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Original Articles

Assessing the sustainability of tilapia farming in biofloc-based culture using emergy synthesis

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ABSTRACT

Biofloc technology (BFT) has been called an environmentally friendly aquaculture approach. The sustainable characteristics of biofloc-based culture are usually linked to the efficient use of water and nutrients and the minimal discard of effluent to the environment. Given the scarcity of sustainability assessment of biofloc-based systems, it is still unclear whether the positive characteristics of BFT make it a real sustainable approach for aquaculture. This study aimed to investigate and apply the emergy synthesis to assess the sustainability of commercial Nile tilapia fingerlings production in a biofloc-based system. The tilapia fingerlings produced on the BFT farm showed a UEV of 2.04E + 03 sej/J, renewability of 32.73%, EYR of 1.00, EIR, and ELR of 2.05, and ESI of 0.49. Compared to other aquaculture systems, the evaluated BFT farm presented emergy indicators with values characteristic of potentially sustainable production. Electricity has the highest representativeness in the emergy input, making the system dependent on resources from the larger economy. The low UEV indicates that the BFT farm is efficient in terms of converting the invested emergy into the system's output (tilapia fingerlings). A sensitivity analysis shows that replacing the hydroelectric source of electricity with photovoltaic will not improve the emergy performance of the evaluated BFT farm.

1. Introduction

Aquaculture has been the fastest-growing food production activity in recent years, but there are many concerns about how sustainable this rapid expansion has been (Custódio et al., 2020; FAO, 2020). This is because aquaculture has been based mostly on monoculture, generally depending on large volumes of water, high quantities of fishmeal for manufacturing feed, and extensive land areas to obtain high productivity (Rodrigues et al., 2019; Boyd et al., 2020). Additionally, the inadequate discard of aquaculture waste in the environment may cause negative impacts, such as soil and water contamination, pathogen transmission, and eutrophication of water bodies. These environmental issues harm the sustainability of aquaculture (Verdegem, 2013; Boyd et al., 2020). As a solution to these problems and aiming at a sustainable development of aquaculture, biofloc-based systems have been proposed (Bossier and Ekasari, 2017).

Biofloc technology (BFT) is an aquaculture production method initially created to solve problems with diseases spread in shrimp culture (Browdy et al., 2012; Treece, 2019). Recently, BFT has also been successfully applied to culture tilapia (*Oreochromis* sp.) (Pinho et al., 2021a; Emerenciano et al., 2021), one of the most produced fish species in the world (FAO, 2020). The operational concept of BFT aims at preventing the accumulation of toxic nitrogen levels by the growth of specific microorganisms in fish tanks (Verdegem and Bosma, 2009; Crab et al., 2012; Avnimelech, 2015). BFT is usually run in a closed system setup, with minimal water and nutrient discharge, and no need for complex filters. For this purpose, the conversion of nitrogen into microbial biomass occurs by providing sufficient aeration and manipulating the carbon:nitrogen (C:N) ratio of the water (Crab et al., 2012; Hargreaves, 2013). The microbial community of BFT recycles the nutrients, maintains good water quality, and serves as an *in situ* complementary food for cultivated animals (Hargreaves, 2013; Correa et al., 2020; Sgnaulin et al., 2020; Wasielesky et al., 2020).

Over the last decades, BFT has been seen as an environmentally

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friendly aquaculture approach (Emerenciano et al., 2013; Bossier and Ekasari, 2017). The sustainable characteristics of biofloc-based culture are usually linked to the efficient use of water and nutrients to intensively produce shrimp and/or fish and the minimal discard of effluent to the environment (Burford et al., 2004; Avnimelech, 2015). The low dependence on water makes BFT a promising alternative for aquaculture production in temperate, arid, and urban areas (Browdy and Moss, n.d.). Additionally, a biofloc-based system in closed environments avoids cultivated species from escaping and the spread of diseases (Rego et al., 2017). Another positive aspect of BFT is the constant availability of microbial flocs as supplementary food, reducing the feed conversion ratio and the dependence on feed (Emerenciano et al., 2013; Avnimelech, 2015). As a result, an increase in growth and survival of tilapia compared to recirculating aquaculture system is achieved (Azim and Little, 2008; Luo et al., 2014; Brol et al., 2017; Pinho et al., 2021a)

