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Sustainability of tilapia production systems

Luiz Henrique Castro David

Jaboticabal, São Paulo
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Abstract

Numerous systems, models, and production techniques have been developed to minimize the environmental impact of aquaculture and make this activity more sustainable. In this context, the thesis aims at developing and investigating sustainable production systems for tilapia farming in Brazil. The thesis comprises eight chapters. Chapter 1 brings a brief theoretical background, the research objectives and thesis approach and outline. Chapter 2 reviews the standards, potentialities, deficiencies, and applications of the emergy method in the sustainability assessment of aquaculture production systems. In this chapter, we also discuss and propose improvements on the emergy synthesis for measuring aquaculture sustainability. In Chapter 3 and 4, the sustainability of commercial tilapia production in aquaponics and biofloc-based systems were evaluated, respectively, using emergy synthesis. We also indicate alternative management to reduce systems' issues and boost the sustainability of them. An innovative way to account for ecosystem services and disservices within emergy synthesis is proposed and discussed in Chapter 3 to accurately capture the environmental performance for aquaponics systems. The findings presented in Chapter 3 and 4 suggest that aquaponics and biofloc are systems potentially sustainable for tilapia farming in Brazil. However, improvements should be done in both food production systems to improve their sustainable performance. Chapter 5 and 6 investigate the technical feasibility of reducing the amount of feed in periphyton-based systems to produce tilapia in ponds and cages located in a farm dam. The tilapia growth performance presented in Chapter 5 indicates that the proposed production models are promising strategies for using natural food in a periphyton-based system and reusing effluents from monocultures. On the other hand, Chapter 6 shows that rearing tilapia in a farm dam with water poor in nutrients result in low availability of the periphyton and, consequently, the tilapia under feed restriction could not take advantage of the periphyton as natural food. In the study presented in Chapter 7, we show the consumer preferences and perceptions regarding the market for sustainable/certified aquaculture products in Brazil. As the main result of Chapter 7, we found that most Brazilian fish consumers are aware of what certification is and the aspects involved in it. In general, the set of information and findings presented in this thesis can be considered as an important step to support the development of public policies and certification programs to make aquaculture a more sustainable activity.

Keywords: Aquaponics; Biofloc; Cages; Emergy; Ponds.

Resumo

Inúmeros sistemas, modelos, e técnicas de produção tem sido desenvolvidas para minimizar o impacto ambiental da aquicultura e fazer essa atividade mais sustentável. Nesse contexto, essa tese tem como objetivo desenvolver e investigar sistemas sustentáveis para produção de tilápia no Brasil. A tese é composta de oito capítulos. O Capítulo 1 compreende um breve embasamento teórico, os objetivos e a abordagem da tese. O Capítulo 2 analisa os padrões, potencialidades, deficiências e aplicações da síntese em emergia na avaliação da sustentabilidade dos sistemas de produção de aquicultura. Neste capítulo, também discutimos e propomos melhorias na síntese em emergia para medir a sustentabilidade da aquicultura. Nos Capítulos 3 e 4, a sustentabilidade da produção comercial de tilápia em sistemas aquapônicos e baseados em bioflocos foi avaliada usando síntese em emergia. Também indicamos uma gestão alternativa para reduzir os problemas dos sistemas e aumentar a sustentabilidade dos mesmos. Uma maneira inovadora de contabilizar os serviços e desserviços do ecossistema na síntese em emergia é proposta e discutida no Capítulo 3 para medir com precisão o desempenho ambiental dos sistemas aquapônicos. Os resultados apresentados nos Capítulos 3 e 4 sugerem que a aquaponia e o bioflocos são sistemas potencialmente sustentáveis para a criação de tilápia no Brasil. No entanto, melhorias devem ser feitas em ambos os sistemas de produção para melhorar seu desempenho sustentável. Os Capítulos 5 e 6 investigam a viabilidade técnica de reduzir a quantidade de ração em sistemas baseados em perifíton para produzir tilápia em viveiros e em tanques-rede alocados em pequenos reservatórios. O desempenho do crescimento da tilápia apresentado no Capítulo 5 indica que os modelos de produção propostos são estratégias promissoras para o uso de alimentos naturais em um sistema baseado em perifíton e reutilização de efluentes de monoculturas. Por outro lado, o Capítulo 6 mostra que a criação de tilápia em pequeno reservatório com água pobre em nutrientes resulta em baixa disponibilidade do perifíton e, consequentemente, a tilápia sob restrição alimentar não poderia aproveitar o perifíton como alimento natural. No estudo apresentado no Capítulo 7, mostramos as preferências e percepções dos consumidores em relação ao mercado de produtos aquícolas sustentáveis / certificados no Brasil. Como resultado principal do Capítulo 7, descobrimos que a maioria dos consumidores brasileiros de pescado está ciente do que é certificação e dos aspectos envolvidos nela. De maneira geral, o conjunto de informações e resultados apresentados nesta tese pode ser considerado um passo importante para apoiar o desenvolvimento de políticas públicas e programas de certificação que tornem a aqüicultura uma atividade mais sustentável.

Palavras-chave: Aquaponia; Biofloco; Emergia; Tanque-rede; Viveiro.

Chapter 1

Introduction

The consumption of fish has increased considerably in recent years driven by population growth and preference for healthy sources of animal protein by consumers (Moura et al., 2016; FAO, 2020). However, extractive fishing continues to supply constant quantities of fish and does not follow the increased demand (FAO, 2016; 2018; 2020). This scenario favors the rapid growth of aquaculture, making it the fastest-growing agricultural activity in the last decades (FAO, 2020). In Brazil, aquaculture follows this same growth trend and reached 802,930 t in 2020, an increase of 5.93% over the previous year when the amount was 758,006 t (PEIXE BR, 2021). The total volume of fish produced in Brazil is dominated by freshwater fish farming and represented mainly by semi-intensive tilapia and round fish culture in ponds and intensive tilapia production in cages. Tilapia farming represents more than 60% of this total (468,155 t), and it is responsible for placing Brazil amongst the four largest producers of this species in the world, only behind China, Indonesia, and Egypt (FAO, 2020; PEIXE BR, 2021).

In conjunction with the accelerated growth of aquaculture, there are concerns about the future of aquatic-based animal production, mainly regarding the negative environmental impacts that it may cause (Nhu et al., 2016; Henriksson et al., 2017). The aquaculture growth implies the increase of culture areas and in the high use of inputs for production, mainly feed (Samuel-Fitwi et al., 2012). Such problems are intensified when linked to incorrect management in aquaculture, for example, the irrational use of water, release of nutrient-rich effluents in the environment, introduction and spread of diseases, use of exotic species, pollution from drug residues (Samuel-Fitwi et al., 2012; Ottinger et al., 2016; Fry et al., 2016).

Numerous systems, models, and production techniques, such as bioflocs, aquaponics, integrated multitrophic aquaculture (IMTA), and recirculating aquaculture system (RAS), have been developed to minimize the environmental impact of aquaculture and make this activity more sustainable (Boyd et al., 2020). These aquatic-based food production systems adopt different approaches to improve the efficiency of production, increasing productivity and reducing the waste of resources, such as nutrients, water, and energy (Aubin et al, 2019). In addition to these systems, periphyton-based systems have been used as an approach to cycle the nutrients in the water, promote the growth of natural food (periphyton) and consequently reduce the dependence on commercial feed. Recent studies have shown that the use of substrates to growth periphyton in tilapia farming is technically efficient (Garcia et al., 2016), economically profitable (Garcia et al., 2017) and potentially sustainable (David et al., 2018).

The concept of sustainability establishes that the growth of any productive activity is limited (Johnston et al., 2007). This is because societies and their economies are based on the exploitation of natural resources, and the environment is not able to provide resources and absorb impacts in an unlimited way (WCED, 1987). According to 2030 Agenda for Sustainable Development, it is necessary to comprise sustainable consumption and production, sustainably manage natural resources, and take urgent action on climate change to support the needs of the present and future generations. In the case of aquaculture development, it must be based on sustainable practices (Valenti et al., 2018). Aquaculture sustainability is boosted by prioritizing the best alternatives to minimize environmental impacts and social costs. In this way, the aim of sustainable aquaculture production practices is to obtain high productivity using the minimum resources, seeking the success of long-term production (Boyd et al., 2020).

Measuring the degree of sustainability of aquaculture systems and which managements interfere with their sustainability is essential to developing strategies of production that meet the sustainable development goals described in the 2030 Agenda by the United Nations. As a way of providing the technical and scientific basis needed for the elaboration of these strategies, there are methods capable of assessing the sustainability of production systems. From the information obtained in these assessments, it is possible to determine management and public policies aiming at the sustainable development of aquaculture (Garcia and Kimpara, 2012). Among the available methods, the most popular and used for aquaculture are the Ecological Footprint, Life Cycle Analysis, Indicators of Sustainability, and Emergy Synthesis

(Valenti et al., 2010; Garcia and Kimpara, 2012). Emergy synthesis (ES) is a scientifically consolidated environmental accounting method used to assess the sustainability of a wide range of production systems. In the case of aquaculture, the synthesis results in indicators that measure the efficiency of systems in converting inputs into output (Brown and Ulgiati, 2004). Furthermore, the emergy indicators can point out which managements adopted in production demand more emergy and, based on that, more sustainable management alternatives can be suggested (Garcia et al., 2014; Amaral et al., 2016; David et al., 2018). However, the use of emergy synthesis to assess the sustainability of aquaculture is still in its infancy and little is known about the strengths and weaknesses of applying this method in aquaculture systems.

General objective

This thesis aims at developing and investigating sustainable production systems for tilapia farming in Brazil.

Specific objectives

(i) To evaluate, discuss and propose improvements on the emergy synthesis method as a tool for assessing the sustainability of aquaculture production systems.

(ii) To assess the sustainability of commercial tilapia production systems, such as bioflocs and aquaponics, using emergy synthesis.

(iii) To identify the problems in the tilapia production systems and propose management and techniques that improve their sustainability.

(iv) To identify and value ecosystems services and disservices promoted by tilapia production systems and accounting for them using emergy synthesis.

