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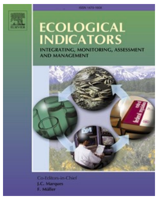

Sustainability assessment of FLOCponics compared to stand-alone hydroponic and biofloc systems using emergy synthesis

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ABSTRACT

FLOCponics is an intensive integrated agri-aquaculture system that combines biofloc-based aquaculture with hydroponics. Since research on FLOCponics is in its early stage of development, and many aspects of this system still need to be explored, the objective of this study was to assess and discuss the sustainability of a FLOCponics system and compare it to stand-alone biofloc and hydroponic cultures. This investigation will lead to a novel perspective of what troubling points need to be covered in the FLOCponics research field before they turn into a commercial scale problem. To do this, we conducted an experiment-based study by applying emergy synthesis to assess the sustainability of tilapia juveniles and lettuce production in FLOCponics, biofloc and/or hydroponic systems. The results indicate that the resources from the larger economy were the inputs that made the greatest contribution in all systems. Overall, most of the emergy indicators are similar for all systems, suggesting that FLOCponics, biofloc and hydroponic systems use low amounts of natural renewable resources, cause a moderate environmental load (EIR and ELR of 3.1 to 3.6), and lead to environmental stress seven times higher than the contribution to the economy (ESI of 0.3). Unit emergy values (UEVs) are different for each system, indicating that, under the evaluated conditions, FLOCponics (UEV: 2.54E + 06 sej/J) is more efficient than hydroponics (UEV: 5.55E + 10 sej/J) and less efficient than a biofloc system (UEV: 1.42E + 06 sej/J). Our findings provide valuable insights regarding the (un)sustainable aspects of FLOCponics and direct further research to improve the system's emergy performance. Based on the emergy performance, FLOCponics can be considered a promising sustainable food production approach, mainly considering that it is a system under development and there are still many opportunities for improvement.

1. Introduction

Integrated Agri-AquaCulture (IAAC) systems have been labelled as sustainable and efficient means of producing food (Boyd et al., 2020; FAO, 2020). The rationale of IAAC is based on recovering the waste of one sub-activity (agriculture or aquaculture) and reuse it as an input for another (Zajdband, 2011). Integrating plant culture with aquatic animal production mainly aims to improve the use of nutrients introduced into the system, optimise water use (see Eslamian et al. (2018) and Ostad-Ali-Askar et al. (2018) for use of water resources under climate change), prevent waste discharge, diversify production, and provide food security for local consumers (Farrant et al., 2021; Lennard and Goddek, 2019). IAAC is an ancient practice used for local and small-scale producers, predominantly in Asia. In the last decades, however, there has been a shift towards modern and intensive IAAC systems to meet the growing demand for sustainable food provision (Edwards, 2003).

FLOCponics is a modern integrated aqua-agriculture system in its initial stage of development (Pinho et al., 2022b). FLOCponics combines the intensive production of aquatic organisms using biofloc technology with vegetable production in hydroponic systems (Kotzen et al., 2019; Pinho et al., 2021a). Biofloc aquaculture systems are based on promoting the growth of specific microbial communities *in situ* in the fish tanks

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to intensify and increase the biosecurity of fish and shrimp production (Avnimelech, 2015; Browdy et al., 2012; Dauda, 2020). The microorganisms are responsible for maintaining water quality and serve as food for the cultivated organisms, decreasing the need for water renewal and the use of commercial feed (Emerenciano et al., 2017; Martínez-Córdova et al., 2017; Mugwanya et al., 2021). Hydroponics is a soilless plant production method. When operated as a stand-alone system, the typical way to supply water and nutrients required by plants in hydroponics is from a balanced nutrient commercial solution (Maucieri et al., 2019). Aiming at improving of its efficiency and reducing the environmental impact of both systems, FLOCponics uses the excess of nutrients from biofloc to nourish hydroponic plants (Emerenciano et al., 2021; Pinheiro et al., 2017; Pinho et al., 2017). In terms of productive results, Pinho et al. (2021b) reported recently that FLOCponics is technically viable and provides similar fish and vegetable growth performance for stand-alone biofloc and hydroponic systems. Contrary to other FLOCponics studies that did not compare FLOCponics to the stand-alone systems (Lenz et al., 2017; Pickens et al., 2020; Pinho et al., 2017; Rocha et al., 2017), Pinho et al. (2021b) presented a robust experimental design to draw such conclusions as they simultaneously evaluated fish and vegetable growth in these production systems under the same climate conditions and using the same type of resources.

