared to traditional cultures, while others found the opposite. One of the key challenges of using FLOCponics is the effective control of solids. Refining the system's design was the main recommended improvement. Moreover, this paper highlights that the commercial application of FLOCponics will require extensive research that clarifies its technical and economic aspects, originating from experimental or pilot-scale setups with characteristics similar to commercial production. This review provides and discusses information that can be useful for the effective development of FLOCponics, guiding further research to make FLOCponics commercially feasible and thus contributing to sustainable aquaculture production.

KEYWORDS
aquaponics, biofloc, FLOCponics, food production system, integrated systems, sustainability

1 | INTRODUCTION

The global demand for safe and healthy food has increased significantly in the last few years due to world population growth, projected to reach 9.7 billion people in 2050.[1] Providing them with healthy food is a major global challenge, especially in the current scenario of natural resource scarcity.[2,3] Many countries still face problems with hunger while others are trying to address their high rates of population obesity and malnutrition.[4] Hence, investment and research into sustainable food production technologies that produce nutritious food and consume fewer natural resources are needed.[5-7] Modern aquaculture systems, for example, can contribute to the production of fish for a healthy human diet in a more sustainable way.[8,9]

In recent years, aquaculture has been the fastest growing animal production activity and has increasingly contributed to the fish supply worldwide.[9] There are several ways to classify aquaculture systems, ranging from the degree of intensification and the use of feed, to water renewal or the environment where the farm is installed.[10] Most of the global aquaculture volume is produced in semi-intensive pond systems or intensively in cages.[9] The pond and cage systems in general require a low degree of technology and, when well-managed, are efficient for fish production.[11,12] However, in some situations where proper management is not carried out, that is, no treatment of the effluents occurs or the carrying capacity of the environment is neglected,[7,13-15] eutrophication of waterbodies might result.[16] In addition, these traditional pond and cage aquaculture systems depend on large volumes of water, extensive areas of land, and/or in some critical scenarios the use of antibiotics to achieve high productivity.[7,17,18] All these environmental problems undermine aquaculture's sustainability.[19,20]

In order to ensure that the growth of aquaculture does not occur in a disordered way, which will consequently affect its full development, new technologies and management strategies have been proposed to adapt aquaculture to sustainable production methods.[19,21] Sustainable aquaculture systems are those that enable maximum production per volume with minimum negative environmental impact and less use of resources.[22] In this sense, in the last decade an increased number of studies have been seen which focused on closed aquaculture systems which require low volumes of water and minimize effluent discharge. Examples of these types of systems are the recirculating aquaculture systems (RAS) and those using biofloc technology (BFT).[23,24] RAS is a filter-based aquaculture system where water is constantly recirculated and partially reused.[25] For this, mechanical filters are used to remove the solid wastes and biofilters, colonized by nitrifying bacteria, are required to convert the toxic metabolic wastes from fish (ammonia is oxidized into nitrite and then to nitrate) and to purify the water.[23,26] BFT is a closed aquaculture system based on the microbial-loop concept, where the growth of a specific microbial community, such as heterotrophic and nitrifying bacteria, is stimulated in the fish and/or shrimp tanks.[7,27-29] Compared to the traditional low-technology aquaculture systems, RAS and BFT offer the advantage of producing aquatic animals in a controlled environment, with a high degree of water reuse and predictable harvesting schedules.[23,27] However, these systems are highly dependent on electricity for adequate operation, and specialized labour. Besides that, RAS and BFT are usually employed in monocultures and do not reuse the leftover nutrients to nourish other species in traditional configurations.[30,31]

Integrated multi-trophic aquatic systems are recognized as a modern and more sustainable production method.[7,32] Multi-trophic systems combine the culture of fed species with extractive species, aiming to simulate a natural ecosystem. By this mix of species, the accumulated nutrients and by-products from the fed culture are used by the extractive species for their own growth.[7,33] Nutrient reuse allows the minimization of the environmental impacts of food production, reduction of the costs of fertilizers and water, and contributes to the development of circular food production.[34,35] Moreover, the integration of systems and species with different trophic functions increases the variety of products offered and provides food security for local consumers.[36,37]

Aquaponics is an example of an integrated agri-aquaculture system which combines aquatic animal and vegetable production.[38] The most common and traditional aquaponics system configuration integrates freshwater RAS and hydroponics systems in one loop.[39,40] However, aquaponics is a research field under development and variations on the common one-loop configuration are frequently being proposed to improve the efficiency in the food production process.[41] Examples of different system designs are: decoupled aquaponics systems,[42,43] multi-loops aquaponics systems,[44,45] algaeponics systems,[46] maraponics systems,[47] and the use of biofloc technology[41] or FLOCponics systems, as recently named by Pinho et al..[48]

FLOCponics is defined as the integration of biofloc-based aquaculture with hydroponics.[48] Thus, FLOCponics is an alternative type of aquaponics system where RAS is replaced by a system based on BFT. Kotzen et al.[41] presented a brief overview of the research carried out on the integration of BFT and plant production. However, they do not provide detailed information about the productive results reached or a critical discussion of the challenges and contributions of such integration to sustainable food supply. The aims of this paper are to: (i) present FLOCponics systems, the justifications for its employment, and an overview of the technical results that have been achieved so far; (ii) discuss the economic and environmental aspects of these systems and the relevance of its development to the food supply; and (iii) highlight current FLOCponics challenges and give directions for further research.

To achieve the aforementioned aims, this review is structured into a further six sections. Firstly, a brief overview of biofloc technology and aquaponics is given in *sections 2* and *3*. Then, FLOCponics systems are presented in *section 4*. This section is divided into subsections in which a theoretical background is introduced, and information regarding the system setups, water quality and nutrient recycling, and productive results of plant and fish achieved in FLOCponics research are detailed. The main potential technical-economic, social and environmental characteristics of FLOCponics are shown in *section 5*. Lastly, the challenges of FLOCponics are discussed in *section 6* and the final remarks are presented in *section 7*.

2 | BIOFLOC TECHNOLOGY

Biofloc Technology (BFT) was developed in the 1970s, by the French Research Institute for Exploitation of the Sea (IFREMER).[29,49] Their aim was to improve the productive performance of aquatic animals and solve problems of disease outbreaks in marine shrimp farming.[29,49] The promising results of BFT were disseminated and, due to its flexibility, such technology is also currently applied in fish farms. Biofloc-based culture is characterized by the presence of specific microbial communities, which enable the intensive and biosafe culture of aquatic organisms.[27,50,51] The growth of heterotrophic bacteria is stimulated by the manipulation of the carbon:nitrogen (C:N) ratio, normally ranging from 10 to 20:1, with constant water movement and aeration and minimal water exchanges.[27,52] In addition to heterotrophic bacteria, chemoautotrophic bacteria and planktonic organisms, mainly microalgae, copepods, cladocera, protozoa and rotifers, are also frequently reported in biofloc cultures.[53-55] The predominance of each group of microorganisms will depend on the target shrimp/fish species, the productive management, and the inputs used.[28,54] Such predominance will define the BFT trophic level, usually categorized as photoautotrophic (algae-based system), chemoautotrophic (based on nitrifying bacteria), heterotrophic (based on heterotrophic bacteria), or mixotrophic systems.[27,29]

Under proper operation of the system, biofloc microbial aggregates confer several benefits to aquaculture production. Suitably operating a biofloc-based system means, in general, providing the water quality and nutrients required for the growth of the target species and microorganisms.[56] In *in situ* BFT, the microorganisms are constantly available, rich in nutrients, and complement the nutritional requirements of the reared animals.[57-59] Consequently, BFT allows for the application of nutritional management strategies which reduce expenses and the negative impacts of aquaculture, for instance, the reduction of fish meal and protein levels in the diets used.[60-63] The biofloc microbiota also confers stability on the system and maintains water quality by recycling the nutrients, incorporating ammonia excreted by organisms into bacterial biomass and promoting the microbial-loop.[28,64] In addition, BFT contributes to minimizing the occurrence of diseases. An improvement in the nutritional and immunological status of the animals through the consumption of bioactive compounds in the bioflocs, and a reduction in the presence of pathogens, has already been reported.[52,65] Recent research has also demonstrated the positive effect of BFT on gut microbiota[66] and on health and enzymatic activity.[67]

Biofloc technology has been employed in aquaculture farms and research centers worldwide. In recent years, the number of publications has significantly increased. A total of 138 articles about 'biofloc' were published between 2001 and 2010, and this number increased to 635 between 2011 and 2019 (source: ScienceDirect 2020). There are already several reviews and overviews on this topic. The papers range from the definition and detailed explanation of BFT[27,51,68] to more specific subjects, such as the profile of microorganisms usually found[69] and their positive effect on water quality,[28,70,71] animal health[65] and nutrition.[49,54,57,72,73] Most research articles on BFT evaluate the production of Pacific white shrimp *Litopenaeus vannamei*[29,59,64,74] and tilapia *Oreochromis spp.*,[67,75,76] although some studies have already shown the suitability of BFT for other species.[31]

The benefits of BFT are numerous and well known. However, it is a complex system,[27] not applicable to all aquaculture species,[77] and commercially should be applied with proper technical supervision. Some examples of BFT disadvantages in relation to other aquaculture technologies are: (i) the need for intensive monitoring of the physical-chemical parameters of the water; (ii) continuous dependence on electricity; and (iii) the need for specialized labour.[7,31] Moreover, the accumulation and high (toxic) concentration of nutrients, such as nitrate and phosphate as a result of high fish/shrimp stocking density and low water renewal,[51,78] may affect the efficiency and stability of the system in the long-term. In this sense, its integration with hydroponic vegetable production (in a FLOCponics system) could be an alternative to minimize these problems.[41]

3 | AQUAPONICS

In aquaponics systems, aquaculture effluents are transformed by nitrifying bacteria into bioavailable nutrients for plants, supporting almost full feed utilization and plant growth.[79-81] In aquaponics, nutrients are recycled and low volumes of water are used,[38] which reduces the negative environmental impacts usually associated with low efficiency in the use of natural resources in conventional food production.[82]

To make agri-aquaculture integration viable, a basic layout including some indispensable components is required. An aquaponics system basically consists of aquatic organism tanks and filters (mechanical and biological), which make up the recirculating aquaculture system, connected to hydroponic beds.[83] Changes in this layout can be found depending on the adopted production scale, that is, whether it is for hobby, small-scale (semi-commercial) or large-scale (commercial) production. Small-scale production is usually low-cost and flexible in terms of materials used and species produced, while commercial aquaponics needs high investment, labour and upgrading.[84] Different designs, greenhouse environment, management and type of hydroponic bed are often reported for large production systems.[84,85] The objective of the entrepreneur and the requirements of the reared species will define which layout should be used.

Many potential species can be produced in aquaponics depending on the employed system design.[86] For the success of aquaponics, the aquaculture species must have suitable characteristics for production in intensive recirculating aquaculture systems. They should be rustic and tolerate high stocking densities, handling, and a wide range of physical–chemical water parameters.[40] Although there are some reports on the culture of other aquatic organisms, the production of fish, mainly tilapias (*Oreochromis* spp.), catfish (order Siluriformes) and salmonids, are predominant in aquaponics farms.[40,85,87,88] Regarding the plants, in general, those that are produced in hydroponics systems thrive in aquaponics. Plant production in aquaponics is directly related to the nutritional characteristics of fish/shrimp feed and the rate of nutrient mineralization by microorganisms.[89,90] Besides that, plant growth frequently depends on extra fertilization to better meet its nutritional requirements.[90,91] In contrast to coupled systems, meeting the nutritional requirements and water conditions for each loop (aquaculture, hydroponics and filters) is possible in decoupled systems due to the individualization of the productive units.[44,92] It is worth noting that the terms coupled and decoupled aquaponics systems were recently renamed as 'permanent coupled' and 'on-demand coupled' systems, respectively.[93] However, even though these new nomenclatures should be used in further studies, in the present paper, the system layouts were referred coupled and decoupled as labelled in the reviewed papers. Regardless of the design employed or species grown, aquaponics is recognized as offering a wide variety of products that ensure safe and healthy food. This is mainly because minimal or no chemicals such as pesticides and antibiotics are used.[16,36]

Although aquaponics is an emerging food production technology, several articles have already been published about it. Goddek et al.[89] presented a detailed review on the characteristics and opportunities of aquaponics. They also discussed the challenges for commercial aquaponics production and the trade-offs between the needs of fish, filter-bacteria and plants in a coupled system. These trade-offs and the dynamics of the decoupled system were discussed in depth by Goddek et al..[43] After the publication of 160 articles between 2015 and 2019, Yep and Zheng[40] updated the general trends of aquaponics and showed that research focused on system design, hydroponics components, fish species, plant species and microflora has increased. Besides these topics, others relating to and focused on aquaponics production have also been investigated and reviewed. For example, studies on economic viability,[94-97] sustainability,[98-100] simulation and predictions through mathematical models,[101-104] use of aquaponics as an educational tool,[105] applicability of multi-loop aquaponics systems[106,107] and application of other aquatic animal species[41] are also found in the literature. In most of these papers, it is emphasized that aquaponics systems carry great potential to overcome some of the technical and environmental challenges of the agricultural and aquaculture sector.

Some fields of aquaponics still require research and must be improved in order to exploit their full potential. For example, a few studies have recently been developed on how the nutrients of RAS water-sludge can be recycled and used for plant production.[108,109] Each aquaponics system and species reared need specific water parameters, nutrient balance and pest management. Meeting these specifications is usually the main technical challenge faced by traditional coupled systems.[110,111] In addition, commercial aquaponics is highly dependent on specialized labour, due to the need for multidisciplinary knowledge to run the system.[85,89,98]

4 | FLOCponics

4.1 | Background

Aquaponics and biofloc-based aquaculture are considered environment-friendly approaches to food production. Both are intensive aquaculture systems with a strong focus on nutrient recycling and water saving.[7,112] FLOCponics shares these characteristics. By adopting the principles of aquaponics and bioflocs, FLOCponics can become an additional means to reduce the challenges of the global sustainable food supply. Recently, the term 'FLOCponics' was proposed by Pinho et al.[48] to identify and unify the systems that have been called 'BFT+hydroponics', 'BFT+aquaponics' or 'BFT+plant production'. All these terminologies were used in the search for papers in the ScienceDirect, Google Scholar and Scopus databases, and papers published until September 2020 were considered. The reference lists presented in the articles found were cross-referenced in our review, that is, these lists were checked in order to find the papers that were not discovered at first. In total, twenty-two papers were found and reviewed, of which 4 were theses and 18 were articles published in peer-review journals (3 of them were found by cross-referencing).

In general, the 22 papers found theoretically justified the use of FLOCponics systems by their potential to combine and maximize the advantages of BFT and traditional aquaponics using RAS and/or to minimize their limitations. High nutrient use efficiency and reduction of waste are examples of strengths of aquaponics that can be potentialized in FLOCponics systems.[112,113] Furthermore, the FLOCponics researchers usually state that adding hydroponics production to a BFT farm may expand economic diversity by producing additional value-added products (plants) and reduce the negative environmental impacts of biofloc-based production, such as the accumulation of nitrate and phosphorus in BFT culture and its discharge through solids management.[70,76,114] From an agri-aquaculture production point of view, it is also expected that BFT brings relevant benefits. For example, the improved zootechnical performance reported in BFT compared to RAS cultures[115,116] and the positive effects of BFT on animal nutrition and health[65] suggest that FLOCponics may offer an advantage. Regarding plant growth, the main characteristics that make BFT effluent a promising fertilizer are: (i) the high concentration of nutrients; (ii) the diversity of microorganisms, which are constantly recycling nutrients and may increase their availability or help their absorption by the plants; and (iii) the low investment in filters for water treatment.[49,78,117] Although the authors presented many theoretical advantages of using FLOCponics, some of them were not yet fully proved.

The overview of the objectives and general findings of these papers are described in Appendix I. The details and specific results related to plant and animal growth as well as the system designs and nutrient insights are described in the next subsections. In addition to the 22 papers found, three other peer-review articles that reported on the use of BFT effluent for the production of plants in soil were found.[118-120] However, they do not fit the definition proposed here for FLOCponics (BFT +hydroponics). Because of this, these articles were not considered in the descriptions and discussions of the system.

4.2 | System setups

The employed designs of FLOCponics systems are summarized in Table 1. Most of the experiments were run in coupled system configurations and only 30% used decoupled (on-demand coupled) systems (Figure 1). In coupled configuration, the water and nutrients are fully recirculated between all subsystems (BFT, optional filters and hydroponics). For decoupled FLOCponics systems, the respective subsystems are seen as stand-alone systems and the water and nutrients are directed from BFT, to filters (optional use) and end-up in the hydroponics subsystem. No study compared or evaluated the possible effects of coupled and decoupled configurations on production in FLOCponics systems. Different types of hydroponics subsystems are employed, in which the Nutrient Film Technique (NFT) and Deep Water Culture (DWC) were mostly used (Figure 1). NFT comprises shallow channels where the plants are allocated. A thin layer of nutrient solution flows through these channels to partially irrigate the roots of the plants. In DWC plants are produced in floating supports on tanks filled with nutrient solution.[89,91] No experiment was reported that assessed whether the type of hydroponics system affects the efficiency of FLOCponics systems in terms of food production and nutrient use. In view of this lack of data, it is still unknown which type of hydroponics subsystem works better in FLOCponics.