(v) To develop periphyton-based systems to produce tilapia in ponds and cages under different feed management.

(vi) To determine the consumer preferences and perceptions regarding the market for sustainable/certified aquaculture products in Brazil.

(vii) To generate information to support the development of sustainable public polices and certification protocols for tilapia production.

Thesis approach and outline

To achieve the research objectives, this thesis comprises eight chapters. After the general introduction, **Chapter 2** reviews the standards, potentialities, deficiencies, and applications of the emergy method in the sustainability assessment of aquaculture production systems. A general background about aquaculture sustainability and emergy synthesis procedures are presented in this chapter. In addition, we suggested improvements in the method that can increase the accuracy of the evaluations using emergy synthesis, providing more reliable results that can be used in the definition of public policies for the development of sustainable aquaculture. Chapter 2 addresses the specific objective (i).

Chapter 3 investigates and conducts a sustainability assessment of two urban aquaponic farms in Brazil. This work goes beyond the current studies by filling a gap in the scientific literature on the sustainability of one emerging aquaculture system (aquaponics) using emergy synthesis. An innovative way to account for ecosystem services and disservices within emergy synthesis is also proposed and discussed to accurately capture the environmental performance for such an important food production system. We also indicate alternative management to reduce aquaponics issues and boost the sustainability of this system. This chapter addresses specific objectives (ii), (iii), (iv), and (vii).

Biofloc technology (BFT) has been labeled an environment-friendly aquaculture approach due to its efficient use of water and nutrients to produce fish. However, as far as we know, studies on the sustainability of BFT are yet not reported, and it is unclear whether the positive characteristics of BFT make it a sustainable approach for aquaculture. **Chapter 4** addresses this gap and reaches the specific objectives (ii), (iii), (iv), and (vii) of this thesis by investigating and assessing the sustainability of BFT using emergy synthesis. In this chapter, we also discuss potential alternatives to minimize BFT issues and improve the sustainability of this system.

Chapters 5 and **6** explore the potentialities of periphyton-based systems to make tilapia farming less dependent on feed. Investigating and developing periphyton-based systems for small-scale tilapia producers are the primary focus of our research group. In previous studies, we showed that replacing 50% of feed with periphyton improved the sustainability of tilapia in cages located in hydroelectric reservoirs. Based on the premise that the use of periphyton improves the sustainability of aquaculture, we experimentally evaluate the use different periphyton-based systems for tilapia farming. In the study of Chapter 5, two production models were evaluated using periphyton as a complementary and exclusive natural food source in ponds. Concerning Chapter 6, it shows the results of tilapia growth performance in cages located in a farm dam. Both chapters allowed us to reach the specific objective (v) by evaluating the technical feasibility of tilapia production in ponds and cages under feed reduction and natural food (periphyton) feeding.

The study presented in **Chapter 7** is essential to identify whether Brazilian consumers are concerned with sustainable aquaculture production and if they value the consumption of this type of product. This chapter describes the preferences and perceptions of the Brazilian fish consumer regarding the certified fish market in Brazil and generates information to support investments in this area. Chapter 7 addresses the specific objective (vi) of this thesis.

Lastly, in **Chapter 8** the final remarks are presented.

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Chapter 2

Emergy synthesis for aquaculture: A review on its constraints and potentials.

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Emergy Synthesis for Aquaculture: A review on its constraints and potentials

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Abstract

The search for healthier protein sources and the growing demand for food by an increasing world population require aquaculture systems to not only be economically and technologically viable, but also sustainable. Among other methods, emergy synthesis is a powerful tool to assess the sustainability of production systems in a biophysical perspective. However, applications of emergy synthesis on aquaculture systems are seldomly found in the scientific literature. This work provides a literature review on emergy synthesis applied to aquaculture systems and discusses its constraints and potentials. The sixteen papers published between 2000-2020 support the adoption of polycultures more than monocultures and highlight the importance of feed (4-70%) in the total emergy required by aquaculture systems, which require efforts for natural food. Methodological aspects of emergy synthesis applied in aquaculture systems that deserve attention by developers and analysts to avoid mistakes and erroneous conclusions were identified and discussed, and we propose some ways to solve them. These aspects are mainly related to inaccurate unit emergy values for water and feed, dubious procedures in quantifying and classifying water as renewable or non-renewable resources, and the need to recognize the importance in accounting for ecosystem services and disservices. After overcoming these methodological inconsistencies, we foresee that emergy synthesis has potential political implications in supporting most sustainable aquaculture systems through economic (tax reduction and loans with reduced interests) and political (green labels) incentives. All these policies are important to achieve the ultimate goals of the United Nations' Agenda 2030.

Keywords: aquaculture production, integrated systems, sustainability assessment, feed, ecosystem services and disservices, public policies.

1. Introduction

The consumption of aquatic foods has grown in recent years due to population growth and the increase in preference for animal protein from healthy sources (Moura *et al.* 2016). Fisheries have provided a constant amount of fish food in recent years, but they have failed in complying with the growing human demand for this animal protein source. The increased demand for food fish has resulted in an exponential spread of aquaculture production systems, becoming the fastest growing agricultural practice over the last decades (FAO 2018). At the same time, many concerns are being discussed about the future of aquaculture concerning sustainability, especially because it is highly dependent on non-renewable resources, e.g., feed (manufactured), electricity, and fossil fuels, and usually releases concentrated waste to the environment (Nhu *et al.* 2016; Henriksson *et al.* 2017). Depending on the technical management adopted, aquaculture might use natural resources over the regional biocapacity and can interfere in the maintenance of biodiversity, since aquaculture production systems can cause eutrophication of water bodies, release drug residues, and disseminate diseases in the natural environment (Asche *et al.* 2009; Fry *et al.* 2016; Ottinger *et al.* 2016). These effects are known as negative externalities or ecosystem disservices. On the other hand, aquaculture can also generate benefits or positive effects on the natural environment, which are known as ecosystem services (Aubin *et al.* 2014). An example of an ecosystem service for aquaculture is improving the water quality around oyster farms (McDonough *et al.* 2014; Lemasson *et al.* 2017; Han *et al.* 2017). Evidently, there is a trade-off between economic, social, and natural issues resulting from aquaculture protein production. Aiming to maximize the positive aspects while at the same time reducing the negative ones, public and private institutions are engaged in developing and promoting more sustainable aquaculture production systems (Alexander *et al.* 2016).

In the scientific and technical literature on aquaculture, misunderstandings regarding the concept of sustainability and others, such as best management practices (BMP) and responsible aquaculture (Boyd *et al.* 2007), can be identified. The latter relies on compliance to moral and ethical values of a society, while the BMP focuses on increased efficiency in production systems that may contribute to sustainability, as a secondary goal (Valenti *et al.* 2011). For example, some aquaculture production systems manage the use of resources towards higher efficiency and, therefore, can reduce their negative impacts on the natural environment (Boyd *et al.* 2007). Systems that apply BMPs focus on specific actions to improve their efficiency by reducing the demand for resources such as water and energy, resulting in lower loads in the environment and reduced production costs. While the application of BMPs can be seen as a positive aspect, its concept and goals can only superficially explain the deeper meaning of sustainability. In other words, BMPs in aquaculture should not be considered as synonymous of sustainable aquaculture (Valenti *et al.* 2011). Reducing the use of water, medicines or fossil fuel energy will not make aquaculture sustainable, because a systemic view of production is necessary (Read & Fernandes 2003; Valenti *et al.* 2011).

Considering the business-as-usual approach as supported by the BMPs, allied to faster growth of aquaculture production systems, may lead to technical advancements and environmental protection laws that hardly will contribute to the sustainable development of aquaculture (Boyd 2003). Although seen as essential to generate new technical management that makes production systems (Valenti *et al.* 2018) more efficient and ecological, the theme of sustainability in aquaculture is still recent and there are few research groups studying the application of sustainability assessment methods (Hau & Bakshi 2004; Chen *et al.* 2017). This also explains the reduced number of scientific publications on this subject. There are many methods available that aim to assess the sustainability of production systems in qualitative and/or quantitative aspects, which can be also applied to aquaculture. More than providing a simple diagnosis, most of these methods are important because they provide clear information of actions on the production systems that should be improved to achieve higher degrees of sustainability (Fezzardi *et al.* 2013).

Each method is based on different conceptual models of sustainability, has different windows of interest, concepts, rules, specific accounting meanings and units of measurement (Agostinho *et al.* 2019; Giannetti *et al.* 2019). Among others, the use of Emergy Synthesis (ES) (with an 'm'; Odum 1996) is rapidly increasing to assess the most different production systems, which according to Garcia *et al.* (2014), can shape public policies towards having a sustainable aquaculture. ES is an environmental accounting tool based on the so-called 'strong' conceptual model of sustainability, in which socioeconomic growth is limited by the Earth's biocapacity. ES considers a donor side perspective in providing resources, therefore 'value' is objectively measured in a biophysical approach rather than subjective as in most economic approaches (Odum 1996).

From a systemic perspective and thinking, ES identifies all energy flows supporting a production system, and then quantifies all the effort made by nature in providing these energy flows (Odum 1996; Brown *et al.* 2000). Although respecting the thermodynamic laws regarding energy conservation and entropy, ES recognizes that energy has different 'qualities' according to their position in a hierarchical energy transformation network, which allows it to account for all energy flows from economic and environmental sources to produce goods and services (Odum 1996; Brown & Ulgiati 2016). ES is able to convert all energy input flows into a production system in a single unit of 'solar emjoules' (sej), establishing indicators useful for environmental performance assessment of different production systems (Odum 1996; Ortega *et al.* 2008; Amaral *et al.* 2016). It should be noted that ES requires a vast amount of data that are difficult to obtain and the method occasionally needs to be slightly adapted from case to case. Moreover, ES results are sometimes complex to interpret. Despite these possible disadvantages, all the positive characteristics cited before make ES a powerful tool in assessing sustainability.