Despite having a great potential for improving the use of resources and reducing the environmental impact compared to stand-alone systems, FLOCponics seems to demand several other resources to make the integration feasible. For example, FLOCponics would require a high investment in technology, infrastructure, equipment, and qualified/specialised labour to successfully produce fish and plants (Pinho et al., 2022a). Moreover, the high demand for electricity to maintain constant aeration in biofloc fish-tanks may be an issue in FLOCponics (David et al., 2021b; et al., 2022b; Walker et al., 2020). These drawbacks make the sustainable character of FLOCponics systems an issue that needs to be investigated. Sustainability of food production systems has been investigated using scientifically reliable methods. Some studies have been conducted to measure the sustainability of biofloc (David et al., 2021b; de Lima Vieira et al., 2021) and hydroponic systems (Martin and Molin, 2019; Romeo et al., 2018), but none were found for FLOCponics.

Emergy synthesis (ES) is one of the scientific sustainability assessment methods that has been used to evaluate food production systems. ES is a biophysical method based on a “donor side” approach, which means the biospherés capacity to provide resources to maintain the system running over the years (Brown and Ulgiati, 2004a; Odum, 1996). ES recognises the differences in energy quality according to their position in the hierarchical energy transformation network, which allows it to account for all energy flows required directly and indirectly from economic and environmental sources to produce goods and services (Brown and Ulgiati, 2016; Odum, 1996). ES converts all energy input flows into a single unit of 'solar emjoules' (sej), thus making it viable to compare different energy flows and establishing indicators for environmental performance assessment of different production systems (Odum, 1996). More than providing a simple sustainability diagnosis, emergy synthesis usually provides clear information on where, when, and sometimes how to improve existing production systems to achieve higher degrees of sustainability (David et al., 2021a). A recent study assessed the sustainability of a tilapia biofloc-based farm using ES (David et al., 2021b), showing that the biofloc-based farm had potentially sustainable characteristics and could be even more sustainable if the electricity use was optimised. In addition to evaluating case studies, ES is also a valuable tool to predict, through simulations, whether systems that have not yet been commercially implemented or are at an early stage of development will be sustainable over time, thus supporting further decision making (Campbell, 1998; Zhan et al., 2020; Zhao et al., 2020). Such a possibility of investigating systems before implementing them makes ES an appropriate method to assess the sustainability of FLOCponics systems.

Since research on FLOCponics is beginning, and many aspects of this system still need to be explored, the objective of this study was to investigate, assess and discuss the sustainability of the FLOCponics system as a potentially sustainable alternative for stand-alone biofloc or hydroponic cultures before such an integrated system becomes widespread. This investigation will lead to a perspective of what troubling points need to be covered in the FLOCponics research field before they turn into a commercial scale problem. For this purpose, we used the innovative approach of emergy synthesis to compare the sustainability of hydroponic and biofloc systems with the sustainability of integrated FLOCponics system, based on experimental results.

2. Methods

2.1. General information and data collection

Sustainability assessment was conducted in three different food production systems: a hydroponic, biofloc, and FLOCponics systems. The data used in this theoretical experiment-based study derived from Pinho et al. (2021b). Pinho et al. (2021b) compared the production of fish and vegetables in these three systems under the same environmental conditions. The fish produced was Nile tilapia (*Oreochromis niloticus*) in the juvenile phase (1–30 g), and lettuce (*Lactuca sativa*) was the vegetable cultivated from seedling until reaching a commercial size. Since each production system has its own characteristics, the experimental devices were built following such characteristics, thus they had different productive areas and times (production cycle period). To present a fair comparison between the systems, all data were standardised to one square meter in one year of production (Table 1).

A 100 m^2 greenhouse at the Aquaculture Center of São Paulo State University (Unesp) in Jaboticabal, São Paulo, Brazil (21°14′05′’S, 48°17′09′’W) was used. The greenhouse was covered with a 1.5 mm plastic liner and a shading net to reduce the luminosity by 40%. The plastic on the sides of the greenhouse was movable to allow the regulation of the temperature inside the greenhouse through wind circulation. The water used in all systems for the initial supply of the tanks and replacing the evapotranspiration losses came from an artesian well. The insolation, wind and evapotranspiration were calculated based on the weather dataset provided by the AgroClimatological Station of Unesp (Campus Jaboticabal-SP), monthly average values for 2019.

The electricity used to keep the aeration and pumping systems running came from the municipal grid. The aeration was provided by an

Table 1
Technical characteristics of the hydroponic, biofloc, and FLOCponics systems for tilapia juveniles and lettuce production.

Item	Unit	Hydroponics	Biofloc	FLOCponics
Area	m^2	0.84	1.44	2.28
Initial water supply	m^3/year	2.09	0.48	0.60
Replacement water	m^3/year	0.75	0.77	0.76
Electricity consumption	kWh/year	948	1486	2436
Stocked fish	unit/year	–	1955	1955
Initial average weight of fish	kg/fish	–	0.001	0.001
Final average weight of fish	kg/fish	–	0.030	0.030
Vegetable seedlings	unit/year	330	–	330
Feed	kg/year	–	50.3	57.0
Compound fertiliser	g/year	2546	–	2189
Molasses	kg/year	–	1.95	1.95
Skilled labour	h/year	182.5	182.5	365
Non-skilled labour	h/year	365	365	547.5
Effluent treated	m^3/year	2.09	0.25	0.25
Vegetables produced	kg/year	31.76	–	39.21
Fish produced	kg/year	–	63.16	57.94
Fish production	cycles/ year	–	6.5	6.5
Vegetable production	cycles/ year	17.4	–	17.4