With respect to the aquaculture subsystem, tanks with different volumes have been used, varying from 125 to 1000 L to more than 100,000 L. The high volumes of fish tanks (>100 m^3) were reported by Rahman,[121] Blanchard et al.,[122] Pickens et al.[123] and Doncato and Costa.[124] These authors took the effluent from BFT tanks daily or weekly, streaming the water for plant production in decoupled systems. In addition, a remarkable feature was the use of artificial substrates in the shrimp tanks by Silva,[125] Neto,[126] and Poli et al..[114] These authors did not test the effects of the substrates on FLOCponics production, they were used as a management usually recommended for shrimp growth in BFT.[127-129] The adoption of substrates has been proposed to increase the surface area of the tank and favour the growth of periphyton.[54] Periphyton-based aquaculture brings advantages such as serving as a complementary food for the cultivated animals and assisting in the cycling of nutrients.[130] Studies on the use of substrates in FLOCponics systems should be carried out to better understand its effect on animal and plant growth, as well as on the quality and amount of nutrients available for the hydroponics subsystem.

In BFT production, the use of simple settling tanks is often needed to control the solids concentration in the fish/shrimp tanks.[27,131,132] A high concentration of solids can negatively impact the operation of the system since it can result in higher oxygen demand. The recommended range of solids concentration for the production of tilapia and shrimp in biofloc-based systems are 5 to 50 and 5 to 15 ml L^{-1}, respectively, usually measured as volume of bioflocs in Imhoff cones.[28,57] The use of filters in FLOCponics research seems to be optional and varies according to each investigation. In total, 65% of FLOCponics systems employed some type of filters between the BFT and hydroponics subsystems (Figure 1). Settling tanks were always present in the filter systems and extra biological filters in 23% (Table 1). In general, only information about the total volume and type of filter used in the FLOCponics filter system has been reported so far. Unlike in biofloc-based systems without integration, the use of filters in FLOCponics was intended to try to avoid the flow of particulate matter to the hydroponics subsystems as such particulates may impair plant growth. Except for the systems run by Fimbres-Acedo et al.,[133,134] Doncato and Costa,[124] all the others constantly recirculated the water through the filters and 46% of them used some mechanisms to return the decanted biofloc/sludge to the BFT subsystem. Fimbres-Acedo et al.[133,134] employed a decoupled system where the hydroponics subsystems received water from the BFT subsystem only in the beginning and middle of the experiment. At these moments, the water from the BFT subsystem was pumped to the 300 L settling tank and left to settle for 24 h. Subsequently, the supernatant was transferred to a 1000 L aerobic mineralization bioreactor (AEMBR), filtered with a 5 μm bag filter and then directed to the hydroponics subsystem. Doncato and Costa[124] directed the water from the BFT tanks to the settling tank and bag filters and then to the hydroponics subsystems once a week. With this procedure, the authors managed to reduce the concentration of suspended solids between the affluent and effluent of the filters by 71%. The frequent use of filters in FLOCponics indicates that the BFT management should focus on providing inorganic nutrients to the hydroponics subsystem instead of directing the microbial flocs to it.

A lack of standardization in the proportions of water volumes of the hydroponics, BFT, and filter subsystems was detected among the reviewed papers (Table 1). A wide variation was also observed in the water flow through the hydroponic beds, varying from 0.06 to 13.1 L min^{-1}, and in the strategies to direct the water from BFT to hydroponics subsystems in decoupled systems. The lack of a standard among the system setups points out that FLOCponics is still in its initial stage. It further indicates a research gap related to the dimensioning of hydroponics and filter subsystems in relation to the BFT tanks. The implications of this lack of standardization are discussed in *section 6*.

In general, simple greenhouses covered with transparent plastic polyethylene and a shading net (20–50% of light retention) were home to most of the experimental FLOCponics systems. These structures tend to have low effectiveness in climate control. Rocha et al.,[112] Castro-Mejía et al.,[135] Castro-Castellón et al.,[136] Martínez-Meingüer et al.[137] and Pickens et al.[123] reported different structures. Castro-Mejía et al.,[135] Castro-Castellón et al.,[136] Martínez-Meingüer et al.[137] carried out the experiments in an indoor lab using LED light to support plant growth. Pickens et al.[123] used greenhouses equipped with environmental controls for year-round production. Rocha et al.[112] did not use a greenhouse or any covered structure to run their low-cost FLOCponics systems.

TABLE 1 Overview of system setups in FLOCponics research

Reference	System configuration	HP subsystem	BFT subsystem	Filters	†HP:BFT:FT volume	‡Water flow (L min^{-1})
Barbosa[146]	Coupled	DWC: 3 tanks of 120 L each	Fish tank: 500 L	[2ni] Treatment with filters: 18 L settling tank, bag filter and 70 L biofilter and sump	0.72: 1.0: 0.18 (with filter) 0.72: 1.0: 0.0 (without filter)	8.0
Castro-Castellón et al.[136]	Coupled	DWC: Floating structure on top of the fish tank (Ø 100 cm)	Fish tank: 125 L	-	-	-
Castro-Mejía et al.[135] *Martínez-Meingüer* et al.[137]	Coupled	NFT: pipelines measuring 10 cm in diameter and 1 m in length	Fish tank: 160 L	-	0.19: 1.0: 0.0	-
Lenz et al.[140]	Coupled	DWC: 9 tanks of 72 L each	Fish tank: 500 L	[2m]Two settling tanks (100 and 10 L), a bag filter, 60 L biofilter and 150 L sump	1.30: 1.0: 0.64	1.1
Neto[126]*Pinheiro* et al.[78,113] *Silva*[125]	Coupled	NFT: 0.3 – 0.8 m^2 placed on top of the shrimp tank	Shrimp tank: 800 L	[2p]40 L settling tank	0.02 – 0.06: 1.0: 0.05	3.0
Pinho et al.[117]	Coupled	DWC: 9 tanks of 150 L each	Fish tank: 500 L	[2ni]100 L settling tank, 60 L biofilter, and 100 L sump	2.70: 1:0: 0.52	8.0
Pinho et al.[48]	Coupled	DWC: 3 tanks of 150 L each	Fish tank: 500 L	[2a]Two settling tanks (100 and 10 L) and 70 L sump	0.90: 1:0: 0.36	8.0
Poli et al.[114]	Coupled	NFT: 0.3 m^2 placed on top of the shrimp tank	Fish tank: 90 L Shrimp tank: 800 L	-	0.02: 1.0: 0.0	10.8
Rocha et al.[112]	Coupled	[(1)]DWC: 700 L	[1] Fish tank: 300 L	-	2.33: 1.0: 0.0	10.8
Zidni et al.[179]	Coupled	NFT	Fish tank: 375 L	-	-	-
Blanchard et al.[122]	Decoupled	Other: 16 buckets of 11 L each	Fish tank: 102,000 L	[2nr]Two settling tanks connected in a series (1500 L each)	0.002: 1.0: 0.03	Plants received between 6 and 8 L of biofloc effluent every day
Doncato and Costa[124]	Decoupled	NFT: pipelines measuring 10 x 5 cm and 3 m in length connected to a 450 L sump	Shrimp tank: 40,000 L	[2ni]500 L settling tank, bag filter (50 μm) and 3000 L reservoir	-: 1.0: 0.04	13.1

(Continues)

TABLE 1 (Continued)

Reference	System configuration	HP subsystem	BFT subsystem	Filters	†HP:BFT:FT volume	‡Water flow (L min^{-1})
Fimbres-Acedo et al.[133,134]	Decoupled	NFT: pipelines measuring 7.6 cm in diameter connected to a 250 L sump	Fish tank: 1000 L	(2nr) 300 L settling tank, 1000 L AEMBR and bag filter (5 μm)	0.25: 1.0: 1.30	HP subsystems received water from the BFT subsystem in the beginning and middle of the experiment
Martinez-Cordova et al.[148]	Decoupled	NFT: pipelines measuring 4 cm and 6 m in length	Fish tank: 400 L	–	-	Every three days the water from the HP subsystem was discharged, and replaced with water from the fish tanks, with or without bioflocs.
Pickens et al.[123]	Decoupled	Other: 0.32 m^2 pots filled with grade perlite and a steel cable trellis system running the length of the greenhouse	Fish tank: 100,000 L	(2ni) Two settling tanks connected in a series (1900 and 1000 L)	0.001: 1: 0.015	0.06 in increasing times of irrigation per day throughout the experiment
Rahman[121]	Decoupled	DWC: 24 buckets of 6 L each	Fish tank: 125,000 L	(2nr) Settling tank	0.001: 1.0: -	The water in each plant bucket was completely exchanged every day

–No data available or component not present.

(1)Hydroponics bed and BFT tank shared the same 1000-L tank, which was separated by a 0.26-mm net. (2)Management of the settled biofloc/sludge: returns to the BFT subsystem through a) airlift system; p) pump; or m) manual; nr) collected for further analysis or did not return to BFT subsystem; and ni) no information provided. HP: Hydroponics. BFT: Bioflocs technology. FT: Filters. DWC: Deep water culture. NFT: Nutrient film technique. AEMBR: Aerobic mineralization bioreactor.

†Water volume ratio between the subsystems, based on the initial volume without considering water exchanges.

‡Water flow in the hydroponics subsystem.

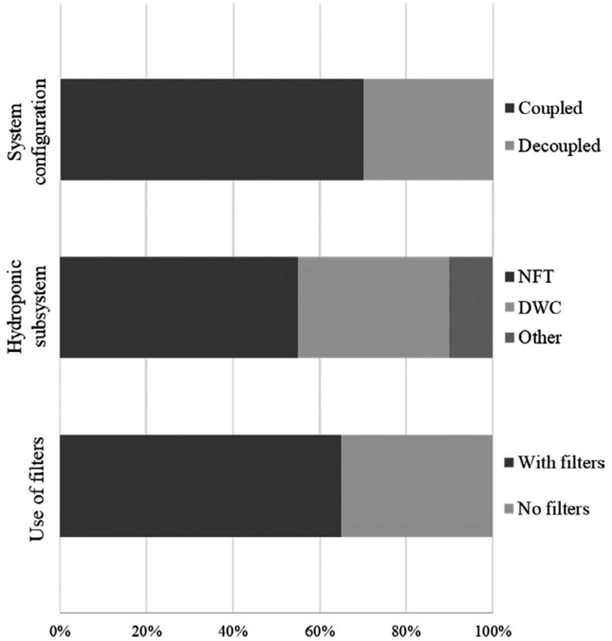

FIGURE 1 Proportion of the use of different system setups in FLOCponics research. DWC: Deep Water Culture. NFT: Nutrient Film Technique

4.3 | Water quality and nutrient recycling

One of the main characteristics of biofloc-based systems is the ability of BFT microorganisms to recycle nutrients and maintain ideal water quality for the reared animal species.[28] Phytoplankton, nitrifying bacteria and heterotrophic bacteria contribute to ammonia-nitrogen cycling by converting the toxic ammonia-nitrogen to nitrate or assimilating it into bacteria biomass.[27,138] All these types of nitrogen conversion usually happen at the same time and the predominance of one depends on the nutrient management of the system.[65,68] Additionally, the physical-chemical parameters of the water must meet the requirements of these microorganisms. In particular, high levels of dissolved oxygen (DO) and alkalinity, as well as a high C:N ratio, should be provided. Detailed information about the water quality required for BFT microorganism growth and the standard values of water parameters that must be maintained in the fish or shrimp tanks in BFT systems can be found in Avnimelech,[27] Emerenciano et al.[28] and Samocha and Prangnell.[139]

The results of the experiments run in FLOCponics systems and focused on animal production (Appendix I) showed that most of the physical-chemical water quality parameters remain within the acceptable ranges for fish or shrimp production. An exception was the volume of bioflocs (total suspended solids), which was lower than recommended. For example, Lenz et al.[140] and Pinho et al.[48,117] reported, respectively, 2.6 to 4.9 ml L^{-1}, 0.2 ml L^{-1} and 0.2 to 0.95 ml L^{-1} as mean values of volume of bioflocs in tilapia culture, which are below the minimum recommended of 5 ml L^{-1}.[57] However, these low values seemingly did not affect the maintenance of water quality and nitrogen recycling by the microorganisms. Based on that, it is reasonable to state that the relation between microbial activity and volume of biofloc in FLOCponics, and even in BFT monocultures, is highly variable and still unclear.

For plants, some physical-chemical parameters of water often seem to be non-ideal, mainly regarding the pH and suspended solids values in the coupled FLOCponics systems. The recommended pH range for hydroponics production is generally between 5.5 and 6.5 to ensure high nutrient availability for plant uptake.[141] Despite that, most of coupled FLOCponics systems reported so far were run with pH close to neutrality. In a decoupled system, Blanchard et al.[122] evaluated the effect of four pH levels (5.0, 5.8, 6.5 and 7.0) on nutrient availability in the hydroponics subsystems. The authors showed there were no overarching effects on plant growth that would demand pH regulation in the FLOCponics system. With respect to suspended solids in water, a very low concentration of solids must be maintained in the hydroponics subsystems to avoid the deposit of bioflocs in the plant roots and consequently the impairment of the breathing process and the absorption of nutrients by plants.[142] However, high solids concentration in the hydroponics tanks have been reported in FLOCponics systems.[41,76,143] Keeping biofloc concentration in the fish tanks at appropriate levels for animal production and at the same time maintaining low solids concentration in the hydroponics subsystems seems to be one of the trade-offs of coupled FLOCponics.

The input of nutrients and their transformation by microorganisms are as important as providing ideal conditions of water quality for all subsystems. In traditional aquaponics, most of the nutrients that nourish plants are expected to come from the RAS effluent,[84] and should also be the case in FLOCponics. The addition of organic and inorganic carbon sources to regulate the heterotrophic community and water alkalinity, respectively, may offer extra nutrients in FLOCponics as compared to RAS, where feed is commonly the only source of nutrients in the aquaculture subsystem. Both procedures are often required to promote the growth of BFT microorganisms.[27,28] Table 2 compares the nutritional management and sources of nutrients used in FLOCponics research. No standardization of these factors among the studies was found, probably due to the different species used, animal size, maturation stage of the bioflocs, and carbon source. Hydroponic fertilizers were used only in four studies.[121,124,135,137] It should be noted that little data is provided on the profile of macro- and micro-nutrients of the nutrient sources. The information is usually limited to the dietary protein content and the type of carbon source used.