ES can be applied to the most different systems, including assessing small monocultures (Odum 2000; Lima *et al.* 2012), large production systems (Brown & Ulgiati 2002; Cheng *et al.* 2017), ecosystems and local behaviours (Lei *et al.* 2008; Liu *et al.* 2008; Pulselli 2010), aquaculture systems (Garcia *et al.* 2014; David *et al.* 2018), or whole countries (Huang 1998; Brown *et al.* 2009; Siche *et al.* 2010). During the last decades, the number of publications in the scientific literature regarding ES increased (Figure 1) due to its strong scientific-based characteristics in quantifying sustainability and supporting decision makers in having more sustainable production systems. The total number of publications on ES approximately has increased linearly over the past 20 years, while ES for aquaculture shows a low and constant number of publications every year.

Specifically, for aquaculture, the use of ES is relatively new (Figure 1) and is lower in number compared to other multicriteria methods (Garcia *et al.* 2016; Pinho *et al.* 2017; Coutinho *et al.* 2018; Vergara-Solana *et al.* 2019; Battisti *et al.* 2020). Although the growing number of articles that used ES to support discussions and proposals for more sustainable aquaculture production systems is seen as a positive aspect, misunderstandings and/or a lack of clear criteria is generally found in published articles. These problems are found mainly in the use of emergy value units - a conversion factor used in ES - labelling a resource as renewable or non-renewable, and procedures for establishing and evaluating ecosystem services and disservices of specific production systems, among other important aspects that deserve attention so as to improve the method to obtain more sustainable aquaculture production systems.

This review was performed due to the growing demand for more sustainable aquaculture production systems that recognize the Earth’s biophysical restrictions in providing resources and diluting residues, and due to the existing scientific robustness of ES as a tool in quantifying this sustainability. This paper aims to provide a review of the most recent and important high quality published papers on aquaculture systems in order to sustain a discussion on its main outcomes, gaps, and patterns, as well as focusing on the application of the ES method to assess their advantages and limitations when evaluating aquaculture systems.

2. Review methodology

There are four parts in this review paper. The first part is a quantitative summary of what has been studied on ES for aquaculture, including regional distribution, main outcomes, objectives, and specificities of production systems. Secondly, these identified resources as main contributors to the emergy performance of aquaculture systems are discussed in detail to identify improvements in the technical-management of these systems. Thirdly, misunderstandings, limitations and potentials are discussed about how to account for key energy inputs when applying ES on aquaculture systems. Fourthly, the importance of ES for the advancement of a sustainable aquaculture is discussed considering what has been done in the field and its importance.

Our review process includes exclusive articles in English published in refereed journals. The Science Direct (sciencedirect.com), Web of Science (webofknowledge.com) and Google Scholar (scholar.google.com) databases were used as references to support our review. Papers published until January 2020 were considered and the following terms were set in the fields of titles, abstracts and/or keywords: “emergy synthesis + aquaculture”, “emergy + aquaculture”, “emergy assessment + aquaculture”, “emergy analysis + aquaculture”, “emergy accounting +

aquaculture”, “aquaculture production + emergy”, and “fish farming + emergy”. Using these terms, the search returned many articles with emergy and/or aquaculture, however we selected only those that used ES to assess the sustainability of aquaculture systems. The reference lists presented in the articles were cross-referenced in our review, in other words, they were also verified in order to find the articles that were not selected at first. This method of searching and selecting articles was also used to prepare Figure 1.

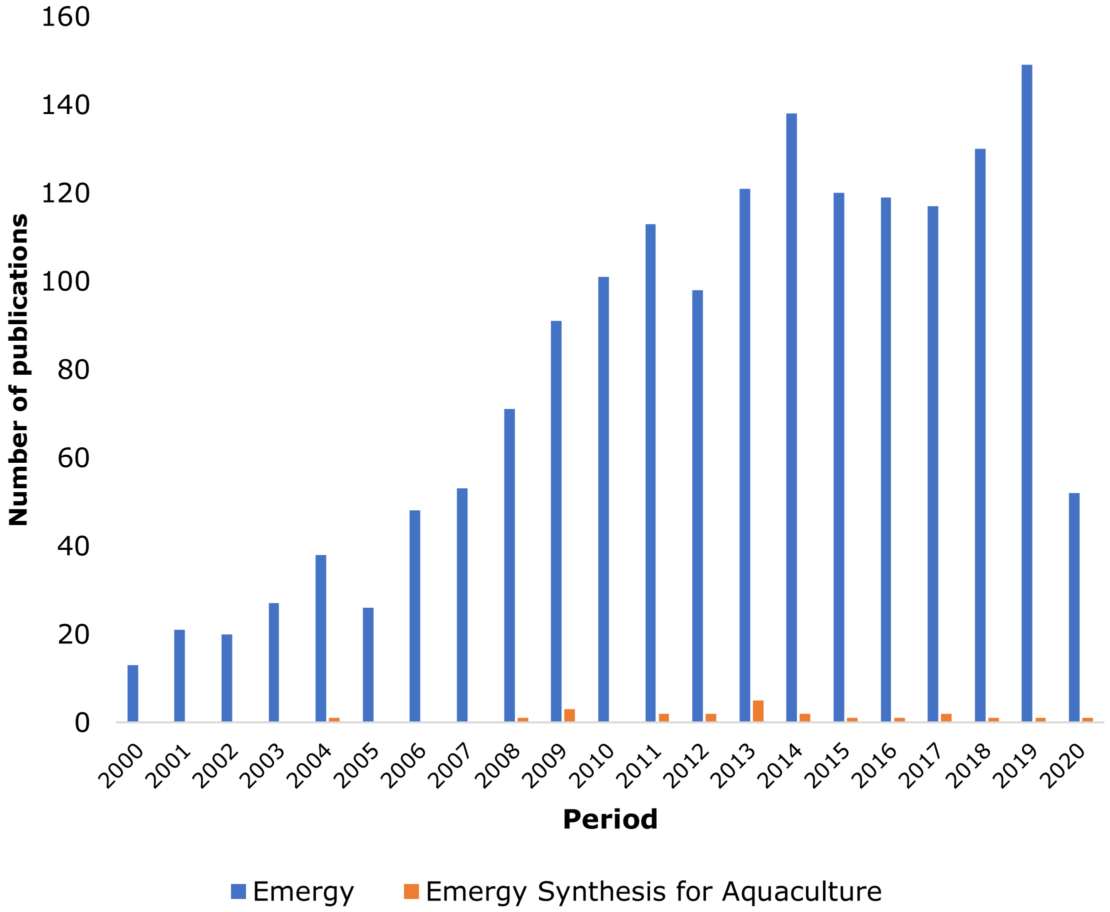

Figure 1. Evolution in the publication of scientific articles and review in the last 20 years with the theme emergy compared to emergy applied for aquaculture. Sources: The Science Direct, Web of Science and Google Scholar databases.

3. Overview of emergy synthesis applied to aquaculture systems

Using ES in aquaculture has become more popular recently. According to our review, besides existing work published in 1991, only after 2000 can an increase of published papers be observed, reaching 16 papers until January 2020. In general, ES has been used to assess sustainability of monocultures, integrated production (polyculture), levels of intensification (intensive, semi-intensive, extensive) and alternatives to traditional management. Applications occurred in production systems for different scales, species, regional distribution, levels of intensification, management, and structures. Table 1 presents an overview of papers considered in our review work.

Table 1. Overview of published papers that applied emergy synthesis on aquaculture production systems between 1991 and 2019.

Species and production systems	**Objectives**	**Main outcomes**	**Reference**
Shrimp mariculture.	Evaluate the shrimp pond mariculture in Ecuador.	Fuels, services, and post-larvae represented the largest emergy expenditure. In addition, pond yields are much higher than the less intensive systems. This may indicate a wasteful process that uses too many resources for the results obtained. It may mean the system is vulnerable to being replaced by less intensive, older systems when prices vary.	Odum & Arding (1991)
Salmon (*Salmo salar*) in pond monoculture.	Evaluated the sustainability of salmon pond monoculture in United States.	Results showed that the value paid for salmon farmed in ponds should be two times higher as the current price if the environmental resources were valued. Ecosystem performance of salmon production showed that more emergy was needed for this farming than for production of most cultured fish species.	Odum (2000)

Grains, pig and fish in integrated production system and in subsystems in a separated way.	Evaluated environmental aspects of integrated production systems of grains, pig and fish in small farms in the South region of Brazil.	Integrated system had better emergy efficiency, it was more sustainable and less stressful to the environment compared to grain, pigs and fish production subsystems in a separated way. Thus, using integrated systems was encouraged by the authors, because the transfer of emergy between the cultures can be an important strategy to sustainable production.	Cavalett *et al.* (2006)
Gilthead Sea Bream (*Sparus aurata*) in an inshore fish farming system.	Evaluated the environmental sustainability of an inshore fish farming system in Italy.	The inshore fish farming in a protected area of the Mediterranean Sea caused high environmental stress. The largest inputs of emergy were the purchase of fingerlings, goods and services provided. These last two were the main inputs of non-renewable resources into the system. The high dependence on resources from economy and the inability to exploit local natural resources affected the sustainability of this productive process.	Vassallo *et al.* (2007)
Gilthead Sea Bream (*Sparus aurata*) in an inshore fish farming system.	Verified if a dynamic emergy approach can be used to improve the management of a fish farm by assessing the variations of emergy and transformities during the rearing process. Also, detected the phases	The results showed that the patterns of emergy use oscillated over a year due to variations in the climate, the availability of renewable resources and the price of inputs. Among the considered flows, the	Vassallo *et al.* (2009)

	of the process that most affect the emergy value of a fish reared in the examined system structure.	purchase of fingerlings represented the largest emergy contribution. Thus, to improve the sustainability of the analysed system, authors suggested that productive schedules should be adopted to improve the efficiency of process, according to seasonal availability of resources and local climatic conditions.	
Monoculture of eel (*Anguilla japonicus*), weever (*Micropterus salmoides),* and polyculture of ophicephalus (*Channa argus*) and mullet (*Mugil cephalus*) in ponds.	Evaluated the sustainability of three production systems through emergy and economic assessment, in China.	The three studied systems presented similar emergy characteristics, but different economic features. Eel farming proved to be the best option for improving the local economy and did not increase the environmental impact. The production of fingerlings in the farm was the strategy found in all cultures to reduce the cost of production and the high input of resources from economy. The study showed that the presence of natural reserves could increase regional sustainability, although these reserves was not economically viable. The authors emphasized that the emergy synthesis proved to be a good complement to economic assessment in the evaluation of the production efficiency, environmental impacts, economic	Li *et al.* (2011)