air blower and distributed in each system by micro-perforated diffusers. A power generator was available as a backup for eventual power failures. Considering that constant aeration and water movement are crucial in the fish tank of biofloc and FLOCponics systems, the generator was considered equipment for both systems. Other equipment included (to use in all systems) a multiparameter required to monitor the physical–chemical parameters of the water on a daily basis (e.g., temperature, pH, electrical conductivity, etc.). Skilled labour was required to control critical operations in all systems, such as deciding when and how much fertiliser or extra carbon source should be supplemented. Non-skilled labour performed all other hand-operated activities. We included a waste treatment system in all systems to treat the discharged water (rich in nutrients and solids) before it becomes an environmental problem (David et al., 2022, 2021b). As each system will have a different amount of effluent/waste, the treatment system has been sized to be compatible with each of them.

2.2. *Description of the systems*

The information relevant to the emergy synthesis of each system is presented in the next subsections (for more details, see Pinho et al. (2021b)).

2.2.1. *Hydroponics*

In the hydroponic system, deep-water culture (DWC) was used for lettuce production, where the vegetables were accommodated in floating structures in tanks filled with nutrient solution. In the experiment, two hydroponic tanks, which had a surface of 0.42 m^2 (60 L) each, represented a replicate. Thus, in the present study, a total area of 0.84 m^2 was considered for lettuce production. Lettuce seedlings, 21 days after sowing, were planted in a density of 19 lettuces per m^2 and cultivated for 21 days until harvest.

At the beginning of each lettuce production cycle (every 21 days), the hydroponic tanks were emptied, cleaned, and filled with artesian well water. They were emptied by pumping, and we considered that the discharged water was properly treated in a waste treatment system before being discharged into the environment. After filling the tanks and during the cycles, the electrical conductivity (EC) of the water was measured and a compound commercial fertiliser (Dripsol Folhosas®, concentrated 100 times) was added until the EC reached 1.7 mS/cm. The management of emptying and filling the tanks between the cycles is common in hydroponics, as it is economically cheaper and easier to start the cycle with a balanced solution instead of analysing all nutrients that remained in the water and supplementing only those that were deficient.

The scope boundaries of the hydroponic system are defined in the diagram presented in Fig. 1. All diagrams presented in this study were designed following the methodology proposed by Odum (1996).

2.2.2. *Biofloc*

The biofloc system consisted of a circular fish tank (380 L) and a radial flow settler (decanter, 100 L). In the fish tank, tilapia juveniles were produced in a mixture of water and bioflocs. The radial flow settler was included to control the solids concentration in the fish tank (for details about the radial flow settler operation, see Pinho et al. (2021b)).

Tilapia juveniles were hand-fed with a diet containing 32% crude protein, four times a day, in a production cycle of 56 days. Liquid molasses, as an external carbon source, was added to the fish tank three times a week to maintain a C:N ratio in the water of approximately 15:1. The regulation of the C:N ratio is part of the biofloc-based culture routine to maintain the biofloc microorganisms (Emerenciano et al., 2017). During the experiment, no water or waste was discharged. However, since the control of solids that accumulate in the biofloc water is usually required, we estimated that the sludge (water with an extremely high concentration of solids) discharged is up to 10% of the fish tank volume in each cycle of fish production. Water quality parameters were constantly monitored to ensure optimal conditions for fish growth and maintaining the desired microorganism community. The scope boundaries of the biofloc system are defined in the diagram presented in Fig. 2.

2.2.3. *FLOCponics*

FLOCponics was run in an on-demand coupled system layout (also called decoupled system) and consisted of a fish tank, a radial flow settler (decanter), a bag filter and two hydroponic tanks. In this layout, the water and nutrients were not constantly shared between the aquaculture biofloc-based and hydroponic subsystems. Instead, the nutrient-