Given the aforementioned lack of detailed information on the characteristics of the source of the nutrients fed to the FLOCponics systems it is hard to predict how many nutrients will be available for plant production. In addition, the rate of nutrient recycling and nutrient uptake by the BFT microorganisms are still unclear, which makes predictions very uncertain. Analysing nutrient content on the plant biomass is a way to estimate which nutrients have been minimally provided. Additionally, recent studies have evaluated the macro- and micro-nutrients available in the water and the solid portion (visible biomass) of FLOCponics systems, in an attempt to minimize uncertainty in predictions.[48,123,124,134] In general, lower concentrations of

TABLE 2 The main source of nutrients in FLOCponics

	Feed			BFT maintenance			Other
Reference	Frequency (times per day)	Amount	Composition (%)	C:N ratio	Carbon source	†Method	Alkalinity correction
Barbosa[146]	3	2.2% of fish biomass, 2 g feed day^{-1} $plant^{-1}$	CP: 32	15:1	White sugar	Based on daily input of N-feed, added once a day	-
Blanchard et al.[122]	2	Until satiation	CP: 36 Cfat: 6 Cfib: 3.5 P: 0.9	-			-
Castro-Castellón et al.[136]	2	5% of fish biomass	-	-	Coffee, Yucca, Moringa or Macroalgae	0.1% of fish biomass, added once a day	-
Castro-Mejía et al.[135‡]	-	5% of fish biomass	CP: 35 Cfat: 10	-	Moringa	0.01% of fish biomass	-
Doncato and Costa[124‡]	2	1.5% of shrimp biomass	CP: 35 P: 1.5 Ca: 1.5– 3.0	-			-
Fimbres-Acedo et al.[133,134]	5	1.2-fold daily protein intake	CP: 40.6	13:1	Unrefined sugar	Based on daily input of N-feed, five times per day only in heterotrophic tanks	-
Lenz et al.[140]	3	2.7% of fish biomass, 1 g feed day^{-1} $plant^{-1}$	CP: 32	14:1	Powder molasses	Based on daily input of N-feed, 17 g day^{-1} once a day	10 g Calcium oxide (CaO) were added in all fish tanks in the beginning of the experiment
Martinez-Cordova et al.[148]	-	Until satiation	CP: 30	The fish tanks were supplied with bioflocs produced in an external single bioreactor, fertilized with Triple 17 (17% N, 17% P, and 17% K). Wheat and amaranth seeds were supplied as nucleation substrates at the beginning of the trial or when suspended solids were below 20 ml L^{-1}.			-
Martínez-Meingüer et al.[137‡]	-	5% of fish biomass	CP: 35 vs CP: 47.5	-	Moringa	0.1% of fish biomass	-
Neto[126]	4	-	CP: 35	The addition of organic carbon was not necessary since the BFT was already in a chemotrophic stage and a nitrification process was established.			Calcium hydroxide ($Ca(OH)^2$) was added when the alkalinity was under 120 mg L^{-1}
Pickens et al.[123]	2	13% of fish biomass	CP: 36 Cfat: 6 Cfib: 3.5	The biofloc system used in this study was managed strictly as an autotrophic system with no supplemental carbon inputs			Calcium hydroxide was applied after each feeding to maintain a target pH of 6.8 to 7.0

(Continues)

TABLE 2 (Continued)

	Feed			BFT maintenance			Other
Reference	Frequency (times per day)	Amount	Composition (%)	C:N ratio	Carbon source	†Method	Alkalinity correction
Pinheiro et al.[113]	4	-	CP: 35	The addition of organic carbon was not necessary since the BFT was already in a chemotrophic stage and a nitrification process was established.			Calcium hydroxide was added when the alkalinity was under 120 mg L^{-1}, at a rate of 20% of the daily feed intake
Pinheiro et al.[78]	4	11 to 3% of shrimp biomass	CP: 38	The addition of organic carbon was not necessary since the BFT was already in a chemotrophic stage and a nitrification process was established.			Calcium hydroxide was added when the alkalinity was under 120 mg L^{-1}, at a rate of 20% of the daily feed intake
Pinho et al.[117]	3	5% of fish biomass, 2 g feed day^{-1} $plant^{-1}$	CP: 22	15:1	Powder molasses	Based on daily input of N-feed, added once a day	-
Pinho et al.[48]	4	12% to 6% of fish biomass	CP: 36	20:1	Powder molasses	Based on daily input of N-feed, added once a day	-
Poli et al.[114] - *Shrimp*	4	11 to 2.7% of shrimp biomass	CP: 35	No organic carbon was used because the ammonia did not reach levels above 1 mg L^{-1}			Calcium hydroxide was added daily at a ratio of 25% of the total feed when the alkalinity was below 150 mg L^{-1}
- *Tilapia*	1	1% of fish biomass	CP: 38				
Rocha et al.[112]	3	3% of fish biomass	CP: 32 Cfib: 5.5 Ca: 0.5–2.5 P: 0.6 Fe:0.03	20:1	Molasses, wheat bran and rabbit diet	Water from an *ex situ* BFT was directed to each replicate twice over the experiment	-
Silva[125]	4	-	CP: 35	-			Calcium hydroxide was added when the alkalinity was under 120 mg L^{-1}, at a rate of 20% of the daily feed intake
Zidni et al.[179]	4	5	-	-	Molasses and flour	Water from an *ex situ* BFT was directed to each replicate once a day	-

– No information available.

†Method used for adding the carbon source.

‡Commercial hydroponic fertilizer was used. CP: Crude protein. Cfib: Crude fiber. Cfat: Crude lipid content. Ca: Calcium. P: Phosphor. Fe: Iron. C:N ratio: carbon and nitrogen ratio. BFT: biofloc technology. N-feed: Nitrogen content on animal feed.

nutrients in FLOCponics water as compared to hydroponic solutions have been found.[123] On the other hand, when compared to traditional aquaponics using RAS, higher concentrations of P, K, Ca, S and Fe were found and seem to be associated with the practice of external carbon addition.[48,124] Moreover, high concentrations of nutrients in the solid portion of the decanted bioflocs, which are not bioavailable for plants, was also reported.[121,122,134] Fimbres-Acedo et al.[134] suggested that these solids could be mineralized, enhancing nutrient availability. Studies have recently been carried out to mineralize RAS-sludge via bioreactors and successfully use its effluent as fertilizer in multi-loop aquaponics.[43] The use of mineralized solids/bioflocs biomass to nourish plants in FLOCponics has not yet been well reported.

Using plants as a filter to remove nutrients from BFT water is one of the approaches related to nutrient recycling that has been investigated in FLOCponics research. In these studies, the focus has been on N and P recovery and their transformation into plant biomass. Silva,[125] Pinheiro et al.[78,113] and Poli et al.[114] analysed the recovery of N and P from marine BFT effluent by halophyte plants. Their results showed that 24.1–39.3% of N and 14.8–19.4% of P from the total feed input can be removed as a result of the integration of shrimp and plant production. It is important to mention that both nutrients normally accumulate in BFT water.[70,113] At high concentrations, they can be toxic for the reared animal or, when discharged into natural water bodies, they can be potential causes of water eutrophication.[144]

4.4 | Productive results

Only the experiments that statistically analysed the plant and fish or shrimp growth and provided sufficient data to compare the productive performance were considered in the descriptions below. In general, the FLOCponics studies were conducted mainly by aquaculture researchers. Despite this, twenty-four trials were performed to evaluate plant production (Table 3) and twelve trials tested animal growth (Table 4) in FLOCponics systems.

4.4.1 | Plant production

The use of nutrient-rich effluents from BFT to nourish hydroponic plants is a key point in FLOCponics systems. However, the studies carried out so far have not reached a consensus as to whether FLOCponics has a positive or negative effect on plant yields. To achieve conclusive results on the effect of BFT effluent on plant production, plant growth in this system should be compared with crops in hydroponics, traditional aquaponics using RAS and/or soil-based agricultural methods. At the same time, standardizing the composition of nutrients inputted in all systems might also be done during this comparison. Some of the reviewed papers compared FLOCponics to hydroponics and/or traditional aquaponics, but none of them to soil-based methods. In the studies that compared FLOCponics with other systems, the amount and composition of nutrients offered to the hydroponics subsystem were not the same in all treatments/systems. Eight trials were conducted to evaluate a type of management in FLOCponics and did not compare it to other production systems. Table 3 gives an overview of the experimental design and general results related to plant growth in FLOCponics.

Most of the FLOCponics research evaluated the production of lettuce or salicornia (Table 3). Leafy vegetables such as lettuce have also been widely used in traditional aquaponics systems, mainly due to their low nutritional requirement and fast production cycle.[142,145] Among the trials that cultured lettuce and compared their growth in FLOCponics to other production systems, 19% found better results in FLOCponics, 13% in traditional aquaponics, 25% in hydroponics, and in 44% of the trials no differences between the systems were observed. For those that evaluated a specific factor in the FLOCponics systems, the results of Barbosa[146] and Rahman[121] should be highlighted. They evaluated lettuce production using BFT effluents either treated with filtering devices or not, and no differences in plant growth were found in either study. However, the authors emphasized the presence of solids/bioflocs on plant roots, mostly when filters were not used, and suggested that efficient mechanical filters should be developed to avoid this solids accumulation. In this same study, Rahman[121] also evaluated the effect on lettuce growth of adding fertilizer supplementation to the hydroponics subsystems of the FLOCponics treatments. The author reported that due to the extra fertilizer supplementation the lettuces grew similarly in the hydroponics and FLOCponics systems. Salicornia is a halophyte plant with high market value.[147] The studies that cultured this species did not compare FLOCponics to other production systems. Most of them focused on the benefits of integrating salicornia production and BFT. It is important to mention that findings reported by Doncato and Costa[124] were not considered in Table 3, since the authors did not provide sufficient numerical data. Despite this, their findings bring useful insights about the use of fertilizers in marine FLOCponics, by showing that plants grown with mineral fertilizers added to the water outperform those where mineral fertilizers were added directly to the leaves, or were not added at all.

With respect to other plant species, Fimbres-Acedo et al.[134] demonstrated that plant performance (lettuce, pak-choi, rocket, basil and spinach) can be affected by the BFT trophic level. Their results highlighted the importance of investigating how suitable the species are for a given production situation. Tomato and cucumber were also reported in FLOCponics studies (Table 3). For tomato, Pickens et al.[123] compared its growth in FLOCponics to hydroponics and also before and after fish harvest, that is, in one treatment fish and tomatoes were harvested at the same time (117 days) and in the other tomato cultivation continued for another 40 days after harvesting the fish, and consequently with no more feed intake. The authors showed that, after harvesting the fish, the nutrients in the water were not sufficient to nourish the tomatoes remaining in the FLOCponics system, resulting in lower tomato yield compared to the hydroponics system. For cucumber, Blanchard et al.[122] showed that the leaf elemental composition was within the recommended ranges

TABLE 3 Overview of the experimental designs and results of plants growth in FLOCponics research

Reference	Trial	Species	Period (days)	Density (plant m^{-2})	†Treatments	Yield (kg m^{-2})	General results
Barbosa[146]	1	Smooth lettuce (*Lactuca sativa L.*)	14	16	FLOCponics system with filters (mechanical and biological) vs FLOCponics system without filters	0.87 – 0.90	No statistical difference was found between the treatments for lettuce growth.
	2	Crispy lettuce (*Lactuca sativa L.*)	14	16		0.27 – 0.28	Higher amount of biofilm in the roots of plants grown in FLOCponics without filters was found.
Lenz et al.[140]	1	Smooth lettuce (*Lactuca sativa L.*) Crispy lettuce (*Lactuca sativa L.*) Red lettuce (*Lactuca sativa L.*)	28	20	Two factors: Water salinity (0 and 3 ppt) vs lettuce variety	0.53 – 1.13 0.78 – 1.29 1.06 – 1.21	No statistical interaction between plant and salinity factors was found. Greater lettuce growth was seen at salinity 0. Red lettuce was the one that best adapted to culture in brackish water.
Pinho et al.[117]	1	Butter lettuce (*Lactuca sativa L.*) Crispy lettuce (*Lactuca sativa L.*) Red lettuce (*Lactuca sativa L.*)	21	20	Traditional aquaponics vs FLOCponics systems	1.5 – 1.9 1.0 – 1.4 0.3 – 0.6	Higher plant growth was found in the FLOCponics system for all varieties. Butter lettuce presented the highest growth values, followed by the crispy and the red lettuce varieties.
Pinho et al.[48]	1	Butter lettuce (*Lactuca sativa L.*)	23	20	Two factors: Technology (traditional aquaponics and FLOCponics) vs plant cycle	2.6 – 2.96	There was a statistical interaction between the technology employed and the production cycle in all parameters of plant growth. Similar plant growth was found in the first cycle between both technologies, while higher plant growth was seen in traditional aquaponics in the second cycle.
	2	Butter lettuce (*Lactuca sativa L.*)	23	20		1.8 – 2.62	
Rahman[121]	1	Lettuce (*Lactuca sativa L.*)	28	25	FLOCponics using unsettled effluent vs FLOCponics using settled effluent vs hydroponics systems	1.71 – 3.48	No statistical difference was found between lettuce produced in FLOCponics with and without solids removal, while a difference was seen between them and the hydroponics systems.
	2	Lettuce (*Lactuca sativa L.*)	28	25		0.19 – 3.85	Same results as trial 1 were found.
	3[f]	Lettuce (*Lactuca sativa L.*)	28	25		3.60 – 3.80	The growth and quality of lettuce produced in FLOCponics with and without solids removal and hydroponics were similar.
	4[f]	Lettuce (*Lactuca sativa L.*)	28	25		3.90 – 4.00	Same results as trial 3 were found.

(Continues)

TABLE 3 (Continued)

Reference	Trial	Species	Period (days)	Density (plant m^{-2})	†Treatments	Yield (kg m^{-2})	General results
Rocha et al.[112]	1	Lettuce (*Lactuca sativa L.*)	46	20	Traditional aquaponics vs FLOCponics vs hydroponics systems	0.21 – 1.53	Lettuce growth was lower in the hydroponics systems, and similar in the traditional aquaponics and FLOCponics systems
Fimbres-Acedo et al.[134]	1	Lettuce *(Lactuca sativa)*	35	75	Different biofloc trophic levels (chemo, hetero and photoautotrophic) in FLOCponics systems vs hydroponics systems	4.07 – 27.35	Wet weight of lettuce leaves produced in hydroponics was higher than in all treatments using FLOCponics.
	2	Pak-choi *(Brassica rapa subsp. Chinensis)*	35	75		23.18 – 36.90	Pak-choi cultured in chemotrophic FLOCponics presented lower wet weight than in all other treatments.
	3	Rocket *(Eruca sativa)*	35	75		1.06 – 9.90	Higher wet weight was found in chemotrophic FLOCponics.
	4	Basil *(Ocimum basilicum)*	35	75		6.82 – 12.16	No statistical difference was found between the treatments.
	5	Spinach *(Spinacia oleracea)*	35	75		0.91 – 4.39	Higher wet weight was found in chemotrophic FLOCponics.
Blanchard et al.[122]	1	Cucumber *(Cucumis sativus L.)*	60	13	Four pH levels (7.0, 6.5, 5.8, vs 5.0) during USA spring	8.43 – 8.66 ‡	The growth rate of the cucumber was different between the treatments, with higher values at pH 7. No statistical difference was found for yields.
	2	Cucumber *(Cucumis sativus L.')*	60	13	Four pH levels (7.0, 6.5, 5.8, vs 5.0) during USA summer	9.50 – 9.70 ‡	No statistical difference was found between the treatments.
Pickens et al.[123]	1	Cherry tomato cvs. "Favorita" *(Solanum lycopersicum var. cerasiforme)*	149–157	3.2	Two factors: nutrient source (FLOCponics and hydroponics system) vs harvest time (before and after fish harvest)	5.5 –11.4 ‡	Statistical difference in tomato yield was found only after fish harvest, when the results in the hydroponics systems were higher.
	2	Cherry tomato cvs. "Goldita" *(Solanum lycopersicum var. cerasiforme)*	149–157	3.2	Two factors: nutrient source (FLOCponics and hydroponics system) vs harvest time (before and after fish harvest)	4.3 – 10.5‡	Statistical difference in tomato yield was found for both harvest times, when the results in the hydroponic system were greater.
Martinez-Cordova et al.[148]	1	Jalapeño pepper (*Capsicum annum*)	48	2.5	Traditional aquaponics vs FLOCponics systems	4.0 – 4.25‡	No statistical difference was found between the treatments for jalapeño pepper growth.

(Continues)

TABLE 3 (Continued)

Reference	Trial	Species	Period (days)	Density (plant m^{-2})	†Treatments	Yield (kg m^{-2})	General results
Neto[126]	1	*Sarcocornia ambigua*	83	100	Two proportions of feed per m^{-2} of plant: 50 vs 100 g feed per m^{-2}	0.9 – 1.14	Statistical difference was found for final biomass with better results in the treatment with 50 g feed per m^{-2}. No difference was found for final yield.
Pinheiro et al.[78]	1	*Sarcocornia ambigua*	57	40	Four water salinities: 8, 16, 24 vs 32 ppt	0.38 – 0.61	No statistical difference was found between the treatments.
Silva[125]	1	*Sarcocornia ambigua*	70	100	Four different periods of water pumping in the hydroponic beds over a day: 6, 12, 18 vs 24 h	1.1 – 1.9	No statistical difference was found between the treatments for lettuce growth.

†When FLOCponics is not mentioned in the treatments column, it indicates that this was the only system used.
‡Yield was calculated as a sum of marketable fruit. ƒ Extra fertilizer was added into the hydroponics subsystems in the FLOCponics systems.

even though the nutrient concentrations in the BFT effluent would be considered low. The production of aromatic herbs and pepper was also investigated in a FLOCponics system, but only preliminary results have been published so far.[135,148]

In addition to the yields presented in Table 3, special attention should also be paid to crop quality due to its key role in market competitiveness and consumer perception.[89] Additional analysis such as visual characteristics, composition of nutrients, and indicators of stress were carried out in FLOCponics studies and demonstrated promising results. Pinheiro et al.[78,113] and Silva[125] evaluated the total phenolic compounds and antioxidant activity of *Sarcocornia ambigua* and, according to their results, FLOCponics culture conditions did not induce high plant stress. For the visual characteristics of the plants, some investigations showed positive effects of BFT or no visual symptoms of nutrient deficiencies,[117,123] while others found the opposite.[48,140,146] Visual symptoms of nutrient deficiencies are usually identified by irregular leaf development, discoloured leaves or burned leaves.