		benefits, ecological and the sustainability of aquaculture systems.	
Polyculture of grass carp (*Ctenopharyngodon idellus*) and silver carp *(Hypophthalmichthys molitrix*) in cages, reared with natural food with plankton; Polyculture of grass carp, silver carp and spotted silver carp *(Aristichthys mobilis)* in ponds, reared with feed; Polyculture of grass carp and silver carp in extensive ponds, reared with feed by grass gathered around.	Compared the different fish farming systems in relation to resource use and environmental impacts, in China.	Results showed that the main difference between the three production systems was the emergy cost associated with the feed adopted for the fish. The emergy indicators showed that the intensive production with feed was not sustainable. The most intensive management system was characterized by an ESI (Emergy Sustainability Index) less than 0.4, while the other systems showed higher sustainable values. However, the use of plankton and grass was not economically viable.	Zhang *et al.* (2011)
Extensive polyculture of grass carp (*Ctenopharyngodon idellus*) and silver carp (*Hypophthalmichthys molitrix*).	Evaluated and compared the environmental performance of four local systems of agricultural production: maize planting, duck rearing, mushroom planting, and carp polyculture, in China.	Duck rearing and mushroom cultivation, activities implemented with the aim of diversifying local agricultural production, were not sustainable. Extensive polyculture of carp presented the best emergy performance, mainly renewability and sustainability indicator.	Zhang *et al.* (2012)

Conventional semi-intensive and extensive organic shrimp farming (*Litopenaeus vannamei*).	Evaluated and compared the sustainable performance of conventional and organic shrimp farming, in Brazil.	Both systems presented high emergy flow of non-renewable resources. However, the results showed that the indicators of renewability, emergy yield ratio and emergy investment ratio were favourable to the organic shrimp farming. New improvements in the organic system were indicated to increase efficiency and ensure its economic sustainability, given the low price practiced to sale of organic shrimp. The authors suggest that multitrophic systems would be very useful because they allow the increase and diversification of production without increasing the consumption of feed, the main non-renewable source used in aquaculture.	Lima *et al.* (2012)
Monoculture of kelps (*Laminaria japonica*) and scallops (*Chlamys farreri*), and polyculture of kelps and scallops.	Evaluated the ecological benefits of monoculture of kelps and scallops, and polyculture of kelps and scallops, in China.	Polyculture had the highest sustainability indicator compared to other two isolated monocultures. The study showed that integration was a sustainable aquaculture model.	Shi *et al.* (2013)
Intensive recirculation salmon (*Salmo salar*) farming; Extensive polyculture of common carp (*Cyprinus carpio*), tench (*Tinca*	Evaluated the environmental performance of the systems combining the emergy assessment and life cycle analysis in France.	Recirculation system, with low feed conversion ratio, presented less environmental impact than the two polyculture farms, when the effects on	Wilfart *et al.* (2013)

tinca), roach (*Rutilus rutilus*), perch (*Perca fluviatis*), sander (*Stizostedion lucioperca*) e pike (*Esox lucius*) in ponds; Semi-intensive polyculture of common carp, tench, reach, perch, sander and pike in ponds.		climate change, acidification, electricity demand, soil degradation and water dependence were considered. However, the recirculation system was identified as highly dependent on resources from economy. Polycultures adequately incorporated renewable resources but had greater environmental impacts due to the inefficient use of economic inputs. This study emphasized that the key factors needed for successful ecological intensification of fish farming should be minimizing the economic inputs, reducing feed conversion ratio and increasing the use of local renewable resources. The combination of these two methods was a practical strategy to study the optimization of efficiency of aquaculture systems.	
Intensive offshore large yellow croaker *(Pseudosciaena crocea)* farming in cages.	Evaluated sustainability of a small fish farm by using a modified ecological footprint approach based on the ecological footprint method and the Emergy Assessment, in China.	The emergy footprint was 1,953.9 hectares, an area 14 times larger than the support capacity and 293 times larger than the physical area occupied by fish farming. This meant that around 2,000 hectares of ecologically productive land were needed to support the fish farming. The most representative inputs of the emergy	Zhao *et al.* (2013)

		footprint were forage, fingerlings, and fuel. The authors concluded that the combination of these two assessment methods can serve as a practical and efficient for comparing and monitoring the environmental impact of fish farming. In addition, the high dependence on external contributions affected the sustainability of fish farming.	
Tilapia (*Oreochromis niloticus*) cage farming.	Evaluated the sustainability of tilapia cage farming in a hydroelectric reservoir, in Brazil. In addition to simulating management techniques and public policies that contribute to sustainability of this production system.	Emergy synthesis showed that the production system is inefficient and pointed out the causes. To solve this problem, it was suggested to adopt managements that proportionally reduce the supply of feed and increase the input of renewable resources. The suggested managements were the reduction in stocking density and the increase in dilution area of the organic load.	Garcia *et al.* (2014)
Indoor, semi-intensive and extensive farming systems of sea cucumber (*Apostichopus japonicus*).	Evaluated the sustainability and environmental impact of three sea cucumber farming, in China.	Indoor systems had greater input and output of resources compared to extensive. The semi-intensive system presented the lowest productivity among the three systems. All emergy indicators of extensive system were better than indoor	Wang *et al.* (2015)

		and semi-intensive systems. This indicated that extensive system exerted less stress on environment, used the available resources more efficiently, and better met the requirements of sustainable development compared to indoor and semi-intensive production system.	
Oyster (*Crassostrea virginica*) aquaculture farm in floating rafts and on-bottom cages.	Evaluated and compared the sustainability of two intensive oyster aquaculture farm, in United States.	Both systems were supported by emergy of resources from economy, such as human-labour, purchase of fingerlings, fuels, goods and services. Compared with other aquaculture products, oyster aquaculture farms were supported by a higher percentage of local renewable resources, mainly by particulate organic matter and estuarine water circulation. Overall, the study showed that oyster aquaculture farms generated less environmental impact, greater sustainability and greater benefit to society than other forms of aquaculture. The authors suggested that reducing fuel and electricity use would be two efficient ways to increase the sustainability of oyster aquaculture farm.	Williamson *et al.* (2015)

Cropping, poultry rearing, and fish production systems.	Evaluated and compared the environmental performance of three monocultures, in China.	Fish farming had the largest input of renewable resources, showing less dependence on economy compared to other crops. Emergy indicators showed that the fish farming system was more sustainable than other crops. The authors recommended public policies that encourage sustainable agricultural production by local producers, besides the use of clean energy in the productions.	Cheng *et al.* (2017)
Tilapia (*Oreochromis niloticus*) cage farming with substrates for periphyton.	Evaluated the sustainability of tilapia cage farming, in Brazil. Emergy accounting was utilized to evaluate whether the use of periphyton as a complementary food and the reduction of storage density improve the sustainability of this production system.	Tilapia cage farming is highly dependent on resources from economy, and feed is mainly responsible for this. Thus, the decrease in stocking density and feed rate, combined with the use of periphyton, improved all emergy indices evaluated. The use of periphyton to feed cultured fish combined with a reduction in feed use and a decrease in the stocking density promote the sustainability on tilapia cage farming.	David *et al.* (2018)

In current practice of aquaculture, given the scarcity of natural resources and the growing pressure for environmentally correct production (Valenti *et al.* 2011), the trend is that producers seek systems or management strategies that correspond to the market demand, current legislation, local weather conditions, and at the same time the use of local, renewable resources to increase their sustainability. However, fully sustainable aquaculture production systems are rarely found. Instead, there is a gradient between sustainable and unsustainable systems. According to Zhang *et al.* (2011), different levels of sustainability can be measured, recognized and categorized. From an emergy perspective, aquaculture as it is currently practiced is highly dependent on resources from economy and non-renewable natural resources which is an indicative of low sustainability. Therefore, identifying the emergy input flows on a production system that can positively or negatively act on its environmental performance is a crucial step to guide aquaculture for sustainable development. Negative aspects indicate weaknesses in the production process and show the need for improvement. For example, Vassallo *et al.* (2007) and Wang *et al.* (2015) showed that using resources from the economy, e.g. labour, fuel, capital costs, etc., is a weakness in aquaculture production in the Mediterranean and China, whereas they could be using local renewable resources to replace those economic resources. Using massive quantities of renewable resources balances the system according to the natural capacity of the region in which they are located, making it economically and ecologically stronger and more sustainable (Vassallo *et al.* 2007; Wang *et al.* 2015).

ES applications can identify the emergy flows of each resource that drives aquaculture production, which verifies where, when and, sometimes, how to improve the systems' emergy performance. ES results show which technical managements can lead to environmental improvements, indicating how they can benefit from the environment and the local economy (Zhang *et al.* 2011; Garcia *et al.* 2014; Williamson *et al.* 2015). Analysing the studies presented in Table 1 enabled us to precisely identify some patterns on the representativeness of the emergy flows that affect aquaculture production. Feed and purchase of juveniles or fingerlings are the items identified with the highest emergy expenditure. Another important aspect is related to monocultures, which commonly demand more emergy from non-renewable resources compared to polycultures or integrated cultures, thus reducing their efficiency and sustainability. Considering the papers presented in Table 1, the adopted production technique and high contribution of non-renewable resources on emergy input flows are the main drivers leading aquaculture to unsustainability. Hence, there is a need for more research to assess alternative production systems that reduce their demand for non-renewable emergy, thus respecting their local biocapacity.

Through the review process, another important aspect is related to accounting procedures in emergy as considered by the authors. Inconsistencies were found regarding the choice of the unit emergy value (UEV) for water and feed input flows, and the way in which water resources were labelled as renewable or non-renewable resources. Furthermore, the lack of inclusion of ecosystem services and disservices, items generated during the production process, in the emergy synthesis of aquaculture systems was also identified. Due to their importance in ES, they are all described in detail in the next sections.