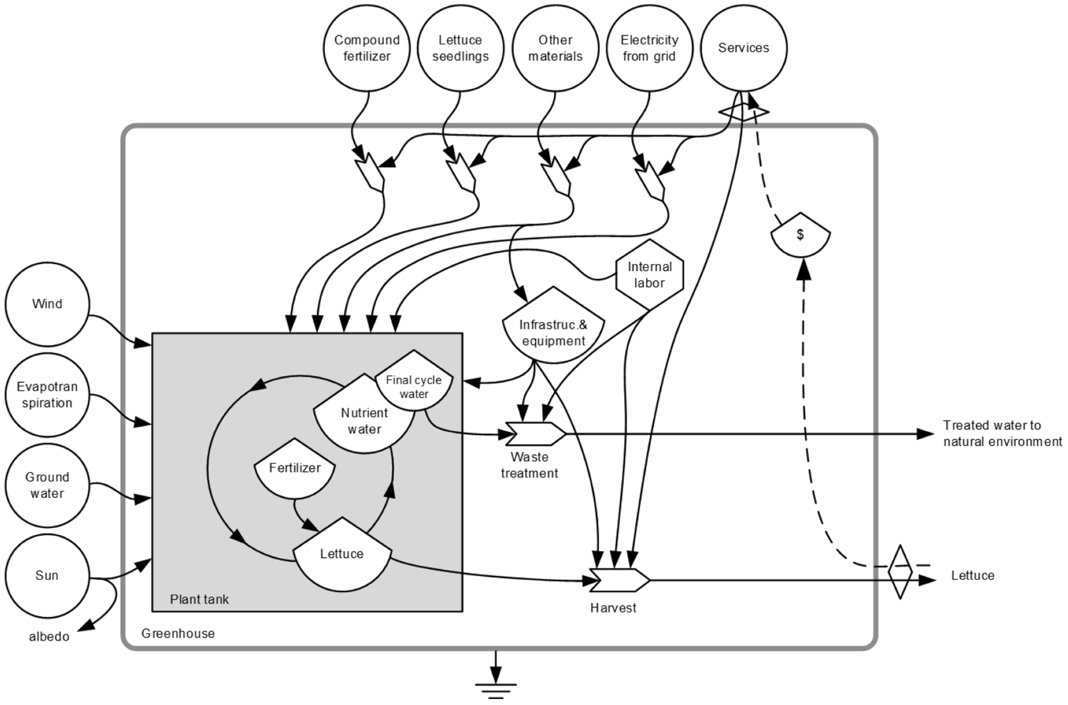

Fig. 1. Energy diagram of the hydroponic system to produce lettuce.

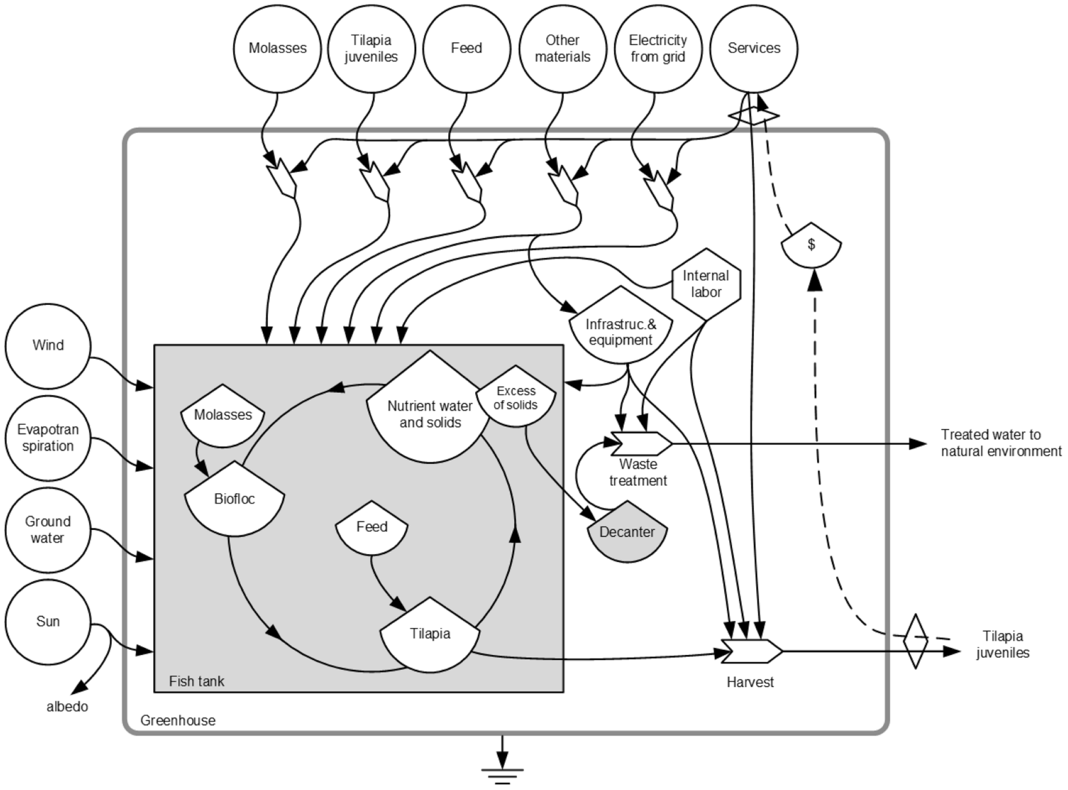

Fig. 2. Energy diagram of the biofloc system to produce tilapia juveniles.

rich water from the biofloc subsystem flows to the hydroponics depending on the vegetables' demands for water and nutrients (Pinho et al., 2022b). Thus, once a day, the water from the fish tank underwent decantation and filtration process in the radial flow settler and bag filter, respectively, before being directed to the plant tanks. The volume of water streamed from the biofloc to the hydroponic subsystems was equal to the evapotranspiration losses in the hydroponic tanks.