In general, the undesirable visual characteristics or poor plant growth sometimes found in FLOCponics research have been related to: (i) the presence of solids/bioflocs on plant roots; (ii) high water pH (>7), affecting the bioavailability of nutrients in the form absorbable by plants; (iii) nutrient imbalance; (iv) the consumption of available nutrients in water by the BFT microorganisms, even though there is a lack of precise information regarding their role on nutrient recycling/removal; and (v) lack of waste management and nutrient optimization through solids/bioflocs reuse or remineralization.[48,112,123,134,140] All of these constraints relating to FLOCponics must be addressed and taken into account in further research. Some alternative solutions for these problems are discussed in *section 6.2*.

4.4.2 | Animal production

The main zootechnical parameters evaluated in FLOCponics experiments, as well as the species, duration and densities used, are presented in Table 4. Most studies were conducted with Nile tilapia (*O. niloticus*) or Pacific white shrimp (*L. vannamei*), except in those of Castro-Castellón et al.[136] and Rocha et al.[112] who cultured *Melanochrimis sp* and South American catfish (*Rhamdia quelen*), respectively. Tilapia and Pacific white shrimp are the most popular species in biofloc-based cultures.[27] This is mainly because both species show tolerance to less than ideal environmental conditions, such as a high concentration of suspended solids and nitrogenous compounds in water, and due to morphological adaptations, which allow them to take advantage of bioflocs as a complementary food.[31,49] Tilapia in the nursery phase with initial weight varying between 0.3 and 4.1 g was the most used.[114,133] Only Fimbres-Acedo et al.[133] reared fish in growth-out phase, harvesting tilapia between 445 and 520 g. However, in shrimp culture, the growth-out phase was carried out, where shrimps with an initial weight of 1.4 g were produced until they reached approximately 12 g.

TABLE 4 Overview of the zootechnical results found in FLOCponics research.

Reference	Species	Period (days)	Density (animal m^{-3})	Initial weight (g)	Final weight (g)	SGR (% g day^{-1})	FCR	Yield (kg m^{-3})	Survival (%)
Fish culture									
Castro-Castellón et al.[136]	*Melanochrimis sp*	120	800	0.8	7.6 – 8.0	1.8 – 1.9	-	5.9 – 6.3	98 – 100
Lenz et al.[140]	*Oreochromis niloticus*	28	90	67.5	94.8 – 98.3	1.2 – 1.3	2.0 – 2.2	8.3 – 8.7	97.8
Pinho et al.[48†]	*Oreochromis niloticus*	46	300	1.1	34.9 – 36.7	7.4 – 7.6	0.8 – 0.9	7.8 – 8.0	96.5 – 98.8
Fimbres-Acedo et al.[133†]	*Oreochromis niloticus*	140	180	0.3	33.8 – 54.2	3.3 – 3.6	1.3 – 1.4	4.8 – 9.1	96.6 – 100
	Oreochromis niloticus	133	55	60.0	445.4 – 520.2	1.5 – 1.6	1.5 – 1.7	21.4 – 23.3	95.0 – 100
Martinez-Cordova et al.[148†]	*Oreochromis niloticus*	56	75	2.1	89.7 – 120.3	6.7 – 7.2	1.1 – 1.4	5.4 – 7.4	80.4 – 82.6
Martínez-Meingüer et al.[137†]	*Oreochromis niloticus*	140	156	-	257.2 – 333.6	1.8 – 2.3	-	-	-
Rocha et al.[112]	*Rhamdia quelen*	46	83	19.5	31.1	1.0	1.1 – 1.3	2.9	100.0
Fish and shrimp culture									
Poli et al.[114‡]	*Oreochromis niloticus*	57	444	4.1	11.4 – 11.5	1.8	0.16	5.1	87.5 – 91.3
	Litopenaeus vannamei	57	312	1.2	14.1 – 14.6	4.3 – 4.4	1.7	4.4 – 4.6	88.0 – 89.3
Shrimp culture									
Neto[126]	*Litopenaeus vannamei*	83	250	1.4	12.9 – 13.3	2.7	1.7	2.8	85.7 – 87.1
Pinheiro et al.[113]	*Litopenaeus vannamei*	73	250	1.4	11.6 – 11.7	2.9	1.7	2.1	72.5 – 74.5
Pinheiro et al.[78]	*Litopenaeus vannamei*	57	300	1.6	11.5 – 12.7	3.4 – 3.6	1.6 – 2.0	2.3 – 3.0	56.3 – 84.0
Silva[125]	*Litopenaeus vannamei*	73	250	2.4	10.9 – 11.2	2.1	1.7	2.4	85.2 – 87.3

†Statistical differences were found.

‡Polyculture focused on shrimp production. Tilapia were fed only once a day with 1% of fish biomass, stimulating tilapia to seek natural food in the bioflocs. SGR: specific growth rate. FCR: feed conversion ratio.

The investigations on the growth performance of aquatic organisms in FLOCponics have evaluated diverse variables (Appendix I). The treatments have tested, for instance: (i) different input of nutrients by varying the carbon source[136] or the trophic levels of the BFT[133]; (ii) different water salinities[78,140]; (iii) the influence of the integration of BFT with hydroponics[113,114]; (iv) the effect of specific management for plant production on shrimp performance[125,126]; and (v) the effect of traditional aquaponics using RAS compared to FLOCponics systems on fish and plant growth.[48,112] Within these studies (Table 3), only Fimbres-Acedo et al.,[133] Martínez-Meinguër et al.,[137] Martinez-Cordova et al.[148] and Pinho et al.[48] found statistical differences in animal growth between the treatments. Fimbres-Acedo et al.[133] observed a positive effect of algae-based photoautotrophic treatment over chemotrophic and heterotrophic treatments in both nursery and growth-out phases. Martínez-Meinguër et al.[137] observed that tilapia fed with 35% crude protein and no fertilizer supplementation outperformed those using higher dietary protein (47.5% crude protein) and fertilizer supplementation in FLOCponics system. Martinez-Cordova et al.[148] showed benefits for tilapia yield and feed conversion ratio when received bioflocs from an *ex situ* BFT. Pinho et al.[48] compared the production of tilapia juveniles in traditional aquaponics and FLOCponics systems and found higher final weight, higher specific growth rate and lower feed conversion ratio in FLOCponics. Interestingly, the authors pointed out that the mean volume of bioflocs in the fish tank was lower than the recommended for BFT culture and potentially impacted the fish performance, which could have been even better if the *in situ* natural food availability was higher. The same trend of a low volume of bioflocs and its impact on fish growth was observed by Rocha et al.,[112] also running coupled systems. However, in contrast to Pinho et al.,[48] the authors did not find statistical differences between aquaponics and FLOCponics for *Rhamdia quelen* production. Both investigations suggested that improvements in system design could optimize BFT and hydroponics integration.

In terms of yields, the current studies revealed that the system's carrying capacity needs to be optimized in FLOCponics. For example, for tilapia, the 23 kg m^{-3} reported by Fimbres-Acedo et al.[133] is far below the 70 kg m^{-3} able to be produced in the growth-out phase in commercial aquaponics with RAS[142] or the maximum of 50 kg m^{-3} in BFT.[76] Meanwhile, in the nursery phase, the values between 7.8 to 8.7 kg m^{-3} achieved[48,140] are within the expected range in BFT systems, that is, between 8 and 10 kg m^{-3}.[76] For shrimp culture, the recommended initial densities for the growth-out phase are 270 to 530 juveniles per m^{-3} to achieve marketable shrimp (>18 g) and yields of 5 to 9 kg m^{-3}. The experiments with shrimp in FLOCponics used similar stocking densities; however, the yields obtained were lower, ranging from 2.1 to 2.8 kg m^{-3}.[113,126] As mentioned above and in the previous sections, when a hydroponics system is connected to BFT tanks the solids/bioflocs in the system are affected. Reducing the volume of bioflocs makes scarce the *in situ* natural food and might change the microbial activity, which is probably the reason for the reported lower yields in FLOCponics compared to biofloc-based monoculture. The current results suggest that improvement of carrying capacity and system design could solve both yield performance and solids management, boosting FLOCponics outcomes, and making them more comparable to commercial aquaponics with RAS.

5 | SUSTAINABILITY ASPECTS

New technologies have recently been developed to lead aquaculture to more sustainable practices. Being sustainable means that aquaculture systems must be technically viable and economically profitable, aiming to supply human needs with respect to safe and healthy food for present and future generations.[7,149,150] Economic assessments of medium and long-term aquaculture projects can provide data for the implementation of management strategies that will contribute to the resilience and longevity of the business.[151] In addition to biological, technical, and economic aspects, understanding the social and environmental impacts of a new production system from a systemic point of view through sustainability assessments is important to provide a basis for the development of appropriate public policies fostering a sustainable growth of the activity.[19,150,152,153]

Sustainability assessment methodologies such as the ecological footprint,[154-156] emergy synthesis,[19,153,157-159] life cycle analysis (LCA)[160-164] and indicators of sustainability[150] have been used to measure the sustainability of aquaculture. For aquaponics production, studies using LCA have shown that the main environmental impacts of aquaponics are related to infrastructure, electricity and feed.[98,99,165] Low water use and the possibility to be adopted as a tool to promote educational, cultural, leisure and tourism values, and landscape improvement are positive aspects usually linked to aquaponics systems.[39,105] For biofloc-based production, Belettini et al.[166] evaluated the carbon footprint of commercial shrimp production using LCA and showed that electricity is also a key impacting factor in BFT, while feed has a minor impact. Sustainability assessments of FLOCponics systems were not found in the literature. The lack of these analyses is probably due to their need for a large and detailed database, which is not yet available for FLOCponics systems.

Even though no results from a sustainability assessment are available, FLOCponics has been presented as an example of a new technology with the potential to minimize some unsustainable characteristics of conventional aquaculture.[76] By replacing the RAS by BFT in a food production system already known to be eco-friendly, some positive aspects of biofloc-based systems and traditional aquaponics can be maximized and some of their limitations reduced. Moreover, the possibility of producing a mix of food products in a small urban area and close to the consumer, causing low environmental impact and generating social benefits, are the main sustainable advantages of the FLOCponics systems. In addition, the fact that these foods are healthy, free of pesticides, and offered to the consumer in a wide variety (fish and vegetables), makes FLOCponics a highly relevant system on the food production field. The main technical-economic, social and environmental characteristics that may justify the recognition of FLOCponics as a sustainable system are summarized in Table 5.

TABLE 5 Main potential technical-economic, social and environmental characteristics of FLOCponics

Characteristic	Technical-economic	Social	Environmental
Positive			
Low water use	X		X
Diversification of production	X		
Efficient use of feed	X		X
Constant nutrient recycling	X		X
Low or zero effluent disposal	X		X
Educational and leisure tool		X	
Promotion of the local economy	X	X	
Prevents species escape	X		
No use of pesticides	X	X	X
Reduced land use	X	X	X
Use of non-productive areas	X		X
Proximity to the consumer	X	X	X
Diluted cost per biomass produced	X		
Low investment in filters	X		X
Improved animal nutrition and health	X	X	
Negative			
Need for skilled labour	X	X	
High cost of equipment	X		
High dependence on electricity	X		X
Low generation of direct jobs	X	X	
Low widespread technology	X		
Intensive control of water parameters	X		
Unpredictability of available nutrients	X		

Table 5 reveals that most of the characteristics of FLOCponics are related to the technical-economic category. At this moment, the main focus of FLOCponics research has been on technical aspects and only one study evaluated the economic feasibility of this system. Castilho-Barros et al.[167] simulated a theoretical commercial-scale FLOCponics system with shrimp (*Litopenaeus vannamei)* integrated with halophyte *S. ambigua* and calculated its profitability. According to these authors, the high market value of these species made the system economically viable, even in pessimistic business plans. They also identified that FLOCponics requires high implementation costs, expensive operating equipment, and highly skilled labour. It is hasty to draw conclusions about the profitability of FLOCponics based only on hypothetical results with specific scenarios, products and markets. However, the three items with the highest costs identified by these authors seem to compose a pattern as they are also the main weaknesses identified for traditional aquaponics,[96,107] biofloc-based monocultures[7,31] and FLOCponics (Table 5). It should be noted that, if the productive potential of FLOCponics is proved, all these costs may be diluted by the highest biomass produced and then this economic issue can be tackled. For example, the electricity cost per kg of food produced in FLOCponics systems will certainly be lower than in biofloc-based monoculture. In addition, the adoption of renewable energy sources such as wind, solar and biogas produced through biodigesters, and the use of infrastructures and equipment with a long useful life would be viable alternatives to further improve the sustainable characteristics of the FLOCponics systems.

Food production systems will always somehow impact the environment, thus those that achieve high yield with minimal negative impact should be encouraged.[159] Determining the trade-off between the benefits and costs of FLOCponics and evaluating the sustainability of real systems are still needed. For these purposes, a larger technical and economic database of FLOCponics must be produced and then analysed through sustainability assessments.

6 | CHALLENGES OF FLOCponics SYSTEMS

FLOCponics is a complex and multidisciplinary food production system, which requires in-depth knowledge in diverse areas such as microbiology, limnology, ecology, aquaculture, engineering, agronomy and hydroponics. Given this complexity, and due to the fact that only a few investigations have been conducted so far, information gaps on FLOCponics need to be addressed by new research. At this initial stage of scientific research, identifying and discussing the challenges and pointing out the opportunities of FLOCponics may guide future studies and then lead to the efficient development of this system. Currently, the challenges of FLOCponics are technical issues, which affect its sustainable and economic aspects. The same trend occurred in BFT, but nowadays it has been fully developed and commercially applied. The main identified challenges and opportunities of FLOCponics are outlined and described below.

6.1 | System setup

The crucial points that need to be adjusted in FLOCponics are the design and engineering of the systems. The layout of FLOCponics systems must be designed to provide the best conditions possible for the production of aquatic animals and plants and the maintenance of BFT microorganisms. The main issue identified is related to keeping suspended solids in the water at suitable concentrations for plant and fish production. As stated in the sections above, plant growth seems to be limited by the excess of solids in FLOCponics systems. Trying to avoid solids in the hydroponics subsystem has resulted in a decrease in the amount of *in situ* food/bioflocs for the animals. Alternatives to solve this problem are the development of mechanical filters that efficiently separate the solids and the liquid fraction of the BFT effluent, and then return the bioflocs to the aquaculture subsystem and direct the water and nutrients to the hydroponics subsystem. Examples of filters that need to be investigated in FLOCponics are bag-filters with backwash technology, drum filters, or even sedimentation tanks with well-planned biofloc return flow. Additionally, the frequency of their use and the water flow into these filters should be set. It is necessary to highlight that all these filters can be used in coupled FLOCponics systems as well. However, as in all coupled systems there will always be trade-off between plant and animal requirements,[43,92] so the employment of a decoupled layout is highly recommended.

Another challenge of FLOCponics systems that needs to be addressed is the high variation of the setups used. For instance, the wide range of water flow rates and volumes of the subsystems (Table 1) indicate that the water velocity and dilution of nutrients available for the plants are totally different among the investigated FLOCponics systems. It could generally be said that the BFT tank can have any dimension, while the hydroponics and filters subsystem should be carefully designed according to the amount of nutrients and solids that will come from the BFT tank. Because of the lack of standardization in the system setups, it is hard to compare the results found and reach concrete conclusions about the efficiency of FLOCponics in producing food.

Based on the findings pointed out in this paper, further studies should focus on: (i) improving the mechanical filters; (ii) defining the ideal proportion of the subsystem volumes based on the nutritional needs of the targeted plant species; (iii) setting the water flow rate in order to promote greater nutrient uptake and recycling, by adjusting it to the hydroponics subsystem; (iv) assessing the differences between the coupled and decoupled layout with reference to the productive capacity of FLOCponics; and (v) understanding whether the type of hydroponic bed, that is, NFT and DWC, affects plant growth in FLOCponics. All of these investigations must be conducted to develop systems with the potential to be applied commercially. The economic viability of the proposed solutions should also always be considered.

6.2 | Plant nutrition, health and production

The success of soilless plant production is directly dependent on the optimal quantity and quality of the nutrients being available in the water. The physical–chemical parameters of the water and the quantity of each macro- and micro-nutrient must be in accordance with the requirement of each plant species. In addition to nutrients, other variables also influence plant growth, for example, environmental parameters such as irradiance, photoperiod, temperature, and humidity.[89,91] Meeting plant needs is generally a challenge in coupled aquaponics using RAS[89] and seems also to be the case in FLOCponics. The critical points related to plant growth identified in the FLOCponics research were outlined in the *section 4.3.1*. All of them somehow affect the uptake of nutrients by plants and can reduce plant quality.