4. Insights into the main issues regarding the emergy synthesis for aquaculture

Aquaculture producers have invested in monoculture, resource-intensive systems to produce large amounts of fish in small physical spaces and short periods of time (Ayroza *et al.* 2011), seeking to meet the growing demand for food (FAO 2018) and at the same time aiming for higher profits. As a consequence, production systems are highly dependent on resources from the economy – mostly fossil-based ones – which cause high pressure on the natural environment by demanding these kinds of resources, and indicated by the environmental loading ratio (ELR) emergy index (Brown & Ulgiati 2004; Zhang *et al.* 2011).

Overall, the reviewed papers showed that traditional intensive aquaculture production systems can hardly have high levels of productivity and at the same time be sustainable (Lima *et al.* 2012), because high productivity is obtained from using large amounts of fossil-based resources, which consequently makes productive systems dependent on resources from the economy. A performance opposite to the one above is shown by those, still traditional, but extensive aquaculture systems that depend on local and more renewable resources, resulting in higher sustainability but with lower productivity.

Aquaculture system efficiency has been mainly based on the mass of aquatic organisms produced per volume of water used during the productive period (Roth *et al.* 2001; Valenti *et al.* 2018). Methodologies currently used to assess aquaculture sustainability do not consider that the intensification of monoculture increases the use of feed per water volume (Garcia *et al.* 2016). Thus, efficiency in aquaculture should reveal more than simply water consumption. At this point, ES appears as an alternative method in estimating system efficiency, because it is able to include the 'quality' of energy through its UEV which represents all the efforts previously made by nature to make the water and feed resources available. Since higher efforts or emergy, mainly from non-renewable sources, are needed to make feed rather than water, feed seems to negatively affect the sustainability of aquaculture (Table 1). In addition, using feed above the recommended levels results in water eutrophication and causes an even higher pressure on the environment. As also identified in the reviewed papers in Table 1, water usually comes from superficial reservoirs or rivers and is labelled as a renewable resource. The quality and source of water are recognized by ES, making it more appropriate in quantifying system efficiency (Odum 2000) than simply accounting for the volume of used water. ES thus reveals new insights into the current ideas about what sustainable aquaculture would be, changing the general idea of water as its 'main villain'.

Evaluating intensive cage farming systems, Vassallo *et al.* (2007) obtained low efficiencies in terms of the unit emergy value (UEV of 2.22E+06 sej/J), low sustainability (ESI of 0.29), and high environmental load ratio (ELR of 5.00). Similar to other references, these emergy indices show low environmental performance as a characteristic for intensive aquaculture systems, in general. However, specific techno-management practices in extensive systems have been adopted to produce fish similarly to fish growth in natural systems, which *a priori* would increase aquaculture sustainability. For instance, Zhang *et al.* (2011) compared different intensification levels for aquaculture production and found higher sustainability (ESI 4.61) and lower loading ratio ELR (0.38) for the extensive system compared to the semi-intensive one (3.98 and 0.55 for ESI and ELR, respectively), but the efficiency as represented by the UEV still showed to be lower (5.23E+05 and 4.61E+06 sej/J). From an economic point of view, the low yields of extensive aquaculture systems reduced the financial returns, making this system limited to local production and consumption of fish and/or farms that seek environmental certification (green labels) to sell their products to a differentiated market.

Integrated aquaculture systems, such as polycultures, are promising alternatives to optimize the use of resources by reducing the dependence on economic inputs (mainly feed) and increasing productivity (Shi *et al.* 2013; Wilfart *et al.* 2013; Cheng *et al.* 2017). Polyculture is a model of production in which more than one non-competitive species from different trophic levels are grown at the same time and culture unit (Boyd *et al.* 2020). In this case, the 'waste' generated by a production chain becomes a 'potential resource' to another, which from a systemic perspective will reduce production costs and emission of pollutants into the environment (Shi *et al.* 2013). For example, Cavalett *et al.* (2006) compared the integrated production of grains, pigs and fish with their production in monoculture systems. Their results showed that the integrated system has higher sustainability, higher efficiency (9.40E+05 sej/J vs. 3.00E+06 sej/J), and a lower loading ratio (ELR of 3.13 vs. 3.59) than monocultures.

Usually, food production in integrated systems shows additional advantages besides better emergy indices. For example, Kremen and Miles (2012) found evidence to support the advantages of biologically diversified farming systems in terms of biodiversity conservation, control of arthropod pests, weeds and diseases, pollination services, soil quality maintenance, energy use efficiency and a reduction in global warming potential, resistance and resilience of farming systems to extreme weather events and enhanced carbon sequestration and water-holding capacity in surface soils. As an example of an integrated system in aquaculture, 'aquaponics' that is a combination of intensive aquaculture with soilless plant production (hydroponics) has been recognized as being environmentally friendly. Although using resources effectively (Pinho *et al.* 2017; Palm *et al.* 2018) and presenting potential economic results when applied commercially (Quagrainie *et al.* 2018; Greenfeld *et al.* 2018), aquaponics is often considered as a tool for education and social inclusion (König *et al.* 2018). Since we did not find any type of emergy synthesis of aquaponic production in the scientific literature, efforts on assessing its sustainability are needed.

5. Aspects that deserve attention when applying emergy synthesis to aquaculture systems

After carrying out a literature review (Table 1), we were able to identify and discuss specific aspects that require attention when applying ES to aquaculture systems. The key aspects are related to the choice of UEV for feed and water input flows, the classification of water input as a renewable or non-renewable resource, the way in which water input is accounted for in emergy tables, and issues related to environmental services and disservices. All these aspects are discussed separately in the next sections for a better understanding.

5.1. Feed

The feed accounts for up to 70% of production costs in intensive aquaculture in monoculture systems when traditional economic evaluations (willingness to pay) are carried out (Ayroza *et al.* 2011). According to most of the studies presented in Table 1, feed is also the most expensive item from an ES perspective. This may be related to its energy-intensive production chain, which demands raw materials (fishmeal, blood meal, bonemeal, feather meal, soybean meal, corn meal, wheat meal, mineral supplements, and vitamins), machinery, equipment, electric power, vehicles, fossil fuels, etc., to be produced and delivered to aquaculture producers. Detailed information on feed production (including the amount and kind of resources and industrial processes) is scarce, usually because industries consider feed production as confidential material that should be maintained to avoid market losses. As a result, the UEV for feed used in most ES studies is based on outdated data, which would reduce the precision of ES results. This requires studies that update the feed UEV.

Management aimed at reducing feed and increasing the use of natural food, e.g., phytoplankton, zooplankton, and periphyton, is encouraged (Cheng *et al.* 2017). The use of natural food to supplement fish feeding was evaluated using ES and showed to be a real alternative to increase the sustainability aspects of systems (Zhang *et al.* 2011; David *et al.* 2018). Artisanal feeds, which are locally made by small producers within their own farms, may be an alternative to replace the manufactured feed. Because local available ingredients are used in the artisanal feeds and a limited number of steps in the production chain are needed compared to manufactured ones, artisanal feed leads to lower dependence on large machinery, fossil fuels and manpower. Another alternative to meet sustainable feeding production is by using Biofloc Technology (BFT). BFT is an intensive aquaculture system technology where microbial communities are stimulated to allow minimal water exchanges, production and availability of *in situ* natural sources of food (Emerenciano *et al.* 2017). As well as the aquaponic system, BFT is usually labelled as sustainable food production (Bossier & Ekasari 2017). However, when considering all the infrastructure and electricity needed to maintain a BFT system, this label is questionable. For both alternatives (artisanal and BFT), to reduce the use of manufactured feed, no papers applying ES to evaluate these two specific productions systems were found in our literature review.

Regarding feeding as one of the most important energetic and/or economic aspects for aquaculture production, inaccuracies in its UEV, even minor ones can cause strong effects on the results of ES. Generally, the UEV chosen by the ES analyst is based on previously published assessments that may not have the same characteristics of the system being evaluated. As the feed represents 4.5% to 76% of the total emergy of intensive aquaculture systems (Table 2), special attention must be given when choosing the feed UEV to increase the accuracy of the study, either for feed or natural food. Differences in feed UEV are mainly related to local food availability, price, nutritional requirement of aquatic species, distance between the industry and ingredient producers, etc. In other words, UEVs can be widely different depending on these aspects.

Table 2. Unit emergy values (UEVs) for feeding as used in the papers presented in Table 1.

Reference	**Specific characteristic**	**Origin of feeding**	**Feeding UEV**	**(sej/unit)**	**Total emergy flow (sej/year)**	**Feeding representatively (%)**
Odum & Arding (1991)	Shrimp production in ponds	Feed	1.31E+05	sej/J	2.18E+21	19.71
Odum (2000)	Salmon pond culture	Organic	2.09E+13	sej/kg	1.94E+20	5.05
Cavalett *et al.* (2006)	Extensive fish production in ponds	Not used	-	-	1.95E+09	-
Vassallo *et al.* (2007)	Marine inshore fish farming	Organic	1.00E+06	sej/J	1.60E+18	11.31
Li *et al.* (2011)	Eel pond farm	Forage	8.32E+11	sej/¥	2.14E+17	76.17
	Weever pond farm	Forage	8.32E+11	sej/¥	3.04E+17	52.30
	Ophicephalus and mullet pond farming	Forage	8.32E+11	sej/¥	2.37E+17	67.09
Zhang *et al.* (2011)	Cage fish farming	Natural (plankton)	3.19E+04	sej/J	2.74E+17	41.24
	Intensive pond fish farming	Feed	1.31E+05	sej/J	1.07E+17	30.75
	Semi-natural extensive pond fish farming	Not used	-	-	7.10E+16	-