The aforementioned benefits of BFT require, on the other hand, an appropriate infrastructure and level of support services. For example, the need for specialized labor, permanent water quality monitoring, and the dependence on electricity to maintain appropriate aeration and water movement are usually reported as drawbacks of biofloc-based production (Walker et al., 2020). A holistic understanding of the BFT operation and microbial interactions and how to maintain the water parameters suitable for each target cultured species are highly needed to profitably run the system (Dauda et al., 2019). All these factors generate doubts about the real sustainability and ecosystem efficiency of BFT, making it necessary to use reliable methods that evaluate the sustainable performance of this technology (David et al., 2020).

Sustainability assessments are essential tools to assist in formulating public policies, pointing out the problems, and indicating alternative practices aimed at sustainable aquaculture (Aubin et al., 2019). Thus, over the last few years, emergy synthesis has been used to measure the sustainability of different aquaculture systems (David et al., 2020). Emergy synthesis is a method that allows measuring the direct and indirect energy required to make a product and/or sustain a system (Odum, 1996). Moreover, this assessment can incorporate environmental, social, and economic aspects into a common unit of measure (solar emjoule), providing indicators to estimate efficiency and sustainability throughout the production process (Odum, 1996; Brown and Ulgiati, 2004). Given the scarcity of studies that measure the sustainability of biofloc-based systems, it is still unclear whether the positive characteristics of BFT make it a real sustainable approach for aquaculture. To answer this question, this study aimed to investigate and apply the emergy synthesis to assess the sustainability of a biofloc-based culture in a commercial BFT farm that produces Nile tilapia fingerlings as a case study. In addition, we identified management options that possibly harm the sustainability of the commercial biofloc-based farm and propose alternative strategies using sensitivity analysis.

2. Methods

2.1. Farm description

The study aimed to assess the sustainability of a commercial BFT farm of Nile tilapia fingerlings (*Oreochromis niloticus*) in the city of Sales Oliveira, São Paulo State, Brazil (20°46′12.3″S; 47°50′26.6″W). The scope boundaries of the BFT system are defined in the diagram presented in Fig. 1. The diagram was designed following the methodology proposed by Odum (1996). Data concerning the investment in infrastructure, productive performance, inputs and outputs of the production, and information about the operation of the system, were obtained by administering a questionnaire, measurements in the field, and observation by the authors. All data collected correspond to one year of