The improvement of the engineering aspects of FLOCponics systems should minimize or even solve some of these problems, which are mainly related to solids control. Furthermore, the use of decoupled layouts will certainly enable pH regulation at ideal levels for each subsystem and the addition of specific minerals directly into the hydroponics subsystem. In contrast to commercial hydroponics which utilize fully formulated fertilizers, in FLOCponics the production costs might be reduced as only specific nutrients would be required due to a wide range of nutrients already available in BFT effluent. For this purpose, detailed information on the quantity of nutrients in the feed and carbon source are required. Additionally, it is highly recommended to deepen the studies on the profile of micro-nutrients present in the process water of the BFT system, given their effect on plant biological processes such as photosynthesis.[91] Comparing the differences in the quality and diversity of the micro-nutrients in the FLOCponics systems and those used in balanced hydroponic fertilizer will clarify whether there is deficiency of specific nutrients. This may enable the design of specific supplementation protocols for each plant species, and, thus, achieve high productivity and quality of vegetables.

Recovering and transforming nutrients from solid biofloc fractions into bioavailable forms through a mineralization process may change future perspectives about the need for extra fertilization in FLOCponics.[122,134] Since a minimum concentration of bioflocs should be kept in the aquaculture subsystem to promote animal growth, the amount and frequency of solids/biofloc removal that will be directed to the remineralization unit, as well as which process will be used, need to be precisely defined. Defining an efficient biofloc remineralization process might be a win-win situation for fish/shrimp production and water treatment research fields. This is mainly because high animal growth performance is reached by constantly removing excess bioflocs/solids,[131,132] and the harvested bioflocs may be relatively carbon-rich, and consequently a desirable substrate for anaerobic bioreactors.

For those that wish to run a coupled FLOCponics system, the tolerance intervals of water quality and overall nutrients concentration for the cultured animals, biofloc microorganisms, and vegetables must be investigated. A key variable in coupled layouts that needs attention is the pH.[44,89] While BFT microorganisms work properly at neutral pH,[28] the plants commonly cultured in hydroponics system (e.g. lettuce, basil, tomato and cucumber) grow better at pH ranging between 5.5 and 6.5.[40,89,141] The effect of neutral pH on plant growth was poorly evaluated and discussed by the studies that ran coupled systems. Finding alternative plant species that required neutral-alkaline pH conditions may be a way to minimize pH issues and run a coupled FLOCponics system successfully. From this perspective, examples of crops that could be investigated in further research are swiss chard, broccoli, head cabbage, and mint.[168]

The influence of nutrient uptake by BFT microorganisms on the availability of nutrients for plant production is yet unclear. At this moment, the results have indicated that running a mixotrophic or chemoautotrophic BFT would be the best option for FLOCponics systems[134,140] due to the expected predominance of nitrifying communities (higher concentration of nitrate in water) instead of a heterotrophic-based medium. Another approach related to BFT microorganisms that must be clarified is whether a thin flocs biofilm on plant roots has the potential to boost or harm the nutrient uptake by the plants. The effect of BFT microorganisms on FLOCponics production clearly needs further investigation.

6.3 | Animal nutrition and production

The main issue for animal production in FLOCponics is to maintain an optimum amount of *in situ* food/bioflocs in the aquaculture tanks. Once the aforementioned improvements in the system design are implemented, the full nutritional advantages of flocs would be achieved. Some of the reported nutritional advantages of using BFT instead of RAS are: (i) reduced feed conversion ratio[74,169,170]; (ii) replacement of fish meal by alternative protein sources[171-173]; and (iii) a reduction of dietary protein content.[60,75,174,175] Studies aiming to assess the applicability of these nutritional strategies should be carried out, since they may reduce feed costs and the environmental footprint of FLOCponics. Moreover, these studies should be run in intensive densities to achieve higher yields.

Only a few animal species have suitable characteristics to be intensively produced in BFT and consequently in FLOCponics systems. Although several studies have shown the viability of other species,[31] biofloc technology is commonly applied to Nile tilapia and Pacific white shrimp culture. Both species are widely reared and contribute to the food supply worldwide. On the one hand, the scarce production of other species with high market value is a limitation of FLOCponics, on the other hand, it is always good to produce well-known products when new technologies are being developed.

6.4 | Practical applicability of FLOCponics

To date, FLOCponics research has been mainly led by aquaculture researchers who normally seek to find solutions to problems directly related to biofloc-based monocultures, that is, the accumulation of nutrients in water and high production costs. The authors have justified using FLOCponics as a way to reuse these nutrients, increase farm profitability by growing other products with market value, and dilute the costs with inputs, electricity and labour. Thus, at first glance, FLOCponics seems to be more applicable for farmers who already apply BFT. A practical example of this is the fact that some commercial BFT farmers have been testing and applying the principles of FLOCponics. Unfortunately, the results held by the private sector are often not shared with the general public.

FLOCponics will probably be an alternative option for the traditional aquaponists or the investor who wants to start an integrated agri-aquaculture farm only when the technical barriers are solved. For instance, a broad range of knowledge is still required to understand the best way to run a FLOCponics system and to maximize its results. Moreover, the choice of the food production system that will be used must take into account several factors, such as market demand, climate, producer experience, technical knowledge, the cost and availability of inputs, among others. Even if the expected positive potential of FLOCponics is proved, a systemic analysis of the whole production scenario should be done aiming to provide guidance as to which system will be most suitable for a given situation.

Most of traditional aquaponics systems are operated at a small-scale run for personal hobby or family subsistence.[110] FLOCponics tends to be the opposite of this. To support the complexity of BFT, a basic infrastructure and a significant investment are likely suited to only medium and large commercial-scale scenarios. Based on that, it is reasonable to state that FLOCponics will rarely be employed as a backyard system. This highlights the necessity to improve and standardize system designs for real production situations. Moreover, technological management supported by studies of modelling and forecasting inputs and outcomes will play an important role in developing FLOCponics, especially in medium to larger scaled farms. Modelling FLOCponics systems is a subject to be investigated; then, it was not explored in this paper.

Finally, it should be mentioned that as FLOCponics is a novel and emergent system, some papers were published after the settled literature search period for this review[176-178] and many others are expected to be published in the next few years. It is, however, noteworthy that our group has been advancing research in this field and recently published the results of a study in which decoupled layout allowed reduction of critical issues related to FLOCponics systems, leading to similar lettuce growth and an 8% reduction in the Nile tilapia dietary crude protein compared to decoupled aquaponics using RAS.[177]

7 | FINAL REMARKS

This review has identified that FLOCponics research is still in its initial stage, which is shown by the small number of papers published so far and the lack of standardization in experimental designs and system setups. At this stage, there are still some inconsistencies regarding the results of animal and plant yields in the FLOCponics systems. For example, 38% of the studies showed worse plant growth in FLOCponics compared to hydroponics or traditional aquaponics. The other 62% highlighted that improvements in the system design are necessary to achieve better plant yields, even though they reported higher or similar results in FLOCponics. An important contribution of this paper was examining the main challenges of FLOCponics systems and suggesting future research to tackle them (*sections 4* to *6*). Among the points discussed, the effective control of solids in order to guarantee a suitable concentration for the hydroponics and aquaculture subsystems was highlighted as the main challenge. For this purpose, it is highly relevant that further investigations determine the ideal management and design of the filtering systems, and the feasibility of decoupled FLOCponics systems.

In terms of applicability, the FLOCponics system is likely to be applied in the short-term by farmers who already operate BFT, adapting their structures to receive the hydroponics subsystem. For BFT production, FLOCponics seems to primarily increase the sustainable character of biofloc-based monocultures by recovering nutrients and expanding product diversity, rather than promoting higher animal growth performance. The integration of BFT with plant production fits with the circular economy concept and might contribute to social licenses and farm diversity. The further commercial application of FLOCponics requires research that provides a solid database, originating from experimental setups with characteristics similar to those of commercial production. In future research, assessing the economic, social-educational and environmental impacts of FLOCponics in an urban setting should be considered, making easier the delivery of products from producer to consumers, with a minimum of middlemen. Lastly, it is expected that the data presented and discussed in this paper will provide guidance and technical support for further FLOCponics development, boosting both research and commercial application, and thus contributing to sustainable aquaculture and plant production.

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DATA AVAILABILITY STATEMENT

NA

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REFERENCES

1. UN. World Population. Prospects. 2019.; 2019.;.https://population.un.org/wpp/
2. Conijn JGG, Bindraban PSS, Schröder JJJ, Jongschaap REE. Can our global food system meet food demand within planetary boundaries? *Agric Ecosyst Environ*. 2018;251:244-256. https://doi.org/10.1016/j.agee.2017.06.001
3. FAO. The Future of Food and Agriculture.; 2018.Food and Agriculture Organization of The United Nations (FAO)
4. Byerlee D, Fanzo J. The SDG of zero hunger 75 years on: Turning full circle on agriculture and nutrition. *Glob Food Sec*. 2019;21:52-59. https://doi.org/10.1016/j.gfs.2019.06.002
5. Pretty J, Sutherland WJ, Ashby J, et al. The top 100 questions of importance to the future of global agriculture. *Int J Agric Sustain*. 2010;8(4):219-236. https://doi.org/10.3763/ijas.2010.0534
6. Ickowitz A, Powell B, Rowland D, Jones A, Sunderland T. Agricultural intensification, dietary diversity, and markets in the global food security narrative. *Glob Food Sec*. 2019;20:9-16. https://doi.org/10.1016/j.gfs.2018.11.002
7. Boyd CE, Abramo LRD, Glencross BD, et al. Achieving sustainable aquaculture: Historical and current perspectives and future needs and challenges. *J World Aquac Soc*. 2020;51(3):578-633. https://doi.org/10.1111/jwas.12714
8. Thilsted SH, Thorne-Lyman A, Webb P, et al. Sustaining healthy diets: The role of capture fisheries and aquaculture for improving nutrition in the post-2015 era. *Food Policy*. 2016;61:126-131. https://doi.org/10.1016/j.foodpol.2016.02.005
9. FAO. The State of World Fisheries and Aquaculture 2020. Food and Agriculture Organization of The United Nations (FAO); 2020. https://doi.org/10.4060/ca9229en
10. Tidwell JH. Characterization and Categories of Aquaculture Production Systems. In: Tidwell J, ed. *Aquaculture Production Systems*. Wiley-Blackwell; 2012:64-78. https://doi.org/10.1002/9781118250105.ch4
11. Masser MP. Cage Culture in Freshwater and Protected Marine Areas. In: Tidwell JH, ed. *Aquaculture Production Systems*. Wiley-Blackwell; 2012:119-134. https://doi.org/10.1002/9781118250105.ch6
12. Tucker C, Hargreaves J. Ponds, In: Tidwell JH, eds. *Aquaculture Production Systems*. Wiley-Blackwell; 2012:191-244. https://doi.org/10.1002/9781118250105.ch10
13. Boyd CE. Guidelines for aquaculture effluent management at the farm-level. *Aquaculture*. 2003;226(1–4):101-112. https://doi.org/10.1016/S0044-8486(03)00471-X
14. Turcios A, Papenbrock J. Sustainable treatment of aquaculture effluents—What can we learn from the Past for the future? *Sustainability*. 2014;6(2):836-856. https://doi.org/10.3390/su6020836
15. Henares MNP, Medeiros MV, Camargo AFM. Overview of strategies that contribute to the environmental sustainability of pond aquaculture: rearing systems, residue treatment, and

environmental assessment tools. *Rev Aquac*. 2020;12(1):453-470. https://doi.org/10.1111/raq.12327
16. Joyce A, Goddek S, Kotzen B, Aquaponics WS. Closing the Cycle on Limited Water, Land and Nutrient Resources. In: Goddek S, Joyce A, Kotzen B, Burnell G, eds. *Aquaponics Food Production Systems*. Springer International Publishing; 2019:19-34. https://doi.org/10.1007/978-3-030-15943-6_2
17. Boyd CE, Gross A. Water use and conservation for inland aquaculture ponds. *Fish Manag Ecol*. 2000;7(1–2):55-63. https://doi.org/10.1046/j.1365-2400.2000.00181.x
18. Lulijwa R, Rupia EJ, Alfaro AC. Antibiotic use in aquaculture, policies and regulation, health and environmental risks: a review of the top 15 major producers. *Rev Aquac*. 2020;12(2):640-663. https://doi.org/10.1111/raq.12344
19. David LHC, Pinho SM, Garcia F. Improving the sustainability of tilapia cage farming in Brazil: An emergy approach. *J Clean Prod*. 2018;201:1012-1018. https://doi.org/10.1016/j.jclepro.2018.08.124
20. Ahmed N, Thompson S, Glaser M. Global aquaculture productivity, environmental sustainability, and climate change adaptability. *Environ Manage*. 2019;63(2):159-172. https://doi.org/10.1007/s00267-018-1117-3
21. Ahmed N, Thompson S. The blue dimensions of aquaculture: A global synthesis. *Sci Total Environ*. 2019;652:851-861. https://doi.org/10.1016/j.scitotenv.2018.10.163
22. van Rijn J. Waste treatment in recirculating aquaculture systems. *Aquac Eng*. 2013;53:49-56. https://doi.org/10.1016/j.aquaeng.2012.11.010
23. Ebeling JM, Timmons MB. Recirculating Aquaculture Systems. In: Tidwell JH, ed. *Aquaculture Production Systems*.. Wiley-Blackwell; 2012:245-277. https://doi.org/10.1002/9781118250105.ch11
24. Khanjani MH, Sharifinia M. Biofloc technology as a promising tool to improve aquaculture production. *Rev Aquac*. 2020;12(3):12412. https://doi.org/10.1111/raq.12412
25. Verdegem MCJ. Nutrient discharge from aquaculture operations in function of system design and production environment. *Rev Aquac*. 2013;5(3):158-171. https://doi.org/10.1111/raq.12011
26. Rurangwa E, Verdegem MCJ. Microorganisms in recirculating aquaculture systems and their management. *Rev Aquac*. 2015;7(2):117-130. https://doi.org/10.1111/raq.12057
27. Avnimelech Y. *Biofloc Technology a Practical GuideBook*, 3rd ed. The World Aquaculture Society; 2015.
28. Emerenciano MGC, Martínez-Córdova LR, Martínez-Porchas M, Miranda-Baeza A. Biofloc Technology Technology (BFT): Tool for Water Quality Management in Aquaculture. In: Tutu H, ed. *Water Quality*. London: INTECH; 2017: 91–109. https://doi.org/10.5772/66416
29. Samocha TM. Sustainable Biofloc Systems for Marine Shrimp. Elsevier. 2019; https://doi.org/10.1016/C2018-0-02628-6
30. Badiola M, Basurko OC, Piedrahita R, Hundley P, Mendiola D. Energy use in Recirculating Aquaculture Systems (RAS): A review. *Aquac Eng*. 2018;81:57-70. https://doi.org/10.1016/j.aquaeng.2018.03.003
31. Walker DAU, Morales Suazo MC, Emerenciano MGC. Biofloc technology: principles focused on potential species and the case study of Chilean river shrimp *Cryphiops caementarius*. *Rev Aquac*. 2020;12(3):1759-1782. https://doi.org/10.1111/raq.12408
32. Goddek S, Joyce A, Kotzen B, Dos-Santos M. Aquaponics and Global Food Challenges. In: Goddek S, Joyce A, Kotzen B, Burnell G, eds. *Aquaponics Food Production Systems*. Springer International Publishing; 2019:3-17. https://doi.org/10.1007/978-3-030-15943-6_1
33. Nederlof MAJ, Jansen HM, Dahlgren TG, et al. Application of polychaetes in (de)coupled integrated aquaculture: Production of a high-quality marine resource. *Aquac Environ Interact*. 2019;11:221-237. https://doi.org/10.3354/AEI00309
34. Bohnes FA, Hauschild MZ, Schlundt J, Laurent A. Life cycle assessments of aquaculture systems: a critical review of reported findings with recommendations for policy and system development. *Rev Aquac*. 2019;11(4):1061-1079. https://doi.org/10.1111/raq.12280
35. Reid GK, Lefebvre S, Filgueira R, et al. Performance measures and models for open-water integrated multi-trophic aquaculture. *Rev Aquac*. 2020;12(1):47-75. https://doi.org/10.1111/raq.12304
36. Kyaw TY, Ng AK. Smart Aquaponics System for Urban Farming. *Energy Procedia*. 2017;143:342-347. https://doi.org/10.1016/j.egypro.2017.12.694
37. Gott J, Morgenstern R, Turnšek M. Aquaponics for the Anthropocene: Towards a 'Sustainability First' Agenda. In: Goddek S, Joyce A, Kotzen B, Burnell G, eds. *Aquaponics Food Production Systems*. Springer International Publishing; 2019:393–432. https://doi.org/10.1007/978-3-030-15943-6_16
38. Lennard W, Aquaponics GS. The Basics. In: Goddek S, Joyce A, Kotzen B, Burnell G, eds. *Aquaponics Food Production Systems*. Springer International Publishing; 2019:113–143. doi:doi.org/https://doi.org/10.1007/978-3-030-15943-6_5
39. König B, Janker J, Reinhardt T, Villarroel M, Junge R. Analysis of aquaponics as an emerging technological innovation system. *J Clean Prod*. 2018;180:232-243. https://doi.org/10.1016/j.jclepro.2018.01.037
40. Yep B, Zheng Y. Aquaponic trends and challenges – A review. *J Clean Prod*. 2019;228:1586-1599. https://doi.org/10.1016/j.jclepro.2019.04.290
41. Kotzen B, Emerenciano MGC, Moheimani N, Aquaponics BGM. Alternative Types and Approaches. In: Goddek S, Joyce A, Kotzen B, Burnell GM, eds. *Aquaponics Food Production Systems*. Springer International Publishing; 2019:301-330. https://doi.org/10.1007/978-3-030-15943-6_12
42. Kloas W, Groß R, Baganz D, et al. A new concept for aquaponic systems to improve sustainability, increase productivity, and reduce environmental impacts. *Aquac Environ Interact*. 2015;7(2):179-192. https://doi.org/10.3354/aei00146
43. Goddek S, Espinal CA, Delaide B, et al. Navigating towards decoupled aquaponic systems: A system dynamics design approach. *Water (Switzerland)*. 2016;8(7):1-29. https://doi.org/10.3390/W8070303
44. Goddek S, Joyce A, Wuertz S, et al. Decoupled Aquaponics Systems. In: Goddek S, Joyce A, Kotzen B, Burnell GM, eds. *Aquaponics Food Production Systems*. Springer International Publishing; 2019:201-229. https://doi.org/10.1007/978-3-030-15943-6_8
45. Goddek S, Keesman KJ. Improving nutrient and water use efficiencies in multi-loop aquaponics systems. *Aquac Int*. 2020;28(6):2481-2490. https://doi.org/10.1007/s10499-020-00600-6
46. Addy MM, Kabir F, Zhang R, et al. Co-cultivation of microalgae in aquaponic systems. *Bioresour Technol*. 2017;245:27-34. https://doi.org/10.1016/j.biortech.2017.08.151
47. Kotzen B, Appelbaum S. An investigation of aquaponics using brackish water resources in the Negev Desert. *J Appl Aquac*. 2010;22(4):297-320. https://doi.org/10.1080/10454438.2010.527571
48. Pinho SM, David LHC, Goddek S, Emerenciano MGC, Portella MC. Integrated production of Nile tilapia juveniles and lettuce using biofloc technology. *Aquac Int*. 2021;29(1):37-56. https://doi.org/10.1007/s10499-020-00608-y
49. Emerenciano M, Gaxiola G, Cuzon G. Biofloc Technology (BFT): A Review for Aquaculture Application and Animal Food Industry. In: Matovic MD, ed. *Biomass Now - Cultivation and Utilization*. London: INTECH; 2013: 301-328. https://doi.org/10.5772/53902
50. Verdegem MCJ, Bosma RH. Water withdrawal for brackish and inland aquaculture, and options to produce more fish in ponds with present water use. *Water Policy*. 2009;11(S1):52-68. https://doi.org/10.2166/wp.2009.003
51. Crab R, Defoirdt T, Bossier P, Verstraete W. Biofloc technology in aquaculture: Beneficial effects and future challenges. *Aquaculture*. 2012;357:351-356. https://doi.org/10.1016/j.aquaculture.2012.04.046