The same feeding and C:N ratio management for fish culture were performed in the biofloc and FLOCponics systems. We also assumed the same amount of sludge discharge in both systems. In the hydroponic subsystem, the effluent from the biofloc subsystem was the main resource for lettuce nutrition and irrigation. However, when the electrical conductivity of the hydroponic tank water did not reach the desired value (approximately 1.7 mS/cm) the same compound commercial fertiliser was added. The scope boundaries of the biofloc system are defined in the diagram presented in Fig. 3.

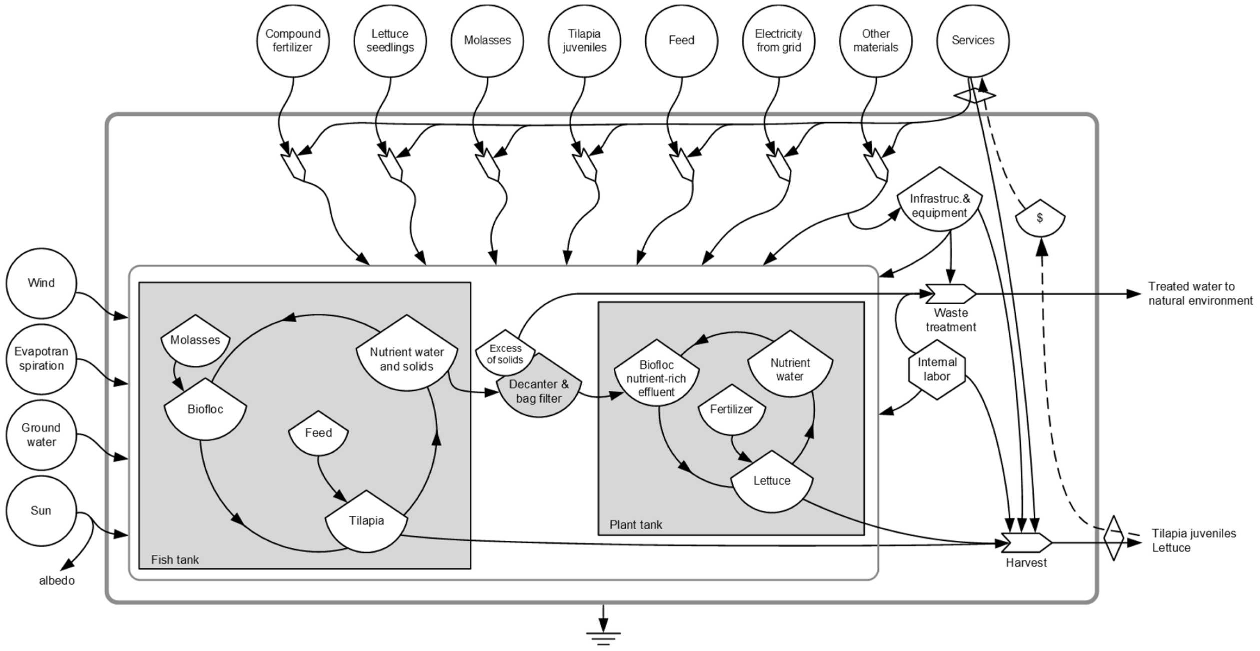

Fig. 3. Energy diagram of the FLOCponics system to produce tilapia juveniles and lettuce.

2.3. *Emergy synthesis*

The emergy synthesis (ES) was the method chosen to measure the sustainability of the hydroponic, biofloc, and FLOCponics systems. ES methodology includes the spatiotemporal boundaries of the analysed production system and its emergy baseline, identifying all the necessary resource inputs and classifying them into renewable, non-renewable and resources from the larger economy. After this classification, inputs were quantified and converted into solar emjoules (sej, emergy unit). Afterwards, the emergy flow, system outcomes, and emergy indicators were calculated (Brown and Ulgiati, 2004b). In this study, all UEVs (Unit Emergy Value) used are according to the 1.20E + 25 sej/year baseline (Brown et al., 2016).