Zhang *et al.* (2012)	Semi-natural extensive pond fish farming	Not used	-	-	7.16E+16	-
Lima *et al.* (2012)	Semi-intensive pond	Feed	2.05E+09	sej/g	5.84E+16	7.1
	Organic pond	Not used	-	-	5.16E+16	-
Wilfart *et al.* (2013)	Salmon	Feed	9.80E+08	sej/J	2.63E+18	45.63
	Extensive pond farming	Wheat	1.20E+06	sej/J	9.10E+17	63.74
	Semi-extensive pond farming	Feed + Wheat	1.20E+12	sej/kg	2.80E+17	12.96
Garcia *et al.* (2014)	Intensive tilapia cage farming	Feed	1.00E+06	sej/J	1.09E+17	76.43
Wang *et al.* (2015)	Indoor sea cucumber farming	Feed	1.92E+12	sej/kg	8.32E+18	21.15
	Semi-intensive sea cucumber farming	Feed	1.92E+12	sej/kg	1.91E+17	4.52
	Extensive sea cucumber farming	Not used	-	-	1.59E+17	-
Williamson *et al.* (2015)	Oyster farming	Natural (microalgae)	5.00E+04	sej/J	2.96E+13	16.42
David *et al.* (2018)	Traditional cage system	Feed	9.96E+04	sej/J	3.80E+15	67.08
	Traditional cage system with periphyton	Natural (periphyton)	2.71E+03	sej/J	2.45E+15	51.82
	Lower stocking density with periphyton	Natural (periphyton)	2.71E+03	sej/J	1.49E+15	38.77

From the reviewed papers in Table 2, the UEVs for feeding (sej/J, sej/kg and sej/g) showed high variability. For example, it ranges from 3.19E+04 sej/J for natural food (plankton) to 9.80E+08 sej/J for feed in salmon farms. This raises doubts about the accuracy of obtained results from those papers, as well the lack of standards for ES applications. We strongly support additional studies towards more precise and/or representative feed UEV for different production systems, species, and locations, since it is the most important input flow in aquaculture ES. Advances were made from a study conducted by Giannetti *et al.* (2019), who showed a linear relationship between energy and UEV, corroborating the hierarchical organization of the biosphere in terms of energy quality, according to the hypothesis of H.T. Odum and also allowing UEV estimates as a first proxy when UEVs are missing. It is important to emphasize that the need to expand the conversion factor database is also a 'temporal' aspect, because when more studies are carried out and the results obtained, more data is available, resulting in more accurate and standardized UEV values. However, emergy analysts who evaluate aquaculture production systems should make additional efforts to estimate and/or evaluate the feed that precisely represents the case in point, rather than using 'borrowed' UEVs from the literature and generating uncertainties. This issue also happens in other methods such as life cycle assessments, ecological footprint and embodied energy analysis. Nevertheless, while larger numbers of precise UEVs are still missing, an uncertainty analysis could be applied in ES (Li *et al.* 2011; Hudson & Tilley 2014).

5.2. Ecosystem services and disservices

Another aspect that deserves attention in sustainability assessments are the ecosystem services and disservices (ES&D) (MEA 2005; Shah *et al.* 2019). This concept has become popular in the field of environmental research and policy making in the past 20 years, since it was realized that food production systems can provide benefits beyond food (Aubin *et al.* 2019; Custódio *et al.* 2020). These production systems are managed mainly to provide food, fibre, and energy. At the same time, they can deliver a variety of ecosystem services, such as water quality regulation, climate regulation, and carbon storage, which indirectly controls greenhouse gas emissions. On the contrary, food production systems may also cause soil erosion, nitrogen leaching, and habitat deterioration, which are considered as ecosystem disservices (Shah *et al.* 2019).

Identifying ecosystem services and disservices (ES&D) from aquaculture production systems is an important and necessary aspect to differentiate those systems that consider their environmental, economic, and social benefits (services) and the negative impacts (disservices) on the society (Aubin *et al.* 2019; Shah *et al.* 2019). Identifying, defining, and quantifying ES&D can be considered as vital when dealing with the Earth's biocapacity to support human-made systems. The amount and/or value of ES&D should be accounted for in sustainability analyses, such as emergy synthesis, to better reflect the performance of a production system and define ways to make it more sustainable. Systems that provide ecosystem services should receive some support, while those that cause disservices should be responsible for the damage caused (Custódio *et al.* 2020).

Including ES&D in the revenue or in the production costs has been a challenge for economists and environmental scientists involved with aquaculture sustainability studies (Valenti *et al.* 2018). Although some authors have suggested ways to measure and value ES&D (Table 3), there is a lack of a conceptual framework supporting the identification and linkage of ES&D with different aquaculture systems, as well as its integration with sustainability assessment tools (Kim *et al.* 2017; Alleway *et al.* 2019; Willot *et al.* 2019). Within this context, there is an opportunity to use emergy synthesis as a potential tool to provide this framework (Ortega & Bastianoni 2015).

Table 3. Ecosystem services and disservices of aquaculture production systems.

Items	Quantification approach	Inclusion approach	Reference
Ecosystem services			
Climate regulation service	Greenhouse gas balance	Carbon credit	Boyd *et al.* (2010), Thompson *et al.* (2014), Malik *et al.* (2015), Alleway *et al.* (2019), Aubin *et al.* (2019), Custódio *et al.* (2020)
Water purification	Removal of N, P in the water and indicators of eutrophication reduction	Payment for environmental services based on water quality	Alleway *et al.* (2019), Aubin *et al.* (2019), Custódio *et al.* (2020)
Recreation/Ecotourism/ Environmental Education	Number of visitors	Tax of visitation	Alleway *et al.* (2019), Aubin *et al.* (2019), Custódio *et al.* (2020)
Ecosystem disservices			
Greenhouse gas emission	Greenhouse gas balance	Tax of carbon emission	Boyd *et al.* (2010), Thompson *et al.* (2014), Malik *et al.* (2015), Alleway *et al.* (2019), Aubin *et al.* (2019), Custódio *et al.* (2020)
Eutrophication	Discharge of N, P in the water and indicators of eutrophication	Tax of eutrophication based on the cost to remove these nutrients from water	Verdegem (2013), Troell *et al.* (2017)
Effluent contamination by drugs, hormones, and chemicals	Discharge of pollutants in water bodies	Tax of pollution based on the cost to remove these pollutants	Vignesh *et al.* (2011), Lozano *et al.* (2018)

The application of ES&D concepts is recent in aquaculture sustainability assessments (Kim *et al.* 2017; Alleway *et al.* 2019), which explains the existing lack of standards concerning their application in ES studies. Through our literature review and experience in the field of aquaculture and emergy synthesis, we identified some aspects that require more research to overcome this lack of standards. Firstly, there is a need for a clear definition of the aquaculture's ES&D. Efforts in this direction were made by Aubin *et al.* (2019), who could be used as the first reference. They provided a list of ES&D from a general perspective, although it is worth mentioning that the ES&D differs for specific production systems. Secondly, there is a clear need regarding how to quantify ES&D. As presented in Table 3, ES&D are mostly quantified in economic units and then considered in emergy synthesis, however the inherent subjectivities behind economic methods require more objective (biophysical) approaches. Nevertheless, until a standardized and biophysical based approach is established, evaluating ES&D from an economic perspective would be a way to recognize their importance when dealing with sustainability assessments. Thirdly, there is a clear need on how to account for ES&D within ES. In the literature, there is a tendency to consider ecosystem services as a coproduct (an emergy output) and seeing it as positive aspect, while disservices are usually considered as a system input (an emergy input) and seeing it as a negative aspect. Both are usually estimated under economic approaches, and their classification as a non-renewable (N), renewable (R) or economic resources (F), as necessary within emergy synthesis, still lacks understanding, however relevant papers are still scarce and do not allow in-depth evaluations.

A balance between ecosystem services and disservices is necessary to determine, beyond the magnitude of the benefit or damage, environmental debit or credit generated by the production system (Ortega & Bastianoni 2015). Similar to other anthropic production systems, modern aquaculture is challenged to be efficient, highly productive and, at the same time, to cause a low load on the natural environment. Studies on ES&D in aquaculture are recent and regulatory agencies are still unaware of how to use them in public policies. Worst situations happen when society does not understand the concepts and/or physical relations of ES&D on limits of growth – maybe due to the neoclassical economic theories behind societal intellectual development. At this point, besides a change in development theories we teach our students another important aspect, which is to have more discussions in the scientific arena on ES&D and their importance when dealing with sustainability assessments. Here, discussions about the lack of existing standards in relation to ES&D in the emergy synthesis are of paramount importance and, as suggested by Ortega and Bastianoni (2015), the International Society for the Advancement of Emergy Research (ISAER) has an important role in improving its database with energy diagrams (models), description of input flows, renewability, and supply of updated UEVs for a large number of production systems.

5.3. Water

Concerning water, our literature review showed the existence of three main issues when applying emergy synthesis on aquaculture: (i) outdated UEVs; (ii) classification of water as a renewable or non-renewable resource; (iii) the way in which water is accounted for in emergy tables. Besides water being the fundamental resource for all aquaculture production systems and vastly used in aquaculture emergy synthesis, there is a lack of updated values for water UEV, because it has remained almost unchanged over the last years (Table 4). Thus, water UEV must be revisited and updated, also by considering the advances in emergy analysis and water treatment technologies over the last twenty years. Additionally, clear criteria in labelling water as a renewable (R) or non-renewable (N) resource is generally missing. Notwithstanding, water is usually evaluated or quantified in inappropriate ways by considering the total volume of water that flows through the system and not the water really used. Since water is probably the most used (in mass or volume) resource in aquaculture studies, wrong interpretations of water resource classification, the way in which it is evaluated, and its UEV would result in high inaccuracies on the final numbers and lead to wrong interpretations.

Table 4. Unit emergy values (UEVs) and classification of water resources as usually found in emergy literature applied to aquaculture production systems.