52. Browdy CL, Ray AJ, Leffler JW, Avnimelech Y. Biofloc-based Aquaculture Systems. In: Tidwell, JH, ed. *Aquaculture Production Systems*. Wiley-Blackwell; 2012:278-307; https://doi.org/10.1002/9781118250105.ch12
53. Ray AJ, Seaborn G, Leffler JW, Wilde SB, Lawson A, Browdy CL. Characterization of microbial communities in minimal-exchange, intensive aquaculture systems and the effects of suspended solids management. *Aquaculture*. 2010;310(1–2):130-138. https://doi.org/10.1016/j.aquaculture.2010.10.019
54. Martínez-Córdova LR, Emerenciano M, Miranda-Baeza A, Martínez-Porchas M. Microbial-based systems for aquaculture of fish and shrimp: An updated review. *Rev Aquac*. 2015;7(2):131-148. https://doi.org/10.1111/raq.12058
55. Brol J, Pinho SM, Sgnaulin T, et al. Biofloc technology on the zootechnical performance of tilapia: Effect of strain and stocking density. *Arch Zootec*. 2017;66(254):229-235. https://doi.org/10.21071/az.v66i254.2326
56. Minaz M, Kubilay A. Operating parameters affecting biofloc technology: carbon source, carbon/nitrogen ratio, feeding regime, stocking density, salinity, aeration, and microbial community manipulation. *Aquac Int*. 2021;29(3):1121-1140. https://doi.org/10.1007/s10499-021-00681-x
57. Hargreaves JA. Biofloc production systems for aquaculture. *SRAC Publ*. 2013;4503:1-12.
58. Bossier P, Ekasari J. Biofloc technology application in aquaculture to support sustainable development goals. *Microb Biotechnol*. 2017;10(5):1012-1016. https://doi.org/10.1111/1751-7915.12836
59. Wasielesky W, Bezerra A, Poersch L, Hoffling FB, Krummenauer D. Effect of feeding frequency on the white shrimp *Litopenaeus vannamei* during the pilot-scale nursery phase of a superintensive culture in a biofloc system. *J World Aquac Soc*. 2020;51(5):1175-1191. https://doi.org/10.1111/jwas.12694
60. Ballester ELC, Abreu PC, Cavalli RO, Emerenciano M, de Abreu L, Wasielesky W. Effect of practical diets with different protein levels on the performance of *Farfantepenaeus paulensis* juveniles nursed in a zero exchange suspended microbial flocs intensive system. *Aquac Nutr*. 2010;16(2):163-172. https://doi.org/10.1111/j.1365-2095.2009.00648.x
61. Moreno-Arias A, López-Elías JA, Martínez-Córdova LR, et al. Effect of fishmeal replacement with a vegetable protein mixture on the amino acid and fatty acid profiles of diets, biofloc and shrimp cultured in BFT system. *Aquaculture*. 2018;483:53-62. https://doi.org/10.1016/j.aquaculture.2017.10.011
62. Sgnaulin T, Durigon EG, Pinho SM, Jerônimo GT, de Lopes DL, A, Emerenciano M. Nutrition of genetically improved farmed tilapia (GIFT) in biofloc technology system: Optimization of digestible protein and digestible energy levels during nursery phase. *Aquaculture*. 2020;521:734998. https://doi.org/10.1016/j.aquaculture.2020.734998
63. Sgnaulin T, Pinho SM, Durigon EG, Thomas MC, de Mello GL, Emerenciano MGC. Culture of pacu *Piaractus mesopotamicus* in biofloc technology (BFT): insights on dietary protein sparing and stomach content. *Aquac Int* 2021;29(5):2319–2335. https://doi.org/10.1007/S10499-021-00748-9
64. Krummenauer D, Samocha T, Poersch L, Lara G, Wasielesky W. The reuse of water on the culture of Pacific White Shrimp, *Litopenaeus vannamei*. BFT System. *J World Aquac Soc*. 2014;45(1):3-14. https://doi.org/10.1111/jwas.12093
65. Dauda AB. Biofloc technology: a review on the microbial interactions, operational parameters and implications to disease and health management of cultured aquatic animals. *Rev Aquac*. 2020;12(2):1193-1210. https://doi.org/10.1111/raq.12379
66. Li J, Liu G, Li C, et al. Effects of different solid carbon sources on water quality, biofloc quality and gut microbiota of Nile tilapia (*Oreochromis niloticus*) larvae. *Aquaculture*. 2018;495:919-931. https://doi.org/10.1016/j.aquaculture.2018.06.078
67. Durigon EG, Almeida APG, Jerônimo GT, Baldisserotto B, Emerenciano MGC. Digestive enzymes and parasitology of Nile tilapia juveniles raised in brackish biofloc water and fed with different digestible protein and digestible energy levels. *Aquaculture*. 2019;506:35-41. https://doi.org/10.1016/j.aquaculture.2019.03.022
68. Hargreaves JA. Photosynthetic suspended-growth systems in aquaculture. *Aquac Eng*. 2006;34(3):344-363. https://doi.org/10.1016/j.aquaeng.2005.08.009
69. Martínez-Córdova LR, Martínez-Porchas M, Emerenciano MGC, Miranda-Baeza A, Gollas-Galván T. From microbes to fish the next revolution in food production. *Crit Rev Biotechnol*. 2017;37(3):287-295. https://doi.org/10.3109/07388551.2016.1144043
70. Luo G, Xu J, Meng H. Nitrate accumulation in biofloc aquaculture systems. *Aquaculture*. 2020;520: https://doi.org/10.1016/j.aquaculture.2019.734675 734675.
71. Robles-Porchas GR, Gollas-Galván T, Martínez-Porchas M, Martínez-Cordova LR, Miranda-Baeza A, Vargas-Albores F. The nitrification process for nitrogen removal in biofloc system aquaculture. *Rev Aquac*. 2020;12(4):2228-2249. https://doi.org/10.1111/raq.12431
72. Nevejan N, De Schryver P, Wille M, Dierckens K, Baruah K, Van Stappen G. Bacteria as food in aquaculture: do they make a difference? *Rev Aquac*. 2018;10(1):180-212. https://doi.org/10.1111/raq.12155
73. Sánchez-Muros MJ, Renteria P, Vizcaino A, Barroso FG. Innovative protein sources in shrimp (*Litopenaeus vannamei*) feeding. *Rev Aquac*. 2020;12(1):186-203. https://doi.org/10.1111/raq.12312
74. Wasielesky W, Atwood H, Stokes A, Browdy CL. Effect of natural production in a zero exchange suspended microbial floc based super-intensive culture system for white shrimp *Litopenaeus vannamei*. *Aquaculture*. 2006;258(1–4):396-403. https://doi.org/10.1016/j.aquaculture.2006.04.030
75. Azim ME, Little DC. The biofloc technology (BFT) in indoor tanks: Water quality, biofloc composition, and growth and welfare of Nile tilapia (*Oreochromis niloticus*). *Aquaculture*. 2008;283(1–4):29-35. https://doi.org/10.1016/j.aquaculture.2008.06.036
76. Emerenciano MG, Fitzsimmons K, Rombenso A, et al. Biofloc technology (BFT) in tilapia culture. In: López-Olmeda J, Sánchez-Vázquez J, Fortes-Silva R, eds. *Biology and Aquaculture of Tilapia*. Boca Raton: CRC Press/Taylor & Francis Group; 2021.258–293.
77. Sgnaulin T, de Mello GL, Thomas MC, Garcia JRE, de Oca GARM, Emerenciano MGC. Biofloc technology (BFT): An alternative aquaculture system for piracanjuba *Brycon orbignyanus*? *Aquaculture*. 2018;485:119-123. https://doi.org/10.1016/j.aquaculture.2017.11.043
78. Pinheiro I, Carneiro RFS, Vieira F, et al. Aquaponic production of *Sarcocornia ambigua* and Pacific white shrimp in biofloc system at different salinities. *Aquaculture*. 2020;519:734918. https://doi.org/10.1016/j.aquaculture.2019.734918
79. Wongkiew S, Hu Z, Chandran K, Lee JW, Khanal SK. Nitrogen transformations in aquaponic systems: A review. *Aquac Eng*. 2017;76:9-19. https://doi.org/10.1016/j.aquaeng.2017.01.004
80. Yildiz HY, Robaina L, Pirhonen J, Mente E, Domínguez D, Parisi G. Fish welfare in aquaponic systems: Its relation to water quality with an emphasis on feed and faeces-A review. *Water (Switzerland)*. 2017;9(1):1-17. https://doi.org/10.3390/w9010013
81. Paudel SR. Nitrogen transformation in engineered aquaponics with water celery (*Oenanthe javanica*) and koi carp (*Cyprinus carpio*): Effects of plant to fish biomass ratio. *Aquaculture*. 2020;520: https://doi.org/10.1016/j.aquaculture.2020.734971 734971.
82. Cohen A, Malone S, Morris Z, Weissburg M, Bras B. Combined Fish and Lettuce Cultivation: An Aquaponics Life Cycle Assessment. *Procedia CIRP*. 2018;69:551-556. https://doi.org/10.1016/j.procir.2017.11.029
83. Lennard WA, Leonard BV. A comparison of three different hydroponic sub-systems (gravel bed, floating and nutrient film