The emergy indicators allow for identifying and discussing the distinctions among the three production systems in terms of functional characteristics, including environmental sustainability, resource utilisation efficiency, production pressure load on the resource, degree of renewability of the system, and the origin of the resources it is based on. The indicators also support the choice of the system with the best environmental performance, identification of which managements harm the system's sustainability and suggestions for alternatives. The emergy indicators used in this synthesis considered the partial renewability of each input to properly measure the sustainability of the systems (see formulas in Table 2) (David et al., 2021a). The Unit Emergy Value (UEV) represents the quantity of energy embodied in the output. This indicator measures the amount of emergy necessary to produce a certain amount of energy. Since UEV is defined by the inverse relation of efficiency, the higher the UEV, the lower the system efficiency. Renewability (%R) shows the fraction of renewable resources in relation to the total emergy used. This indicator is used to determine the degree of sustainability of production systems. Emergy Yield Ratio (EYR) is the ratio between the total emergy and the emergy resources from the larger economy. EYR measures how much an investment enables a production system to exploit local resources to further contribute to the economy. The Emergy Investment Ratio (EIR) assesses how the ecosystem responds to an investment of resources from the larger economy. EIR compares alternative inputs that use the same natural resource. The environmental loading ratio (ELR) measures the stress that the system causes on the environment. A value below 2 indicates low stress, values from 2 to 10 a moderate stress, and values above 10 indicate high stress on the ecosystem. The emergy sustainability index (ESI) is the ratio between EYR and ELR. This indicator shows the potential contribution of a resource or process to the economy per unit of environmental loading generated.

2.4. *Sensitivity analysis*

To measure how changes in the inputs will affect the emergy indicators, a sensitivity analysis was performed with respect to the following inputs: electricity, equipment, compound fertiliser and fish juveniles. The quantities of these inputs were increased and decreased by 20% from the initial value. A normalised (non-dimensional) sensitivity coefficient (S_y) was used for a direct comparison. The following equation was used to compute the normalised sensitivity coefficient (Tomovic, 1963): $S_y = (\partial y/\partial x)*(\overline{x}/\overline{y})$, in which y is a specific output and x is a specific input parameter. The overbar indicates nominal values; thus, multiplication by $(\overline{x}/\overline{y})$ normalises the sensitivity value.

Table 2
Emergy indicators used in this synthesis study and their formulas.

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.

3. Results and discussion

Recent research has focused on developing FLOCponics systems as a promising modern integrated agri-aquaculture system to improve the sustainable character of biofloc-based aquaculture and hydroponic food production. Yet, no scientific-based evidence has been presented to date to support (or deny) the narrative that FLOCponics is a more sustainable food production. This study is the first step to fill this gap, as we applied emergy synthesis to assess the sustainability of producing tilapia juveniles and lettuce in FLOCponics systems compared to stand-alone biofloc and hydroponics systems.

The computed emergy indicators for FLOCponics, bioflocs and hydroponic systems is shown in Table 3. The emergy indicator results are a reflection of the particular management practices adopted in each production system (Brown and Ulgiati, 2004c, 1997). However, even with different amounts and types of input and distinct operational characteristics, the findings of this theoretical experiment-based study show that the three evaluated systems have similar emergy performance (Table 3). Such similarity reveals that the reuse of nutrients and water in FLOCponics was not enough to boost the sustainability of the integrated system compared to stand-alone hydroponic and biofloc systems when running on small scale (experimental) systems setups.

The effect of the systems' size can be seen in the renewability results. The renewability values found for all systems (~23%) are lower than the 33% recently reported for tilapia fingerling production on a commercial scale biofloc-based aquaculture farm, also located in São Paulo, Brazil (David et al., 2021b). In line with our findings it is expected that, by expanding the system to commercial size, the emergy demand for equipment needs to be optimised, and the use of renewable resources should be increased, such as electricity from hydropower, both positively affecting the renewability result of all evaluated systems. Another possibility to increase renewability is changing the water source, for instance, from groundwater to spring water or rainwater. Spring water and rainwater are considered renewable water sources, as nature's effort to replenish them is lower than groundwater. Thus, in FLOCponics and other food production systems, replacing groundwater by these other sources should be encouraged.

The other emergy indicators suggest that FLOCponics, biofloc and hydroponic systems use a low amount of natural renewable resources (EIR), cause a moderate environmental load on the input sources (ELR) and an environmental stress seven times higher than the contribution to the economy (ESI). All these results rely on the fact that the evaluated systems highly depend on resources from the large economy (EYR). The emergy synthesis reveals that the FLOCponics system has the highest emergy demand (1.35E + 15 sej/m^2/year), followed by biofloc (1.31E + 15 sej/m^2/year), and hydroponics (1.32E + 15 sej/m^2/year) (see Supplementary Materials Tables S1, S2, S3 and the calculations in

Table 3
Emergy indicators found for the different systems evaluated.

Emergy indicators		Hydroponics	Biofloc	FLOCponics
%R	Renewability	23.6	21.7	21.7
EYR	Emergy yield ratio	1.0	1.0	1.0
EIR	Emergy investment ratio	3.1	3.6	3.6
ELR	Environmental loading ratio	3.1	3.6	3.6
ESI	Emergy sustainability index	0.3	0.3	0.3
UEV	Unit emergy values (sej/J)	5.55E + 10	1.42E + 06	2.54E + 06

Tables S4, S5 and S6). Resources from the larger economy account for more than 50% of emergy demanded in all systems, due to the equipment used to measure the physical–chemical parameters of the water (multiparameter) and maintain constant aeration in the tanks (air blower) (Fig. 4). Electricity was the second input that demanded large amounts of emergy (greater than30%) in all systems.