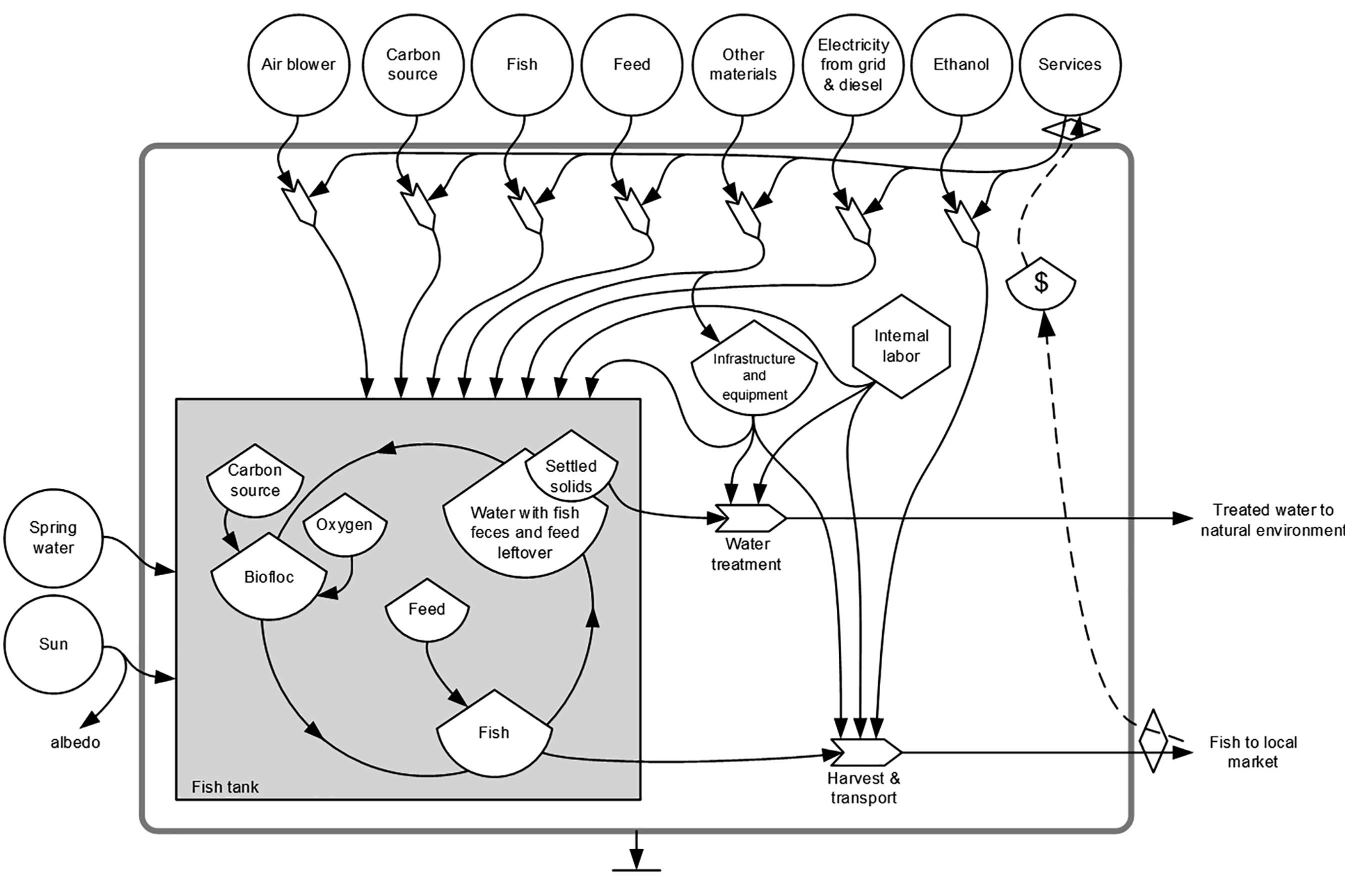

Fig. 1. Energy diagram of the biofloc-based system to produce Nile tilapia fingerlings.

production (Table 1).

The productive structure of the farm was installed within a greenhouse covered with a shading net to reduce luminosity. The BFT system consisted of 10 production tanks, with a volume of 50 m^3 each. Aeration was provided continuously by a traditional air blower and distributed in the tanks by micro-perforated diffusers to promote constant oxygenation and horizontal and vertical movement of the water. The water supply used in the entire production process comes from a river. The annual volume of 800 m^3 water required for the initial filling of all tanks was considered, plus replacement of water by loss evaporation and the discard of 5 m^3 of effluent due to the solid accumulation and discharge. As the farm carried out the production cycles with low or zero water renewals, the volume of bioflocs (solids) tends to increase in the fish tank. The accumulation of solids is even more evident when the growth of the bioflocs' microorganisms is greater than the rate of their consumption by the fish. Management through removal of solids is needed to avoid deterioration of the water quality in the tanks, mainly depletion of dissolved oxygen (Crab et al., 2012). The recommended volume of bioflocs (measured using Imhoff cone) for tilapia fingerlings is between 5 and 20 mL/L (Emerenciano et al., 2017). When the concentration exceeds this range, solids removal must be carried out. The most used strategy to control the high volume of bioflocs in fish tanks is using external clarifiers to remove the settled solids (Gaona et al., 2016). The BFT farm started to use the clarifiers when the volume of bioflocs exceeded 20 mL/L.

The electricity used on the farm to support aeration and heating of the system comes from a hydroelectric plant. Heating was used in the tilapia masculinization process to maintain the water temperature at around 35 °C. After this process, the heater was only needed when the water temperature was lower than 27 °C. The farm had an electricity generator as a backup for eventual power failures. This equipment used diesel as fuel and was automatically activated in cases of power failure to keep the aeration system running. Ethanol was the fuel used in vehicles to transport inputs and products.