technique) in an Aquaponic test system. *Aquac Int*. 2006;14(6):539-550. https://doi.org/10.1007/s10499-006-9053-2
84. Palm HW, Knaus U, Appelbaum S, et al. Towards commercial aquaponics: A review of systems, designs, scales and nomenclature. *Aquac Int*. 2018;26(3):813-842. https://doi.org/10.1007/s10499-018-0249-z
85. Love DC, Fry JP, Li X, et al. Commercial aquaponics production and profitability: Findings from an international survey. *Aquaculture*. 2015;435:67-74. https://doi.org/10.1016/j.aquaculture.2014.09.023
86. Pinho SM, David LH, Garcia F, Keesman KJ, Portella MC, Goddek S. South American fish species suitable for aquaponics: a review. *Aquac Int*. 2021;29(4):1427-1449. https://doi.org/10.1007/s10499-021-00674-w
87. Mchunu N, Lagerwall G, Senzanje A. Aquaponics in South Africa: Results of a national survey. *Aquac Reports*. 2018;12:12-19. https://doi.org/10.1016/j.aqrep.2018.08.001
88. Superior Fresh. Superior Fresh - aquaponics farm. 2020. Accessed March 21, 2021. https://www.superiorfresh.com/
89. Goddek S, Delaide B, Mankasingh U, Ragnarsdottir KV, Jijakli H, Thorarinsdottir R. Challenges of sustainable and commercial aquaponics. *Sustain*. 2015;7(4):4199-4224. https://doi.org/10.3390/su7044199
90. Eck M, Körner O, Jijakli MH. Nutrient Cycling in Aquaponics Systems. In: Goddek S, Joyce A, Kotzen B, Burnell G, eds. *Aquaponics Food Production Systems*. Springer International Publishing; 2019:231-246. https://doi.org/10.1007/978-3-030-15943-6_9
91. Maucieri C, Nicoletto C, van Os E, Anseeuw D, Van HR, Junge R. Hydroponic Technologies. In: Goddek S, Joyce A, Kotzen B, Burnell G, eds. *Aquaponics Food Production Systems*. Springer International Publishing; 2019:77-110. https://doi.org/10.1007/978-3-030-15943-6_4
92. Monsees H, Kloas W, Wuertz S. Decoupled systems on trial: Eliminating bottlenecks to improve aquaponic processes. *PLoS One*. 2017;12(9):1-18. https://doi.org/10.1371/journal.pone.0183056
93. Baganz GFM, Junge R, Portella MC, et al. The aquaponic principle—It is all about coupling. *Rev Aqua*. 2021;https://doi.org/10.1111/raq.12596
94. Bosma RH, Lacambra L, Landstra Y, et al. The financial feasibility of producing fish and vegetables through aquaponics. *Aquac Eng*. 2017;78:146-154. https://doi.org/10.1016/j.aquaeng.2017.07.002
95. Stadler MM, Baganz D, Vermeulen T, Keesman KJ. Circular economy and economic viability of aquaponic systems: Comparing urban, rural and peri-urban scenarios under Dutch conditions. *Acta Hortic*. 2017;1176:101-114. https://doi.org/10.17660/ActaHortic.2017.1176.14
96. Quagrainie KK, Flores RMV, Kim H, McClain V. Economic analysis of aquaponics and hydroponics production in the U.S. Midwest. *J Appl Aquac*. 2018;30(1):1-14. https://doi.org/10.1080/10454438.2017.1414009
97. Greenfeld A, Becker N, McIlwain J, Fotedar R, Bornman JF. Economically viable aquaponics? Identifying the gap between potential and current uncertainties. *Rev Aquac*. 2019;11(3):848-862. https://doi.org/10.1111/raq.12269
98. Forchino AA, Lourguioui H, Brigolin D, Pastres R. Aquaponics and sustainability: The comparison of two different aquaponic techniques using the Life Cycle Assessment (LCA). *Aquac Eng*. 2017;77:80-88. https://doi.org/10.1016/j.aquaeng.2017.03.002
99. Maucieri C, Forchino AA, Nicoletto C, et al. Life cycle assessment of a micro aquaponic system for educational purposes built using recovered material. *J Clean Prod*. 2018;172:3119-3127. https://doi.org/10.1016/j.jclepro.2017.11.097
100. Körner O, Bisbis MB, Baganz GFM, et al. Environmental impact assessment of local decoupled multi-loop aquaponics in an urban context. *J Clean Prod*. 2021;313: https://doi.org/10.1016/J.JCLEPRO.2021.127735 127735.
101. Karimanzira D, Keesman KJ, Kloas W, Baganz D, Rauschenbach T. Dynamic modeling of the INAPRO aquaponic system. *Aquac Eng*. 2016;75:29-45. https://doi.org/10.1016/j.aquaeng.2016.10.004
102. Reyes Lastiri D, Slinkert T, Cappon H J, Baganz D, Staaks G, Keesman K J. Model of an aquaponic system for minimised water, energy and nitrogen requirements. *Water Sci Technol*. 2016;74(1):30-37. https://doi.org/10.2166/wst.2016.127
103. Estrada-Perez N, Hernandez-Llamas A, Ruiz-Velazco J.M.J, et al. Stochastic modelling of aquaponic production of tilapia (*Oreochromis niloticus*) with lettuce (*Lactuca sativa*) and cucumber (*Cucumis sativus*). *Aquac Res*. 2018;49(12):3723-3734. https://doi.org/10.1111/are.13840
104. Keesman KJ, Körner O, Wagner K, et al. Aquaponics Systems Modelling. In: Goddek S, Joyce A, Kotzen B, Burnell G, eds. *Aquaponics Food Production Systems*. Springer International Publishing; 2019:267-299. https://doi.org/10.1007/978-3-030-15943-6_11
105. Junge R, Bulc TG, Anseeuw D, Yavuzcan Yildiz H, Milliken S. Aquaponics as an Educational Tool. In: Goddek S, Joyce A, Kotzen B, Burnell G, eds. *Aquaponics Food Production Systems*.. Springer International Publishing; 2019:561-595. https://doi.org/10.1007/978-3-030-15943-6_22
106. Yogev U, Barnes A, Gross A. Nutrients and energy balance analysis for a conceptual model of a three loops off grid, aquaponics. *Water (Switzerland)*. 2016;8(12): https://doi.org/10.3390/w8120589
107. Baganz G, Baganz D, Staaks G, Monsees H, Kloas W. Profitability of multi-loop aquaponics: Year-long production data, economic scenarios and a comprehensive model case. *Aquac Res*. 2020;51(7):2711-2724. https://doi.org/10.1111/are.14610
108. Monsees H, Keitel J, Paul M, Kloas W, Wuertz S. Potential of aquacultural sludge treatment for aquaponics: Evaluation of nutrient mobilization under aerobic and anaerobic conditions. *Aquac Environ Interact*. 2017;9(1):9-18. https://doi.org/10.3354/aei00205
109. Delaide B, Monsees H, Gross A, Goddek S. Aerobic and Anaerobic Treatments for Aquaponic Sludge Reduction and Mineralisation. In: Goddek S, Joyce A, Kotzen B, Burnell GM, eds. *Aquaponics Food Production Systems*. Springer International Publishing; 2019:247-266. https://doi.org/10.1007/978-3-030-15943-6_10
110. Palm HW, Knaus U, Appelbaum S, Strauch SM. Coupled Aquaponics Systems. In: Goddek S, Joyce A, Kotzen B, Burnell GM, eds. *Aquaponics Food Production Systems*. Springer International Publishing; 2019:163–199. https://doi.org/10.1007/978-3-030-15943-6_7
111. Stouvenakers G, Dapprich P, Massart S, Jijakli MH. Plant Pathogens and Control Strategies in Aquaponics. In: Goddek S, Joyce A, Kotzen B, Burnell GM, eds. *Aquaponics Food Production Systems*. Springer International Publishing; 2019:353-378. https://doi.org/10.1007/978-3-030-15943-6_14
112. Rocha AF, Biazzetti Filho ML, Stech MR, Silva RP. Lettuce production in aquaponic and biofloc systems with silver catfish Rhamdia quelen. *Bol do Instituo Pesca*. 2017;44:64-73. https://doi.org/10.20950/1678-2305.2017.64.73
113. Pinheiro I, Arantes R, do Espírito Santo CM, et al. Production of the halophyte *Sarcocornia ambigua* and Pacific white shrimp in an aquaponic system with biofloc technology. *Ecol Eng*. 2017;100:261-267. https://doi.org/10.1016/j.ecoleng.2016.12.024
114. Poli MA, Legarda EC, de Lorenzo MA, et al. Integrated multitrophic aquaculture applied to shrimp rearing in a biofloc system. *Aquaculture*. 2019;511. https://doi.org/10.1016/j.aquaculture.2019.734274 734274.
115. Luo G, Gao Q, Wang C, et al. Growth, digestive activity, welfare, and partial cost-effectiveness of genetically improved farmed tilapia (*Oreochromis niloticus*) cultured in a recirculating aquaculture system and an indoor biofloc system. *Aquaculture*. 2014;422–423:1-7. https://doi.org/10.1016/j.aquaculture.2013.11.023
116. Guemez-Sorhouet E, Villarreal H, Racotta IS, Naranjo J, Mercier L. Zootechnical and physiological responses of whiteleg shrimp

(*Litopenaeus vannamei*) postlarvae reared in bioflocs and subjected to stress conditions during nursery phase. *Aquac Res*. 2019;50(4):1198-1211. https://doi.org/10.1111/are.13994
117. Pinho SM, Molinari D, de Mello GL, Fitzsimmons KM, Emerenciano MG. Effluent from a biofloc technology (BFT) tilapia culture on the aquaponics production of different lettuce varieties. *Ecol Eng*. 2017;103:146-153. https://doi.org/10.1016/j.ecoleng.2017.03.009
118. Joesting HMM, Blaylock R, Biber P, Ray A. The use of marine aquaculture solid waste for nursery production of the salt marsh plants *Spartina alterniflora* and *Juncus roemerianus*. *Aquac Reports*. 2016;3:108-114. https://doi.org/10.1016/j.aqrep.2016.01.004
119. Doncato KB, Costa CSB. Growth and mineral composition of two lineages of the sea asparagus *Sarcocornia ambigua* irrigated with shrimp farm saline effluent. *Exp Agric*. 2018;54(3):399-416. https://doi.org/10.1017/S0014479717000096
120. de Souza M, Mendes C, Doncato K, Badiale-Furlong E, Costa C. Growth, Phenolics, Photosynthetic Pigments, and Antioxidant Response of Two New Genotypes of Sea Asparagus (*Salicornia neei Lag*.) to Salinity under Greenhouse and Field Conditions. *Agriculture*. 2018;8(7):115. https://doi.org/10.3390/agriculture8070115
121. Rahman SSA. Effluent Waste Characterization of Intensive Tilapia Culture Units and its Application in an Integrated Lettuce Aquaponic Production Facility. Auburn University; 2010. Dissertation.
122. Blanchard C, Wells DE, Pickens JM, Blersch DM. Effect of pH on cucumber growth and nutrient availability in a decoupled aquaponic system with minimal solids removal. *Horticulturae*. 2020;6(1):10. https://doi.org/10.3390/horticulturae6010010
123. Pickens JM, Danaher JJ, Sibley JL, Chappell JA, Hanson TR. Integrating greenhouse cherry tomato production with biofloc tilapia production. *Horticulturae*. 2020;6(3):44. https://doi.org/10.3390/horticulturae6030044
124. Doncato KB, Costa CSB. Micronutrient supplementation needs for halophytes in saline aquaponics with BFT system water. *Aquaculture*. 2021;531: https://doi.org/10.1016/j.aquaculture.2020.735815 735815.
125. da Silva HV. Efeito do estresse hídrico na produção de compostos bioativos de Sarcocornia ambigua em sistema aquapônico com Litopenaeus vannamei. Dissertation. Federal University of Santa Catarina. 2016.
126. Neto J. Cultivo de Sarcoconia ambigua em aquaponia com Litopenaeus vannamei em bioflocos com diferentes áreas de bancada hidropônica. Dissertation. Federal University of Santa Catarina. 2017.
127. Moss KRK, Moss SM. Effects of artificial substrate and stocking density on the nursery production of Pacific White Shrimp *Litopenaeus vannamei*. *J World Aquac Soc*. 2004;35(4):536-542. https://doi.org/10.1111/j.1749-7345.2004.tb00121.x
128. Schveitzer R, Arantes R, Baloi MF, et al. Use of artificial substrates in the culture of *Litopenaeus vannamei* (Biofloc System) at different stocking densities: Effects on microbial activity, water quality and production rates. *Aquac Eng*. 2013;54:93-103. https://doi.org/10.1016/j.aquaeng.2012.12.003
129. Olier BS, Tubin JSB, de Mello GL, Martínez-Porchas M, Emerenciano MGC. Does vertical substrate could influence the dietary protein level and zootechnical performance of the Pacific white shrimp *Litopenaeus vannamei* reared in a biofloc system? *Aquac Int*. 2020;28(3):1227-1241. https://doi.org/10.1007/s10499-020-00521-4
130. Azim M, Verdegem M, Dam A, Beveridge M. Periphyton: Ecology, Exploitation and Management. CABI. 2005; https://doi.org/10.1079/9780851990965.0000
131. Ray AJ, Lewis BL, Browdy CL, Leffler JW. Suspended solids removal to improve shrimp (*Litopenaeus vannamei*) production and an evaluation of a plant-based feed in minimal-exchange, superintensive culture systems. *Aquaculture*. 2010;299(1–4):89-98. https://doi.org/10.1016/j.aquaculture.2009.11.021
132. Gaona CAP, da Serra F.P, Furtado PS, Poersch LH, Wasielesky W. Biofloc management with different flow rates for solids removal in the *Litopenaeus vannamei* BFT culture system. *Aquac Int*. 2016;24(5):1263-1275. https://doi.org/10.1007/s10499-016-9983-2
133. Fimbres-Acedo YE, Magallón-Servín P, Garza-Torres R, et al. *Oreochromis niloticus* aquaculture with biofloc technology, photoautotrophic conditions and *Chlorella microalgae*. *Aquac Res*. 2020;51(8):3323-3346. https://doi.org/10.1111/are.14668
134. Fimbres-Acedo YE, Servín-Villegas R, Garza-Torres R, et al. Hydroponic horticulture using residual waters from *Oreochromis niloticus* aquaculture with biofloc technology in photoautotrophic conditions with *Chlorella microalgae*. *Aquac Res*. 2020;51:1-21. https://doi.org/10.1111/are.14779
135. Castro-Mejía J, Castro-Mejía G, Castro-Castellón AE, Martínez-Meingüer AM, Reséndiz-Corona A. Preliminary study of *Oreochromis nilóticus*, *Coriandrum sativum*, *Anethum graveolens*, and *Petroselinum crispum* growth cultured in Biofloc/aquaponic system. *Int J Fish Aquat Sudies*. 2020;8(3):217-222.
136. Castro-Castellón AE, Castro-Mejía G, Castro-Mejía J, Martínez-Meingüer AM. Culture of Melanochromis sp. and *Lycopersicon esculentum* var. Cerasifonne in a combined system of Biofloc and aquaponics. *Int J Fish Aquat Stud*. 2020;8(2):186-192.
137. Martínez-Meingüer AM. Preliminary study of the growth of *Oreochromis niloticus* var. *Rocky Mountain* and *Lycopersicum esculentum L*. cultured in aquaponic/Biofloc system. *Int J Fish Aquat Sudies*. 2020;8:609-618.
138. Ebeling JM, Timmons MB, Bisogni JJ. Engineering analysis of the stoichiometry of photoautotrophic, autotrophic, and heterotrophic removal of ammonia-nitrogen in aquaculture systems. *Aquaculture*. 2006;257(1–4):346-358. https://doi.org/10.1016/j.aquaculture.2006.03.019
139. Samocha TM, Prangnell DI. Water Quality Management. In: Samocha TM, ed. *Sustainable Biofloc Systems for Marine Shrimp*. Elsevier; 2019:133-151. https://doi.org/10.1016/B978-0-12-818040-2.00007-1
140. Lenz GL, Durigon EG, Lapa KR, Emerenciano MGC. Produção de alface (*Lactuca sativa*) em efluentes de um cultivo de tilápias mantidas em sistema BFT em baixa salinidade. *Bol do Inst Pesca*. 2017;43(4):614-630. https://doi.org/10.20950/1678-2305.2017v43n4p614
141. Tyson RV, Simonne EH, White JM, Lamb EM. Reconciling water quality parameters impacting nitrification in aquaponics: The pH Levels. *Proc Florida State Hortic Soc*. 2004;117:79-83.
142. Rakocy JE. Aquaponics-Integrating Fish and Plant Culture. In: James Tidwell, ed. *Aquaculture Production Systems*. Wiley-Blackwell; 2012:344-386. https://doi.org/10.1002/9781118250105.ch14
143. Pinho SM, Emerenciano MGC. Sensorial attributes and growth performance of whiteleg shrimp (*Litopenaeus vannamei*) cultured in biofloc technology with varying water salinity and dietary protein content. *Aquaculture*. 2021;540: https://doi.org/10.1016/j.aquaculture.2021.736727 736727.
144. Ahmad I, Babitha Rani AM, Verma AK, Maqsood M. Biofloc technology: an emerging avenue in aquatic animal healthcare and nutrition. *Aquac Int*. 2017;25(3):1215-1226. https://doi.org/10.1007/s10499-016-0108-8
145. Diver S. Aquaponics—Integration of Hydroponics with Aquaculture. *ATTRA Natl Sustain Agric Inf* Serv. Published Online. 2006;1-28.
146. Barbosa MP. Tecnologia de bioflocos: Elementos filtrantes afetam a produção aquapônica de alfaces integrado com tilápias? Dissertation. Santa Catarina State University; 2017.
147. Quintã R, Santos R, Thomas DN, Le Vay L. Growth and nitrogen uptake by *Salicornia europaea* and *Aster tripolium* in nutrient conditions typical of aquaculture wastewater. *Chemosphere*. 2015;120:414-421. https://doi.org/10.1016/j.chemosphere.2014.08.017
148. Martinez-Cordova LRR, López-Elías J, Martinez-Porchas M, et al. A preliminary evaluation of an integrated aquaculture-agriculture