The dependence on resources from the large economy has been a recurrent finding in emergy synthesis of intensive food production systems (David et al., 2021a). This is because intensive food production systems consistently require this type of resources for infrastructure (e. g., fish tanks, filters, greenhouse, etc.), equipment, specialised labour, and especially electricity (Ghamkhar et al., 2020). Our results show that the high contribution of these inputs to the total emergy flow is also a concern for intensive integrated biofloc-based agri-aquaculture systems.

In emergy synthesis, the efficiency is measured by the production system's ability to incorporate energy into the product through the production process, given as the unit emergy value (UEV). Although most of the emergy indicators were similar between the systems, the UEVs that were found suggest a different path (Table 3). The UEV found for hydroponics were 10^4 times higher than the UEV of FLOCponics and biofloc, while FLOCponics was almost twice the value of the biofloc system. Compared to the hydroponic system, FLOCponics is much more efficient due to embodied energy in the fish produced. On the other hand, FLOCponics is not as efficient as the stand-alone biofloc system. The difference between the UEV of FLOCponics (2.54E + 06 sej/J) and biofloc (1.42E + 06 sej/J) systems are much smaller compared to the values found for hydroponics (5.55E + 10 sej/J). Still, the UEVs results stress the need for improvements in the FLOCponics subsystem before applying it on a large scale.

A sensitivity analysis was performed for each system. The normalised sensitivity coefficients (S_y) are presented in Table 4 for a direct comparison between the systems and the emergy indicators. The complete set of results of the sensitivity analysis can be found in Supplementary Materials Tables S7–S10. In general, the S_y values indicate that electricity is the most sensitive input in all systems, especially for EIR, ELR, and ESI. This result suggests that the use of renewable energy sources could make the system more sustainable. US$ spent on equipment was the item that most contributed to the total emergy flow (Fig. 4). The sensitivity analysis showed that changes in the quantity (US$/year) of equipment considerably affect the efficiency of the systems (UEV, Table 4). Compound fertilizer and fish juveniles seem to impact the emergy indicators marginally.

A relevant point for discussion is how to increase the efficiency of FLOCponics. Mainly considering that, apart from the UEVs, the overall emergy performance of FLOCponics was similar to stand-alone systems. The UEV results indicate the need for improvement. Table 4 shows that decreasing the dependence on expensive equipment is a promising way to improve the UEVs. Besides that, replacing industrial resources with organic or natural resources will positively affect the sustainability of any food production system (Oliveira Neto et al., 2018), and it will also be the case for FLOCponics. In terms of practical solutions, based on the emergy synthesis outputs and literature review, we identified the following points that must be taken into account in further FLOCponics research to explore its full potential. Firstly, testing and validating different plant species with higher energetic values will very likely lower the UEV of FLOCponics. Lettuce is the main plant produced in freshwater FLOCponics studies (Pinho et al., 2022b), however it is not capable of incorporating significant amounts of energy through the production process. Examples of plants to be tested are tomato, broccoli, spinach, among others. We speculated how a tomato production of 60 kg/m^2/year (equal to 5.27E + 07 J/m^2/year) would affect the UEV of FLOCponics and found a 10% reduction in the UEV compared to lettuce production in the same system setup, indicating improved efficiency. Secondly, the system design and operation must be optimised such that the resources in excess are used wisely. Investigating several system configurations may require costly investments in trials and analyses. Thus, a reasonable way to find optimal management and operation strategies is by applying mathematical models. Modelling has been widely used to predict and simulate complex food production systems aiming at achieving maximum efficiency in the use of resources (Keesman et al., 2019; Lastiri et al., 2018). Lastly, transforming the accumulated and discharged nutrient-rich solids from the biofloc subsystems into valuable co-products has a high potential to improve FLOCponics sustainability. Reusing the biofloc waste will, at first glance, decrease the need for a treatment system. Moreover, recent studies have shown that mineralised aquaculture sludge (solids) can be reused as fertiliser for plant nutrition (Delaide et al., 2019). Consequently, this nutrient recovery will decrease resource input from the large economy and boost FLOCponics system circularity. Recovery of high-valued compounds from the biofloc waste could also be interesting to boost circularity. However, this route may need more advanced treatments and thus higher costs, but it may finally lead to higher sustainability indicators and probably higher profits.