The fish tanks were stocked with tilapia fingerlings with an average weight of 1 g. When the fish reached the weight of approximately 5 g, they were harvested and commercialized to farmers who produce tilapia in ponds or cages. Tilapia production in the fingerling phase has become usual in biofloc-based systems as it provides benefits, such as better feeding management, reduction of the spread of diseases, maintenance of good water quality parameters, and an increase in the number of cycles per year (Sgnaulin et al. 2020; Pinho et al., 2021b). The emergy input of tilapia was not accounted for in the synthesis since fish with such low weight (1 g) would certainly have low embodied emergy, and thus, the input of it was considered negligible.

Three different types of feed were used during one production cycle. The dietary protein concentration decreased during fish growth. Feed 1 was a micro-extruded feed from the Bernaqua brand, it contained 57% of crude protein (CP), and 100 kg were used per cycle in the evaluated period. Both Feeds 2 and 3 were extruded feeds from the Nutripiscis Neovia brand, they contained 45% CP, and they differed only in the pellet size (0.8 mm for Feed 2 and 1.3 mm for Feed 3), 500 kg and 800 kg of each feed were used per cycle, respectively. The farm operated a mature BFT system, i.e., the biofloc community was already established, at a C:N ratio of 15:1. Consequently, during the evaluated year, the addition of sugar cane as a carbon source depended on the concentration of ammonia in the water of each fish tank, corresponding to approximately 10% of the total amount of feed (700 kg). The carbon source (sugar cane) was used to maintain the biofloc community.

The labor activities carried out at the BFT farm were fish stocking, fish feeding, periodic biometrics, harvesting, water quality monitoring, and general cleaning of the system. These activities were performed by 5 employees who dedicated 8 h per day to operate the system manually.

Table 1
Technical and economic characteristics of the production of Nile tilapia fingerlings in the evaluated BFT farm.

Item	Unit	Value
Area	m^2	908
Water initial supply	m^3/year	500
Water replacement	m^3/year	300
Electricity consumption	kWh/year	114,000
Initial average weight of fish	g/fish	1
Final average weight of fish	g/fish	5
Cycle	unit/year	5
Fish produced	unit/year	1,500,000
Carbon source (sugar)	kg/year	700
Feed	kg/year	7000
Feed conversion ratio	–	1.2
Taxes and fees	US$/year	1750
Fuel (ethanol)	L/year	1500
Diesel	L/year	500
Effluent discard	L/year	5000
Human labor	h/day	8
Employees	unit	5

2.2. *Emergy synthesis*

The emergy synthesis' description is given in detail by Odum (1996) and Brown and Ulgiati (2004). The emergy synthesis of a system includes determining the research boundaries, organization of input and output data, determining the emergy baseline, calculating the emergy flow and the emergy indicators. The inputs were listed based on the diagram and classified as Renewable, Non-Renewable, Resources from the larger economy, and Outcomes. All UEVs (Unit Emergy Value) adopted in this study are on the 1.20E + 25 sej/year baseline (Brown et al., 2016). Those originated from an outdated database were converted to this baseline.

Emergy indicators are valuable tools for measuring the ecological and sustainable performance of the system being evaluated. In this study, the partial renewabilities of each input are considered for the calculation of emergy indicators (Agostinho et al., 2008). The inclusion of partial renewabilities is an appropriate approach when the system uses materials and services from the local or regional economy, which could be considered totally or partially renewable. The assumed partial renewability values in this work are based on published scientific papers described in the Supplementary data. Our approach intends to properly evaluate the system sustainability, as suggested by Ortega et al. (2002) and Giannetti et al. (2015). The emergy indicators considered in this study are described below, and their formulas are presented in Table 2.