Reference	**Water Source**	**Classification**	**UEV (sej/J)**	**Original source for water UEV**
Odum & Arding (1991)	Sea water	Renewable	1.54E+04	Estimated
Odum (2000)	Estuarine freshwater	Non-renewable	1.19E+11	Estimated
Cavalett *et al.* (2006)	Ground water	Non-renewable	2.55E+05	Odum & Arding (1991)
Vassallo *et al.* (2007)	Rain	Renewable	1.54E+04	Odum & Arding (1991)
Li *et al.* (2011)	River water	Renewable	5.01E+04	Campbell *et al.* (2005)
Zhang *et al.* (2011)	Ground water	Non-renewable	8.06E+04	Odum (1996)
Zhang *et al.* (2012)	Ground water	Non-renewable	8.06E+04	Odum (1996)
Lima *et al.* (2012)	Estuarine freshwater	Non-renewable	8.10E+04	Brown & Ulgiati (2004)
Wilfart *et al.* (2013)	Ground water	Non-renewable	1.60E+05	Odum & Arding (1991)
Garcia *et al.* (2014)	Spring water	Renewable	1.66E+05	Buenfil (2001)
Wang *et al.* (2015)	Not considered	-	-	
Williamson *et al.* (2015)	Not considered	-	-	
David *et al.* (2018)	Rain	Renewable	2.36E+04	Odum (2000)

By definition, the label 'renewable' depends on the extraction rates, in other words, to be renewable a resource cannot be extracted at higher rates than its natural reposition (Valenti *et al.* 2011). Deep water (groundwater and aquifers) takes, on average, a long time to be renewed, and thus it is usually labelled as a non-renewable resource and has high UEV (Cavalett *et al.* 2006; Wilfart *et al.* 2013). On the other hand, surface waters (rain, rivers, spring water and seawater) require less effort from nature to be cycled and are used at higher rates than groundwater, resulting in lower

UEVs and are labelled as a renewable resource (Odum 2000; Vassalo *et al.* 2007; Li *et al.* 2011; Wang *et al.* 2015; Cheng *et al.* 2017). These concepts and approaches for water classification are usually misunderstood by some emergy analysts when assessing aquaculture systems, since it is not hard to find published papers in which emergy analysts do not provide clear criteria in labelling water resources, thus raising doubts about the obtained results.

Concerning the way water is accounted for in emergy tables, we provide our comments in accordance to the different kinds of aquaculture production management. Figure 2 shows the aquaculture system most often described as traditional during our literature review, which is the system with untreated water renewal prior to disposal. Typically, these are open systems (generally in natural water bodies such as oceans, estuaries, bays, lakes, rivers) or semi-closed systems (those in which water flows through the system once and it is subsequently discharged). Water sources can change depending on the local availability (i.e. rivers or groundwater). In these systems, water flows into the system to fill the ponds and/or cages where the aquaculture production happens. The volume of water flowing in is the same as that of flowing out, but the latter has lower quality with higher concentrations of nutrients and organic compounds. Since these systems rarely have a water treatment process unit, this low-quality water is directly disposed into the natural water bodies, potentially causing a disservice to the environment and society. As we found during our literature review, water is accounted for and classified as renewable (R) or non-renewable (N) in the emergy tables according to its volume and source (river or groundwater), as shown by the input flows in red shown in Figure 2. However, according to the definition of solar emergy - "available solar energy used up directly and indirectly to make a service or product" -, we acknowledge that this procedure in accounting water resources is misleading and should be corrected. The output flow is generally not considered in ES of aquaculture systems and, when considered, is quantified using economic approaches and accounted for as a service (S), as discussed in the previous section.

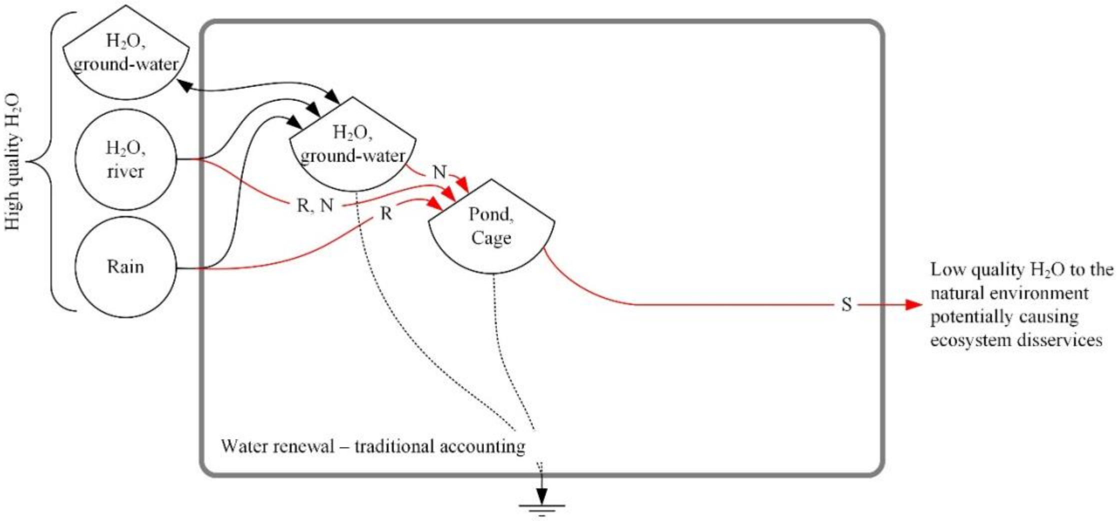

Figure 2. Energy diagram of traditional aquaculture systems as usually found in the emergy literature. Symbols from Odum (1996). Legend: R, renewable; N, non-renewable; S, service.

Figure 3 provides a more aligned perspective with the definition of emergy, in which aquaculture systems should be seen. In this case, a water treatment process is present since the production system is responsible for improving the effluent water quality before discharging the effluent into the natural environment. The treatment must achieve, at least, the same quality standards of the water before it enters the production system. In this type of production system, the amount of water that must be accounted for in emergy tables is that evaporated and embodied in the fish bodies (output flows in red in Figure 3), both classified according to the water source (renewable or non-renewable, R&N). Besides the amount of water, all emergy for the water treatment also needs to be accounted for in the emergy tables, and it is classified as economic resources (materials and services, M&S). In a case where there is no water treatment process, which is often found in rural aquaculture systems (Figure 2), the emergy of water treatment must be estimated accordingly and then accounted for in emergy tables.

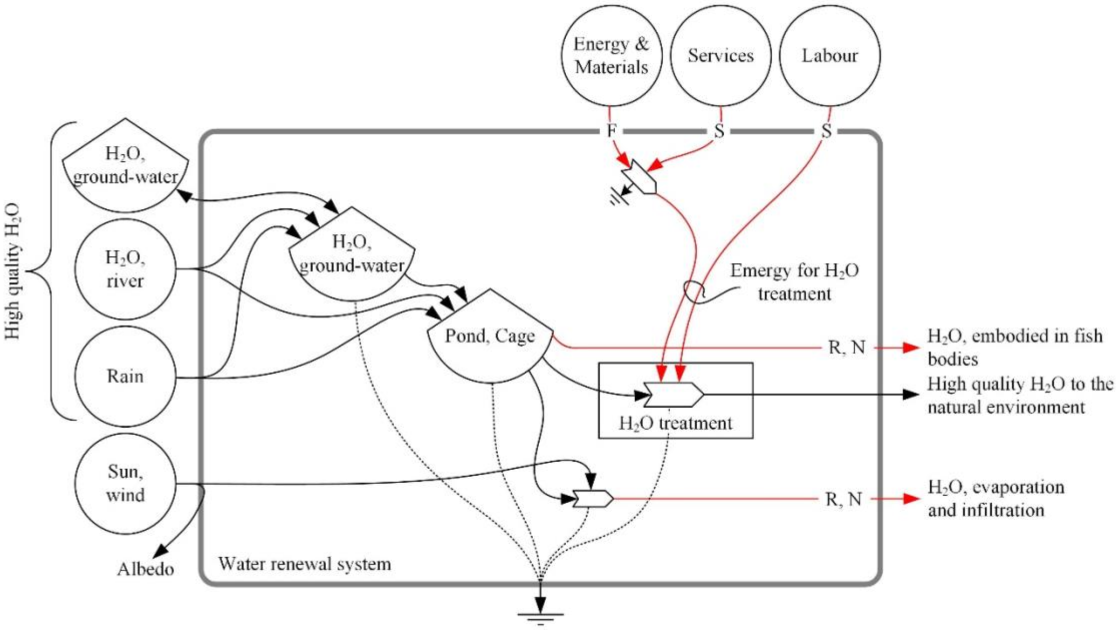

Figure 3. Energy diagram of traditional aquaculture systems with water renewal and treatment as usually found in the emergy literature. Symbols from Odum (1996). Legend: R, renewable; N, non-renewable; M, materials; S, service.

Other aquaculture systems that deserve attention are those with limited water renewal, such as Recirculation Aquaculture Systems (RAS) and aquaponic systems. Figure 4 shows an aquaponic system, in which besides producing fish, the effluent water rich in nutrients and organic matter is used to produce vegetables in a hydroponic way. This system recycles almost all the water demanded in the beginning of the production cycle, losing water exclusively embodied in the harvested fish and vegetables, and due to evapotranspiration. For this system, only the water loss should be accounted for in the emergy tables (output flows in red in Figure 4) and classified as renewable (R) or non-renewable (N) according to its source.