All the proposed changes and further investigations to support the sustainable development of FLOCponics should not be costly and negatively affect the productive performance of the system. Additionally, the improvements must consider the characteristics of each location, such as the origin of the resources, the regional market of fish and vegetable species, and the technologies and professional know-how available. A higher economic benefit/cost of producing food in the

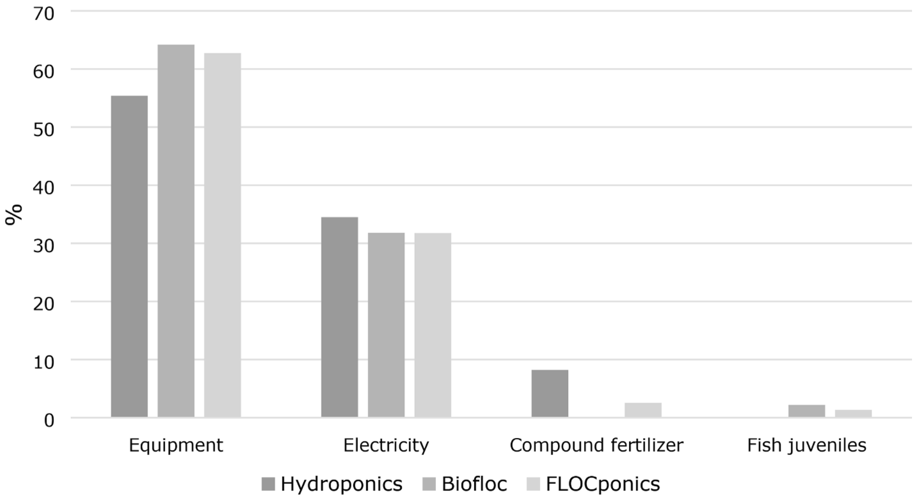

Fig. 4. Contribution of the main inputs to the total emergy flow for the different systems.

Table 4
Normalised sensitivity coefficients found in the sensitivity analysis, performed to measure how the changes in key inputs affect the emergy performance of hydroponic, bioflocs and FLOCponics systems.

Inputs	System	UEV	%R	EIR	ELR	ESI
Electricity (kWh/year)	Hydroponics	0.345	0.653	**−0.886**	**−0.886**	**0.852**
	Biofloc	0.318	0.681	**−0.902**	**−0.902**	**0.867**
	FLOCponics	0.318	0.681	**−0.902**	**−0.902**	**0.867**
Equipment (US$/year)	Hydroponics	**0.432**	0.015	−0.015	−0.015	0.020
	Biofloc	**0.474**	−0.042	0.041	0.041	−0.058
	FLOCponics	**0.467**	−0.033	0.032	0.032	−0.045
Compound fertilizer (g/year)	Hydroponics	0.082	−0.082	0.108	0.108	−0.108
	Biofloc	–	–	–	–	–
	FLOCponics	0.025	−0.025	0.032	0.032	−0.032
Fish juveniles (unit/year)	Hydroponics	–	–	–	–	–
	Biofloc	0.022	−0.022	0.028	0.028	−0.028
	FLOCponics	0.013	−0.013	0.017	0.017	−0.017

UEV: Unit emergy values (sej/J). %R: Renewability. EIR: Emergy investment ratio. ELR: Environmental loading ratio. ESI: Emergy sustainability index. Boldface numbers represent which emergy indicators are more sensitive to changes in the specific input.

FLOCponics system may be expected than in the stand-alone systems due to the higher variety and amount of biomass grown. Nevertheless, when FLOCponics moves beyond the initial stage of development, economic analyses should be combined with sustainability assessments to measure whether and how the system could be profitable.

It should be emphasised that the results presented here are restricted to the pre-set conditions (experimental/small-scale). Nevertheless, our findings are not trivial since they provide valuable insights regarding the (un)sustainable aspects of FLOCponics and direct further research to improve the system's emergy performance.

4. Conclusion

From an emergy synthesis point of view, integrating tilapia production in a biofloc system with hydroponic lettuce culture is as sustainable as the stand-alone systems. Most of the emergy indicators are similar for all systems, suggesting that FLOCponics, biofloc and hydroponic systems use low amounts of natural renewable resources, cause a moderate environmental load (EIR and ELR of 3.1 to 3.6), and lead to environmental stress seven times higher than the contribution to the economy (ESI of 0.3). Unit emergy values (UEVs) are different for each system, indicating that, under the evaluated conditions, FLOCponics (UEV: 2.54E + 06 sej/J) is more efficient than hydroponics (UEV: 5.55E + 10 sej/J) and less efficient than a biofloc system (UEV: 1.42E + 06 sej/J). Thus, the unit emergy value found for FLOCponics was 78% higher than for the biofloc system, indicating that improvements still need to be made. The sensitivity analysis showed that the emergy performance of FLOCponics, biofloc and hydroponic systems are all sensitive to changes in the quantity of electricity and equipment. Given these results and the fact that it is a system under development, FLOCponics can be considered a promising sustainable food production method with still many opportunities for improvement.

CRediT authorship contribution statement

Sara M Pinho: Conceptualization, Methodology, Data curation, Writing – original draft, Writing – review & editing. **Luiz H. David:** Conceptualization, Methodology, Formal analysis, Data curation, Writing – review & editing, Visualization. **Fabiana Garcia:** Writing – review & editing, Visualization. **Maria Célia Portella:** Writing – review & editing, Visualization, Supervision. **Karel J. Keesman:** Writing – review & editing, Visualization, Supervision.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2022.109092.

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