The Unit Emergy Value (UEV) is the quantity of energy embodied in the product. It measures the amount of energy used to generate a certain amount of energy. This indicator assesses the ecosystem efficiency. The lower the UEV, the higher the system efficiency. Renewability (%R) is the proportion of renewable resources in the total emergy used. It indicates the degree of sustainability of a productive system. Emergy Yield Ratio (EYR) is the relation between the total emergy and the emergy resources from the larger economy. This ratio measures how much an investment enables a process to exploit local resources to further

Table 2
Formulas of the emergy indicators used in the evaluation.

Indicator		Formula
UEV	Unit Emergy Value	Emergy/Output
%R	Renewability	100*(R + Mr + Sr)/Y
EYR	Emergy Yield Ratio	Y/F
EIR	Emergy Investment Ratio	(Mn + Sn)/(R + N + Mr + Sr)
ELR	Environmental Loading Ratio	(N + Mn + Sn)/(R + Mr + Sr)
ESI	Emergy Sustainability Index	EYR/ELR

R: renewable natural resources; N: non-renewable natural resources; F: Resources from the larger economy; Mr: renewable materials; Mn: non-renewable materials; Sr: renewable services; Sn: non-renewable services; Y: total emergy. The lowercase letters r and n mean, respectively, renewable and non-renewable fractions of material and services.

contribute to the economy. Emergy Investment Ratio (EIR) evaluates how the ecosystem responds to the emergy invested from the economy. It allows comparing alternatives that use the same natural resource. The environmental loading ratio (ELR) measures the pressure that the system exerts on the environment. A value below 2 indicates low pressure, values from 2 to 10 a moderate pressure, and values above 10 indicate a high pressure on the ecosystem. The emergy sustainability index (ESI) is the ratio between the emergy yield ratio and the environmental loading ratio. It measures the potential contribution of a resource or process to the economy per unit of environmental loading.

As well as food provision, aquaculture also generates ecosystem services and disservices (ES&D). As the ES&D are usually important aquaculture production co-products, they must be accounted for in the emergy synthesis (David et al., 2020). In this study, we use the list published by Aubin et al. (2019) to identify if the BFT farm provided ecosystem services and the disservices according to Zhang et al. (2007) and Shah et al. (2019).

2.3. Sensitivity analysis

Sensitivity analysis allows simulating the replacement of different types of management that will potentially make the system more efficient and sustainable (Häyhä et al., 2011; Li et al., 2011). According to Walker et al. (2020), the high electricity demand for aeration, water movement (to keep the bioflocs in suspension), and water pumping certainly limit the BFT system implementation. Moreover, aquaculture systems that are highly dependent on non-renewable resources tend to be unsustainable over time (David et al., 2020). In Brazil, among other sources such as wind and biomass sources, photovoltaic electricity is known as a sustainable alternative source to replace electricity from hydroelectric and thermoelectric. Considering that photovoltaic panels are an alternative electricity source, applicable for small-scale farms (as the one assessed in this study), we evaluated the operation of the BFT farm using photovoltaic electricity.

3. Results

The BFT farm used 3.20E + 14 sej/m^2/year to produce 6000 kg/m^2/year of tilapia fingerlings (Table 3). Resources from the larger economy had higher emergy demand, represented mainly by electricity (57.5%) and infrastructure and equipment (28.9%). No ecosystem service promoted by this farm was identified. On the other hand, the ecosystem disservice for the effluent treatment by a biodigester was accounted for. The emergy indicators of the BFT farm are presented in Table 4. The sensitivity analysis shows that replacing the source of electricity from hydroelectric by photovoltaic reduced the emergy demand and the UEV by 78% (Table 4). However, the other indicators were negatively affected when simulating the use of photovoltaic electricity.

4. Discussion

This study applied emergy synthesis to assess the sustainability of commercial production of Nile tilapia fingerlings (1 to 5 g) in a BFT farm. It is important to emphasize that all results and points of discussion are specific to the evaluated farm and its management. Although each production has its particularities, the evaluated farm manages and employs structures well accepted and adopted in the BFT field. Moreover, we present the first emergy synthesis of a production system using BFT and give relevant insights to discuss its general sustainable character.