systems (tilapia and peppers) at mesocosm scale. *J Aquac Mar Biol*. 2020;9(1):19-22. https://doi.org/10.15406/jamb.2020.09.00272
149. Santillo D. Reclaiming the Definition of Sustainability. *Environ Sci Pollut Res Int*. 2007;14(1):60-66. https://doi.org/10.1065/espr2007.01.375
150. Valenti WC, Kimpara JM, Preto BDL, Moraes-Valenti P. Indicators of sustainability to assess aquaculture systems. *Ecol Indic*. 2018;88:402-413. https://doi.org/10.1016/j.ecolind.2017.12.068
151. Sabbag OJ, Rozales R, Tarsitano M, Silveira A. Análise econômica da produção de tilápias (*Oreochromis niloticus*) em um modelo de propriedade associativista em Ilha Solteira/SP. *Custos E Agronegócios*. 2007;3(2):86-100.
152. Shang Y. Aquaculture Economic Analysis: An Introduction. The World Aquaculture Society. 1990.
153. Garcia F, Kimpara JM, Valenti WC, Ambrosio LA. Emergy assessment of tilapia cage farming in a hydroelectric reservoir. *Ecol Eng*. 2014;68:72-79. https://doi.org/10.1016/j.ecoleng.2014.03.076
154. Folke C, Kautsky N, Berg H, Jansson A, Troell M. The ecological footprint concept for sustainable seafood production: A review. *Ecol Appl*. 1998;8(1):61-71. https://doi.org/10.1890/1051-0761(1998)8[S63:TEFCFS]2.0.CO;2.
155. Gyllenhammar A, Hakanson L. Environmental consequence analyses of fish farm emissions related to different scales and exemplified by data from the Baltic – a review. *Mar Environ Res*. 2005;60(2):211-243.
156. Madin EMP, Macreadie PI. Incorporating carbon footprints into seafood sustainability certification and eco-labels. *Mar Policy*. 2015;57:178-181. https://doi.org/10.1016/j.marpol.2015.03.009
157. Vassallo P, Bastianoni S, Beiso I, Ridolfi R, Fabiano M. Emergy analysis for the environmental sustainability of an inshore fish farming system. *Ecol Indic*. 2007;7(2):290-298. https://doi.org/10.1016/j.ecolind.2006.02.003
158. Lima JSG, Rivera EC, Focken U. Emergy evaluation of organic and conventional marine shrimp farms in Guaraíra Lagoon. *Brazil. J Clean Prod*. 2012;35:194-202. https://doi.org/10.1016/j.jclepro.2012.05.009
159. David LH, Pinho SM, Agostinho F, Kimpara JM, Keesman KJ, Garcia F. Emergy synthesis for aquaculture : A review on its constraints and potentials. *Rev Aquac*. 2020;13(2):1119-1138. https://doi.org/10.1111/raq.12519
160. Gronroos J, Seppala J, Silvenius F, Makinen T. Life cycle assessment of Finnish cultivated rainbow trout. *Boreal Environ Res*. 2006;11:401-414.
161. Aubin J, Papatryphon E, Van der Werf HMG, Petit J, Morvan YM. Characterisation of the environmental impact of a turbot (*Scophthalmus maximus*) re-circulating production system using Life Cycle Assessment. *Aquaculture*. 2006;261(4):1259-1268. https://doi.org/10.1016/j.aquaculture.2006.09.008
162. Aubin J, Papatryphon E, van der Werf HMG, Chatzifotis S. Assessment of the environmental impact of carnivorous finfish production systems using life cycle assessment. *J Clean Prod*. 2009;17(3):354-361. https://doi.org/10.1016/j.jclepro.2008.08.008
163. Santos AAO, Aubin J, Corson MS, Valenti WC, Camargo AFM. Comparing environmental impacts of native and introduced freshwater prawn farming in Brazil and the influence of better effluent management using LCA. *Aquaculture*. 2015;444:151-159. https://doi.org/10.1016/j.aquaculture.2015.03.006
164. Medeiros MV, Aubin J, Camargo AFM. Life cycle assessment of fish and prawn production: Comparison of monoculture and polyculture freshwater systems in Brazil. *J Clean Prod*. 2017;156:528-537. https://doi.org/10.1016/j.jclepro.2017.04.059
165. Boxman SE, Kruglick A, McCarthy B, et al. Performance evaluation of a commercial land-based integrated multi-trophic aquaculture system using constructed wetlands and geotextile bags for solids treatment. *Aquac Eng*. 2015;69:23-36. https://doi.org/10.1016/j.aquaeng.2015.09.001
166. Belettini F, Seiffert WQ, Lapa KR, Vieira FDN, Santo CMDE, Arana LAV. Carbon footprint in commercial cultivation of marine shrimp: a case study in southern Brazil. *Rev Bras Zootec*. 2018;47: https://doi.org/10.1590/rbz4720160353
167. Castilho-Barros L, Almeida FH, Henriques MB, Seiffert WQ. Economic evaluation of the commercial production between Brazilian samphire and whiteleg shrimp in an aquaponics system. *Aquac Int*. 2018;26(5):1187-1206. https://doi.org/10.1007/s10499-018-0277-8
168. FAO. Small-Scale Aquaponic Food Production: Integrated Fish and Plant Farming. Food and Agriculture Organization of The United Nations (FAO). 2014 http://www.fao.org/3/i4021e/i4021e.pdf
169. Megahed ME, Mohamed K. Sustainable growth of shrimp aquaculture through biofloc production as alternative to fishmeal in shrimp feeds. *J Agric Sci*. 2014;6(6): https://doi.org/10.5539/jas.v6n6p176
170. Ray AJ, Lotz JM. Shrimp (*Litopenaeus vannamei*) production and stable isotope dynamics in clear-water recirculating aquaculture systems versus biofloc systems. *Aquac Res*. 2017;48(8):4390-4398. https://doi.org/10.1111/are.13262
171. Scopel BR, Schveitzer R, Seiffert WQ, et al. Substituição da farinha de peixe em dietas para camarões marinhos cultivados em sistema bioflocos. *Pesqui Agropecuária Bras*. 2011;46(8):928-934. https://doi.org/10.1590/S0100-204X2011000800020
172. Bauer W, Prentice-Hernandez C, Tesser MB, Wasielesky W, Poersch LHS. Substitution of fishmeal with microbial floc meal and soy protein concentrate in diets for the pacific white shrimp *Litopenaeus vannamei*. *Aquaculture*. 2012;342–343:112-116. https://doi.org/10.1016/j.aquaculture.2012.02.023
173. Sousa AA, Pinho SM, Rombenso AN, de Mello GL, Emerenciano MGC. Pizzeria by-product: A complementary feed source for Nile tilapia (*Oreochromis niloticus*) raised in biofloc technology? *Aquaculture*. 2019;501:359-367. https://doi.org/10.1016/J.AQUACULTURE.2018.11.055
174. Jatobá A, Da Silva BC, Da Silva JS, et al. Protein levels for *Litopenaeus vannamei* in semi-intensive and biofloc systems. *Aquaculture*. 2014;432:365-371. https://doi.org/10.1016/j.aquaculture.2014.05.005
175. Panigrahi A, Saranya C, Ambiganandam K, Sundaram M, Sivakumar MR, Kumaraguru vasagam KP. Evaluation of biofloc generation protocols to adopt high density nursery rearing of *Penaeus vannamei* for better growth performances, protective responses and immuno modulation in biofloc based technology. *Aquaculture*. 2020;522:735095. https://doi.org/10.1016/j.aquaculture.2020.735095
176. Ayipio E, Wells DE, Smith M, Blanchard C. Performance of greenhouse-grown beit alpha cucumber in pine bark and perlite substrates fertigated with biofloc aquaculture effluent. *Horticulturae*. 2021;7(6):144. https://doi.org/10.3390/HORTICULTURAE7060144
177. Pinho SM, Lima JP, David LH, et al. Decoupled FLOCponics systems as an alternative approach to reduce the protein level of tilapia juveniles' diet in integrated agri-aquaculture production. *Aquaculture*. 2021;543:736932. https://doi.org/10.1016/j.aquaculture.2021.736932
178. Saseendran S, Dube K, Chandrakant MH, Babitha Rani AM. Enhanced growth response and stress mitigation of genetically improved farmed Tilapia in a biofloc integrated aquaponic system with bell pepper. *Aquaculture*. 2021;533: 736200.
179. Zidni II, Buwono ID, Mahargyani BP. Water Quality in the Cultivation of Catfish (Clarias gariepinus) and Nile Tilapia (Oreochromis niloticus) in the Aquaponic Biofloc System. *Asian J Fish Aquat Res*. 2019;1–6. https://doi.org/10.9734/ajfar/2019/v4i230048

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APPENDIX I.

Overview of FLOCponics papers

Reference	Animals species	Plant species	Objective	Main outcomes
Barbosa[146]	Tilapia (*Oreochromis niloticus*)	†Two varieties of lettuce (*Lactuca sativa L.*)	Evaluate the effect of using filters (mechanical and biological) on the production of lettuce and tilapia in FLOCponics during two 14-day trials.	The use of filters interconnecting the BFT and hydroponics subsystems did not affect plant growth in the first trial, while in the second their use benefited plant growth by reducing the amount of solids in the lettuce roots.
Blanchard et al.[122]	Tilapia (*Oreochromis niloticus*)	†Cucumber (*Cucumis sativus L. 'Delta Star'*)	Determine the effects of pH (5, 5.8, 6 and 7) on nutrient concentrations in water and leaves and cucumber growth in a decoupled FLOCponics system with minimal solids removal during two seasonal 60-day trials	Availability of macro- and micro-nutrients were affected by pH levels. However, they did not have a practical effect on cucumber growth rate over the two growing seasons. Elemental analysis of leaf tissues was within the recommended ranges even though nutrient concentrations in the BFT effluent would be considered low compared to hydroponic solutions.
Castilho-Barros et al.[167]	Pacific white shrimp (*Litopenaeus vannamei*)	*Sarcocornia ambigua*	Perform a commercial-scale economic assessment by using a theoretical model to evaluate marine FLOCponics production in Brazil.	The economic indices showed that the integrated production of shrimp and *S. ambigua* in FLOCponics is economically viable for the specific conditions evaluated.
Castro-Castellón et al.[136]	African cichlid (*Melanochromis sp.*)	Cherry tomato (*Lycopersicon esculentuim var. cerasifonne*)	Evaluate four different carbon sources (coffee, moringa, macroalgae and yucca) on plant and fish production in the FLOCponics system for 120 days.	Fish and tomato produced using coffee and moringa were the ones that presented greater lengths and weights, respectively.
Castro-Mejía et al.[135]	Tilapia (*Oreochromis niloticus*)	Coriander (*Coriandrum sativum*), Dill (*Anethum graveolens*), Parsley (*Petroselinum crispum*)	A preliminary evaluation of tilapia and aromatic plants production in the FLOCponics system for 160 days.	Preliminary insights about the management and production of aromatic plants in FLOCponics.
Doncato and Costa[124]	Pacific white shrimp (*Litopenaeus vannamei*)	†*Sarcocornia neei Lag.*, *Apium graveolens L.*, *Paspalum vaginatum Sw.*	Evaluate the effects of micronutrient supplementation, directly in the water and by foliar spraying, on the growth and biomass production of different halophyte plants in saline FLOCponics.	Water from a FLOCponics system provides the required micronutrients for *S.neei* growth. Micronutrient supplementation in water positively affected the concentrations of iron, manganese and molybdenum, and increased *P. vaginatum* growth. Due to the poor development of *A. graveolens*, the responses to micronutrient additions were not evaluated. Foliar spraying was not effective in improving halophyte growth.

(Continues)

APPENDIX 1 (Continued)

Reference	Animals species	Plant species	Objective	Main outcomes
Fimbres-Acedo et al.[133,134]	†Tilapia (*Oreochromis niloticus*)	†Lettuce (*Lactuca sativa*), pak-choi (*Brassica rapa subsp. Chinensis*), rocket (*Eruca sativa*), basil (*Ocimum basilicum*), spinach (*Spinacia oleracea*)	Evaluate the production of five plant species in different biofloc trophic levels (chemotrophic, heterotrophic and photoautotrophic) in decoupled FLOCponics.	The effluents generated in BFT culture at different trophic levels were able to produce all tested plant species. Pak-choi was the more suitable for heterotrophic BFT effluents, while rocket and basil for chemotrophic and photoautotrophic effluents.
Lenz et al.[140]	Tilapia (*Oreochromis niloticus*)	†Three varieties of lettuce (*Lactuca sativa L.*)	Evaluate the use of effluents from brackish BFT (3 ppm) for the production of lettuce in FLOCponics for 28 days.	The yield of lettuces grown in freshwater FLOCponics was higher than in brackish water. Crisp and red varieties showed tolerance to salinity, which did not occur with the smooth variety. In relation to plant visual characteristics, red variety produced in brackish FLOCponics had the highest score, presenting leaves with higher integrity and intense coloration.
Martinez-Cordova et al.[148]	†Tilapia (*Oreochromis niloticus*)	†Jalapeño pepper (*Capsicum annum*)	A preliminary comparation of tilapia-pepper production in FLOCponics and aquaponics system for 56 days. Additionally, the final effluent of both systems were used to fertilizer a soil-based culture of bell pepper.	The productive performance of tilapia was better in biofloc-based tanks. For the peppers, no differences in plant yield were observed between the evaluated systems.
Martínez-Meingüer et al.[137]	†Tilapia (*Oreochromis niloticus*)	†Tomato (*Lycopersicon esculentum*)	A preliminary evaluation of the use of two commercial diets and extra fertilizer to produce tilapia and tomato in the FLOCponics system for 140 days.	The use of extra fertilizer and the diet with 35% of crude protein (CP) resulted in higher tomato growth. For fish production, higher tilapia weight was found when fed with 35% of CP and no use of fertilizer.
Neto[126]	†Pacific white shrimp (*Litopenaeus vannamei*)	†*Sarcocornia ambigua*	Assess the FLOCponics production of *S. ambígua* and *L. vannamei* under different ratios of feed per m² of plant (50 and 100 g per m²) and its influence in the quality of the culture's water and in the productive performance of the cultivated organisms.	The proportion of 50 g feed per m² of plants was recommended for the FLOCponics production, as it resulted in higher final biomass of *S. ambigua* compared to 100 g feed per m². In addition, the growth of shrimp did not differ between the proportions of feed tested.

(Continues)

APPENDIX 1 (Continued)

Reference	Animals species	Plant species	Objective	Main outcomes
Pickens et al.[123]	Tilapia (*Oreochromis niloticus*)	†Cherry tomato cvs. “Favorita” and “Goldita” (*Solanum lycopersicumva r.cerasiforme*)	Evaluate the FLOCponics effluent as a nutrient solution for cherry tomato culture and compare its production with a hydroponics system, before and after fish harvest.	Before fish harvest, few differences in plant yield were observed between those produced in FLOCponics or hydroponics for the cherry tomato ‘Favorita’, while differences were seen between treatments for the tomato ‘Goldita’ with greater results in hydroponics system. After fish harvest, both cultivars grew better in the hydroponics system. Low concentration of nutrients were seen in FLOCponics effluents, despite no visual symptoms of nutrient deficiencies being observed throughout the experiment.
Pinheiro et al.[113]	†Pacific white shrimp (*Litopenaeus vannamei*)	†*Sarcocornia ambigua*	Evaluate the use of nitrogen and production of the halophyte *S. ambigua* and shrimp in a FLOCponics system compared to shrimp reared in BFT, as well as the antioxidant activity and total phenolic compounds in plants.	The integration of shrimp and *S. ambigua* production improved the use of nitrogen in the system and did not affect shrimp growth. The results also showed that *S. ambigua* culture in FLOCponics may be a promising source of natural antioxidants for human consumption.
Pinheiro et al.[78]	†Pacific white shrimp (*Litopenaeus vannamei*)	†*Sarcocornia ambigua*	Evaluate the relation of water salinity (8, 16, 24 and 32 psu) in the productive performance of Pacific white shrimp and *S. ambigua* cultured in a FLOCponics system.	The salinity between 16 and 24 psu was recommended for the integrated production of *L. vannamei* and *S. ambigua* in FLOCponics, since the performance of the shrimp was not impaired, and the growth of the plants and the removal of nitrogen and phosphate compounds were favoured in this salinity range.
Pinho et al.[117]	Tilapia (*Oreochromis niloticus*)	†Three varieties of lettuce (*Lactuca sativa L.*)	Assess the use of BFT effluent to nourish three varieties of lettuce (red crispy, butter and crispy) produced in FLOCponics during a 21-day period compared to those grown in traditional aquaponics.	The productive performance of lettuce cultured with BFT effluent was better than in traditional aquaponics. Regarding the lettuce varieties tested, butter lettuce presented the best growth results.
Pinho et al.[48]	†Tilapia (*Oreochromis niloticus*)	†Lettuce (*Lactuca sativa L.*)	Compare the productive parameters of Nile tilapia juveniles and butter lettuce grown in FLOCponics to those grown in a traditional aquaponics system during two 23-day trials.	The visual characteristics and growth performance of lettuce grown in FLOCponics were lower than those grown in traditional aquaponics, mainly in the second trial. The zootechnical performance of the tilapia juveniles was better in FLOCponics.

(Continues)

APPENDIX 1 (Continued)

Reference	Animals species	Plant species	Objective	Main outcomes
Poli et al.[114]	Tilapia (*Oreochromis niloticus*) and pacific white shrimp (*Litopenaeus vannamei*)	*Sarcocornia ambigua*	Evaluate the water quality parameters and production of an integrated multitrophic aquaculture (IMTA) system applied to shrimp, tilapia and *Sarcocornia ambigua* in FLOCponics compared to a polyculture of shrimp and tilapia in BFT.	The IMTA in the FLOCponics system resulted in a higher yield of all products than in BFT. However, the presence of *S. ambigua* did not affect nitrogen and phosphorus use, despite reducing the amount of nitrate.
Rahman[121]	Tilapia (*Oreochromis niloticus*)	†Lettuce (*Lactuca sativa L. 'Charles'*)	Compare the production of lettuce nourished by BFT effluent without solids management, BFT effluent with solids management, and commercial hydroponic solution during four 28-day trials.	Plants cultured with a commercial hydroponics solution grew better than those in FLOCponics systems. The presence of suspended solids was a limiting factor for lettuce growth.
Rocha et al.[112]	† Silver catfish (*Rhamdia quelen*)	† Lettuce (*Lactuca sativa L.*)	Evaluate the production of *L. sativa* in hydroponics, traditional aquaponics, and FLOCponics using minimum infrastructure during a 46-day period.	The use of silver catfish effluent to nourish lettuces, in traditional aquaponics and FLOCponics, improved their growth when compared to those produced in hydroponics.
Silva[125]	Pacific white shrimp (*Litopenaeus vannamei*)	†*Sarcocornia ambigua*	Evaluate the production of phenolic compounds and antioxidant activity of *S. ambigua* exposed to different periods of water stress, that is, irrigation periods of 6, 12, 18 and 24 h per day, in a FLOCponics system.	*S. ambigua* cultured with 12 h of daily irrigation resulted in higher production of bioactive compounds without affecting the productivity of plants and shrimp.
Zidni et al.[179]	Catfish (*Clarias gariepinus*) and tilapia (*Oreochromis niloticus*)	Water spinach	Determine the effect of different proportions of catfish and tilapia densities on water quality when integrated with water spinach production in a FLOCponics system.	The results presented were not sufficient to show a relationship between fish densities and water quality.

† Main product focused on the experiment.