Unlike most aquaculture systems assessed by emergy synthesis (Cavalett et al., 2006; Shi et al., 2013; Garcia et al., 2014; David et al., 2018), the feed was not the most representative item in the synthesis of the BFT farm. Such low representativity of the feed is probably due to the low amount of feed usually needed in this production phase (Brol et al., 2017) and also a result of the biofloc uptake by tilapia fingerlings

Table 3
Emergy synthesis of the biofloc commercial farm of Nile tilapia fingerlings.

Note	Item	Unit	Amount (unit/m^2 yr)	UEV (sej/unit)	Emergy (sej/m^2 yr)	Emergy (%)*
Renewable resources (R)						
1	Sun	J	1.67E + 07	1.00E + 00	1.67E + 07	<0.1
2	Springwater	m^3	8.81E + 02	3.27E + 05	2.88E + 08	<0.1
Total (R)					3.05E + 08	
Non-renewable resources (N)						
	None	–	–	–	–	
Resources from the larger economy (F)						
	Renewable materials (Mr)					
3	Electricity	J	8.54E + 08	1.12E + 05	9.56E + 13	**29.9**
4	Ethanol	L	3.11E + 04	4.80E + 04	1.49E + 09	<0.1
5	Carbon source	kg	2.54E-01	4.87E + 12	1.24E + 12	0.4
6	Iron	g	7.88E + 02	3.56E + 09	2.80E + 12	0.9
7	Sand	g	3.00E + 03	1.70E + 09	5.09E + 12	1.6
	Non-renewable materials (Mn)					
8	Electricity	J	4.02E + 08	2.20E + 05	8.84E + 13	**27.6**
9	Ethanol	L	1.32E + 05	4.80E + 04	6.36E + 09	<0.1
10	Diesel	J	1.98E + 07	4.59E + 03	9.10E + 10	<0.1
11	Feed	J	1.02E + 08	9.96E + 04	1.12E + 05	<0.1
12	Carbon source	kg	5.17E-01	4.87E + 12	2.52E + 12	0.8
13	Iron	g	4.63E + 02	3.56E + 09	1.65E + 12	0.5
14	Sand	g	1.25E + 03	1.70E + 09	2.13E + 12	0.7
15	Concrete	g	4.31E + 03	1.38E + 09	5.93E + 12	1.9
16	Pipes	g	2.65E + 03	4.19E + 09	1.11E + 13	3.5
17	Plastic	g	9.73E + 00	4.19E + 09	4.08E + 10	<0.1
	Renewable services (Sr)					
18	Human labor	J	2.76E + 00	3.27E + 06	9.03E + 06	<0.1
	Non-renewable services (Sn)					
19	Infrastructure and equipment	$	1.65E + 01	5.60E + 12	9.25E + 13	**28.9**
20	Human labor	J	3.33E + 04	3.27E + 06	1.09E + 11	<0.1
21	Taxes and fees	$	1.93E + 00	5.60E + 12	1.08E + 13	3.4
	Ecosystem disservices (D)					
22	Effluent treatment by the biodigester	g	8.96E + 00	4.19E + 09	3.75E + 10	<0.1
Total (N + F)					3.20E + 14	
Total emergy (Y) (Y = R + N + F + D)					3.20E + 14	
Output (O)						
23	Fish fingerlings	J	1.57E + 11			

* The items that had the highest representativeness in the emergy flow are highlighted in bold.

Table 4
Emergy indicators for the Nile tilapia fingerlings production in a BFT farm and a sensitivity analysis replacing the electricity from a hydroelectric with a photovoltaic source.

Indicator	Original	Photovoltaic electricity
Total emergy (sej/m^2/yr)	3.20E + 14	2.50E + 14
UEV (sej/J)	2.04E + 03	1.59E + 03
%R (%)	32.73	3.65
EYR	1.00	1.00
EIR	2.05	26.38
ELR	2.05	26.38
ESI	0.49	0.04

UEV: Unit Emergy Value; %R: Renewability; EYR: Emergy Yield Ratio; EIR: Emergy Investment Ratio; ELR: Emergy Loading Ratio; ESI: Emergy Sustainability Index.

as a complementary food source (Pinho et al., 2021b). Keeping the bioflocs available in the fish tank requires input from other energy sources. Thus, electricity was the item with the greatest representativeness in the emergy input, making the system dependent on resources from the larger economy (Table 3). Electricity is usually generated by non-renewable sources (e.g., hydroelectric and thermoelectric). The high electricity consumption from these sources by the BFT farm is the key factor that makes its sustainability questionable.

High demand for infrastructure was also found (Table 3). It was an expected result since BFT systems need a controlled environment with efficient hydraulic and electrical systems (Martínez-Córdova et al., 2016). This infrastructure comprises mainly plastic and other materials with a short useful life and low renewability, increasing the system's emergy demand. Moreover, the high need for equipment to control the operational parameters of the system, especially water quality, is another factor that contributes to the high emergy input. The need for constant water quality control is due to increased organic load and nutrient concentration in the water and the high demand for oxygen and water alkalinity by the biofloc microbial community (Emerenciano et al., 2017). Thus, to enable the bioflocs uptake by tilapia fingerlings as a complementary food source, high emergy for electricity and infrastructure is required, and thus clearly shows the trade-off between feed and electricity.

One of the main characteristics of biofloc-based production is the low water footprint due to the minimal dependence on water replacement and effluent discharge (Jatobá et al., 2019). However, in the emergy synthesis method, the source and quality of the water that returns to the environment affect the system's sustainability results more than the volume of water used (David et al., 2020). As the evaluated farm did not perform any treatment on the discharged effluents/solids, it was considered a disservice. To account for and solve this disservice, we included a device for solids treatment (biodigester) in the synthesis. Another possible alternative to mitigate this disservice could be using the nutrient-rich solids for other purposes, such as an ingredient in fish/shrimp diets (Neto et al., 2015; Shao et al., 2017) or plant fertilizer (Legarda et al., 2019). In general, the BFT farmer could improve the management of the exceed settled solids (bioflocs biomass) to obtain a better emergy performance, and consequently a more sustainable production. That means not discharging the effluent/solids or at least treating them to return to the environment with the same or better quality as the inputted water.

The emergy indicators resulting from the BFT farm assessment are characteristic of potentially sustainable production systems. The low UEV found indicates that the BFT system used by the evaluated farm is efficient in the production of tilapia fingerlings in terms of converting the invested emergy into the system's outputs. The BFT system seems to be even more efficient when compared to traditional production systems such as cages, also recognized as intensive aquaculture system. Other authors found UEV of 2.82E + 05 sej/J to produce tilapia in cages located in a reservoir (David et al., 2018) and 1.35E + 06 sej/J in hydroelectric reservoirs (Garcia et al., 2014). Both values are much higher than the UEV found in the present study (2.04E + 03 sej/J). This higher efficiency may be related to the nutrients recycling by the bioflocs microorganisms and their uptake by tilapia fingerlings. Consequently, the fish usually grow faster in BFT, enabling consecutive productive cycles per year and less feed per fish kg (Avnimelech, 2015; Walker et al., 2020). It is important to note that Garcia et al. (2014) and David et al. (2018) evaluated tilapia production in the grow-out phase (from 40 to 800 g), different from the BFT farm evaluated in this study that reared tilapia from 1 to 5 g. The production of fish in the grow-out phase implies a higher use of resources, such as feed, for a longer period. However, the fish output should be proportional to this higher resource input. Thus, despite the difference between the evaluated production phases, the comparison mentioned above seems fair.

Accounting for the renewable fraction of all the inputs used in the system allowed us to reach precise values of the emergy indicators, mainly renewability. The use of resources with high renewable fractions, such as electricity from a hydroelectric plant, guaranteed high renewability for the BFT farm. This result indicates that the system has a high chance of staying in operation over time (Lefroy and Rydberg, 2003). The system renewability can reach values even higher mainly if management that aims at replacing the non-renewable or low-renewability inputs with renewable or high-renewability resources is applied. Considering the renewable fraction of the inputs for the emergy indicator calculations is a new approach for emergy synthesis of aquaculture systems, we encourage it to be also used in further studies. Due to the methodological differences adopted by previous studies and the present study, except for the UEV, the other emergy indicators presented here are not comparable to the other papers published so far (Vassallo et al., 2009; Garcia et al., 2014; Cheng et al., 2017; David et al., 2018).

Despite the high renewability, the EYR confirms that most of the BFT farm's inputs were resources from the larger economy. One of the issues that these findings points out is that the BFT farm is highly susceptible to market variations and resource availability over time. The same value found for EIR and ELR is related to the non-inclusion of non-renewable resource items in the emergy synthesis (Odum, 2001). The EIR suggests that the amount of renewable resources used by the BFT farm was low compared to non-renewable resources. The EIR indicates that the evaluated farm was not efficient in using local resources. All these results highlight the need to develop new techniques or products applicable to BFT systems to reduce the use of resources from the larger economy. For ELR, the low value (~2) suggests that the BFT production process generated a low pressure on the environment. In contrast, ESI (0.49) shows that despite the low environmental load, the impact of the production process on the economy was low in relation to the environmental stress generated.

Replacing the electricity from a hydroelectric source with photovoltaic did not improve the overall emergy performance of the BFT farm as expected beforehand. Despite reducing the emergy demand and the UEV of the system and not changing the EIR, all other indicators worsened after replacing hydroelectric by photovoltaic sources. The reduction in renewability was due to the need for a large amount of materials with a low renewable fraction in the manufacture of solar panels, such as photoactive materials, glass, and steel. Furthermore, adopting the photovoltaic as the primary source of electricity excludes the electric input from hydroelectricity, which has a high renewable fraction (68%) and helped in the high renewability (32.7%) of the original assessment. The unchanged EYR in the simulated scenario indicates that even replacing the electricity from hydroelectric by photovoltaic, the resources from the larger economy still play an essential role in the BFT farm. The environmental load generated by the system also increases by the adoption of solar panels, a result verified by the high ELR. The ELR result suggests that the BFT farm when using photovoltaic as an electricity source ceases to be similar to a natural production process and becomes comparable to industrial systems (Brown and Ulgiati, 2004). In addition, the reduction in ESI (from 0.44 to 0.03) clearly shows that the environmental load of the simulated BFT farm is much greater than its economic return. This set of results shows that using photovoltaics as electricity source, labeled as renewable, will not always be the solution to improve the sustainability of BFT. The use of photovoltaic electricity was evaluated because it is recognized as a sustainable alternative available in Brazil (Ferreira et al., 2018; Garlet et al., 2019). Also, a grid-connected solar photovoltaic system could be a feasible option for small-scale farmers. However, we encourage investigations on other renewable electricity generating options for BFT farms, such as wind. This source of electricity has been included in the energy matrix of many countries, such as Brazil (EPE, 2021), due to its considerable thermodynamic efficiency with the lowest UEV among various electricity generation processes (Yang et al., 2013).

It is also crucial to point out that future research should focus on reducing the electricity dependence of BFT instead of only changing the electricity source. Also, research on the use and sustainability of more efficient aerator systems is highly recommended. For example, compressor or centrifugal blowers consume less energy and are up to 60% more efficient in maintaining water oxygenation than traditional air blowers (used in the BFT farm assessed). Other potential means to improve the sustainability performance of BFT systems that must be investigated are reusing the discharged solids to avoid the generation of disservices or even diluting the non-renewable resource input per kg of food produced by integrating it with soil-less plant production in a FLOCponics system (Pinho et al., 2021a).

5. Conclusion

From the point of view of emergy synthesis, BFT used by the farm proved to be efficient for producing tilapia fingerlings. Despite the high use of resources from the larger economy, the emergy indicators showed that the production process has potentially sustainable characteristics, capable of keeping the system running over time. Furthermore, it was observed that the use of photovoltaics as an electricity source did not improve the BFT farm's sustainability.

CRediT authorship contribution statement

Luiz H. David: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Visualization. **Sara M. Pinho:** Methodology, Formal analysis, Investigation, Data curation, Writing – original draft. **Karel J. Keesman:** Writing - review & editing, Supervision, Funding acquisition. **Fabiana Garcia:** Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

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

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Supplementary data

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