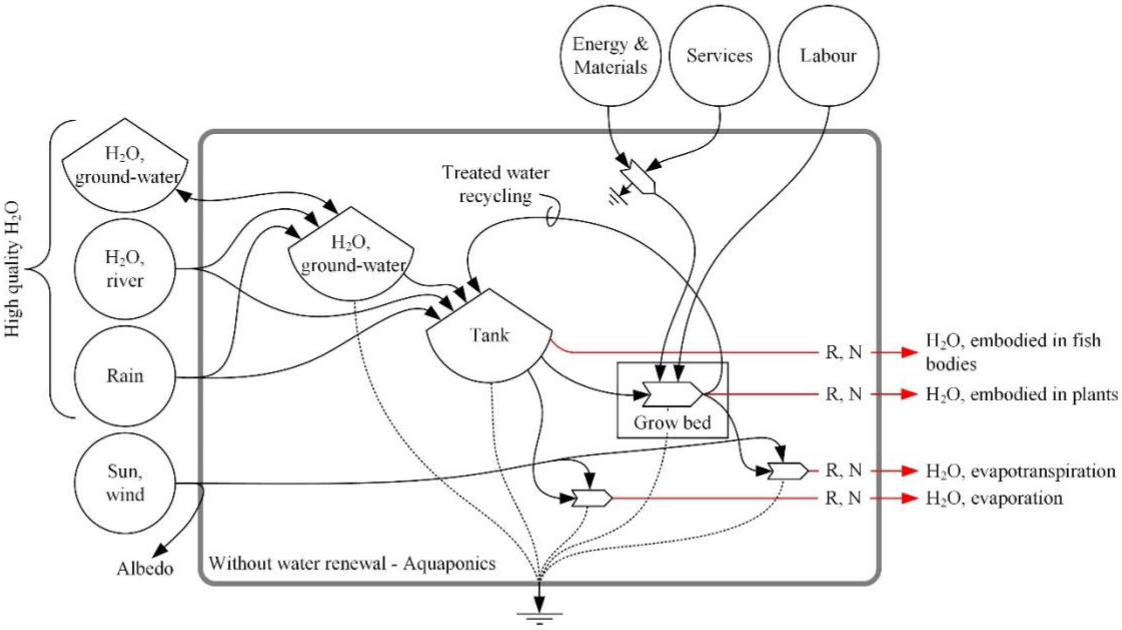

Figure 4. Energy diagram of Recirculation Aquaculture Systems (RAS) combined with hydroponic system, also known as aquaponics system, with limited water renewal. Symbols from Odum (1996). Legend: R, renewable; N, non-renewable.

We have no intention to present all different kinds of aquaculture systems, although most of them are derived from the two presented in Figures 3 and 4 and use the same concepts. Most important is that emergy analysts provide high-quality energy diagrams to better understand and communicate how the system under study works, and always remembering that there is a method as a backbone (emergy accounting) with definitions and rules that must be respected.

6. Emergy synthesis results as support for policies in aquaculture

The results of the sustainability evaluation by the emergy synthesis can serve as a basis for strategies to encourage sustainable practices. Knowing the transformity concept, distinguishing renewable from non-renewable resources and transforming all inputs and outputs into a single unit (emergy) lead to quantifying the sustainability of any product or service and the differentiation between more and less efficient production (Cavalett *et al.* 2006). These differentiations can generate future identifications of aquaculture products through seals and certifications. By doing this, consumers will be able to choose their products based on a categorization of sustainability (McClenachan *et al.* 2016).

The literature on ES for aquaculture proposes creating or adapting public policies that encourage farmers to adopt sustainable practices in their properties and benefit those who already do this (Cavalett *et al.* 2006; Zhang *et al.* 2012). ES could also guide the regulations for using natural resources and the support capacity of aquaculture systems (Garcia *et al.* 2014; Cheng *et al.* 2017). Considering the results of emergy synthesis, it would be possible to create specific lines of credit for sustainable production systems, and to pay farmers who generate positive impacts to society through a Payment for Ecosystem Services policy. In situations such as these, the aquaculture producer could, for example receive benefits by water remediation and by executing an efficient productive system.

Another way of using ES for public policy making is to encourage investments in more sustainable aquaculture systems by eliminating or reducing some taxes (Lomas *et al.* 2008). The change in taxes for other industries is already a reality. For example, the lower taxation of vehicles with less emission of pollutants or the reduction of taxes (up to 100% reduction) for farmers that adopt sustainable practices, such as planting trees on the borders of the production systems, reusing the water or harvesting rainwater, etc. Government programs can also promote aquaculture sustainable production systems by legislating the preference to purchase their products for the supply of public institutions.

Punishment for "bad producers" could be also guided by ES results, i.e. public policies can be developed to add tax to those who insist on practicing unsustainable management. Using the Emergy Exchange Ratio (EER), an ES index which measures the emergy exchanged in a trade or purchase (what is received to what is given) (Brown & Ulgiati 2004), is a way of measuring the monetary value of this punishment. David *et al.* (2018) evaluated different managements for tilapia reared in cages and showed that in the alternative system, with a reduction of 50% of the daily feed and using periphyton as a complementary food, the EER was 0.78. With this result, they showed that tilapia reared in this way may have its sales value reduced by 22% as compared to the traditional system. Under the policy of punishment, this difference in the sale value would be due to the additional taxes for the producers that apply the traditional managements.

In summary, emergy synthesis for aquaculture can guide public policies along two different lines: one that encourages more sustainable producers through specific lines of credit or tax reduction or one that punishes producers who do not use sustainable practices. The decision on which policy to apply will depend on the local and cultural conditions of each community. Nevertheless, the entire aquaculture production chain must be evaluated. In addition to public policies, the understanding and incorporation of sustainability concepts and the interpretation of ES results by the productive sector and society can guarantee the resilience of aquaculture activity over time. For this, it is extremely important that extension workers receive quality training to transfer these new approaches to producers, especially to those with low access to resources and information.

7. Final remarks

Aquaculture systems receive special attention due to their importance in producing proteins to feed the increasing world population. Besides economic and technical aspects, sustainability issues of aquaculture production systems also gain more attention in a world with reduced biocapacity. The most sustainable systems must be identified and supported through public policies and economic incentives.

Besides other methods, emergy synthesis (ES) is a powerful tool for assessing the sustainability of production systems due to its systemic perspective and donor side approach that allows it to quantify natural and economic resources based on their energy quality. ES of aquaculture systems is still in its infancy, which is expressed by the few number (16) of papers identified according to our literature review for the period from 2000-2020. The published papers clearly showed that feed is the most important resource of aquaculture systems, ranging from 4 to 70% of the total emergy required. It is also emphasized that there is a need for more renewable resources, in which natural feed has a huge potential. Additionally, aquaculture systems based on monoculture have lower emergy performance than the integrated ones (polyculture), indicating the latter as a preferable choice towards more sustainable fish protein production.

Another important result from this work was to identify aspects that deserve attention by emergy analysts when studying aquaculture production systems. The identified methodological shortcomings, lack of standards or misunderstandings are as follows: (i) outdated and/or not accurate unit emergy values for feed and water resources; (ii) the procedures used when classifying water input as renewable or non-renewable; (iii) the procedures used when accounting for water input in emergy tables; (iv) the identification and consideration of ecosystem services and disservices resulting from aquaculture. Since feed and water are the main input flows of aquaculture production systems, special attention to these should be given by emergy analysts to avoid misleading results and interpretations.

Regarding policy implications, ES of aquaculture systems can help to support those systems to become more sustainable through different ways, including economic incentives (tax reduction and loans with reduced interests), and establishing the so-called 'labels of sustainability' to increase market acceptance. All these efforts can directly and indirectly push those less sustainable systems to increase their performance, making sustainable designs as a rule as envisioned by the United Nations Sustainable Development Goals in the 2030 Agenda.

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Chapter 3

Sustainability of urban aquaponics farms: an emergy point of view.

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Sustainability of urban aquaponics farms: an emergy point of view

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Abstract

Aquaponics is a food production system that aims higher sustainability by integrating advantages gained from aquaculture and hydroponic production. Aquaponics aims to mimic the biological process that happens in the natural environment in a controlled production system. As it can be applied to small scales, aquaponics is considered an important alternative for urban regions, which have low availability of agricultural land and water resources. Furthermore, the advantage is that it is located close to final consumers. Aquaponics has been labeled as an environmentally friendly food production system, but its demand for energy and materials cast doubt on its sustainability. A systemic understanding of aquaponics production systems is needed to determine the magnitude and balance between its potentialities and constraints, in which emergy synthesis appears as a powerful tool for this purpose. This study applies emergy synthesis to assess the sustainability of two different (scale and marketable products) urban aquaponics farms in Brazil, but differently from other emergy studies, ecosystem services and disservices are included in the analysis as an attempt to represent the system performance holistically. Results show that the type of materials used in aquaponics infrastructures has the highest influence on total emergy demand. Surprisingly, electricity and fish feed showed a low influence on the total emergy, reinforcing the idea that aquaponics systems have a more efficiency feeding management than traditional aquaculture systems. Besides producing vegetables and fish, the inclusion of ecosystem services highlights the importance of aquaponics for educational and tourism purposes. Finally, the obtained indicators from modeling scenarios revealed that replacing the water source and some materials deserves priority attention to increase the sustainability of urban aquaponics farms.

Keywords: Aquaculture; Brazil; Ecosystem services and disservices; Emergy; Urban aquaponics farms.

1. Introduction

The population of cities has increased substantially over the last decades (UN, 2018). Urbanization has become a major global trend, and supporting it demands provision systems for infrastructure, logistics, communication, commerce, cultural aspects, tourism, and employment generation (Leamer and Storper, 2014). This expansion is accompanied by greater demand for food associated with supply chains from rural areas (Santos, 2016). However, producing food in rural areas and transporting it to support cities has been reported as one of the key contributors to increased greenhouse gas emissions, biodiversity loss, water pollution, land-use exhaustion, and a host of other environmental impacts (Goldstein et al., 2016). Thus, adopting urban or peri-urban production systems might be an alternative to help provide sustainable urban food consumption and reduce environmental impacts (Schumacher, 1973; Armanda et al., 2019).

To address food supply problems in cities, production systems located in urban centers have been developed. Compared to rural agriculture, growing food in urban areas has some important advantages, such as proximity to markets, fresh food provision, and reduced transport costs (Artmann and Sartison, 2018). Additionally, local food production also has positive effects in reducing negative environmental impacts due to its insertion in urban centers, promotion of the local economy, and strengthening social development (Goldstein et al., 2016). Vegetable production in urban gardens, buildings and/or house roofs, and hydroponic systems are probably the most popular agricultural food production model in urban centers (Rufí-Salís et al., 2020). Aquaculture, the fastest growing livestock activity in recent years (FAO, 2020), has also followed this trend and developed highly productive technologies for implantation in urban centers. Aquaponics is one of these technologies.

Aquaponics is an integrated food production system that combines fish and hydroponic vegetable crops (Yep and Zheng, 2019). Most aquaponics systems are run in one loop layout where water and nutrients are shared and recirculated between all compartments, i.e., fish tanks, mechanical and biological filters, and the vegetable production bed (Pinho et al., 2021). In an aquaponics system, the wasted nutrients from fish excrete and feed leaching are converted by microorganisms and used as fertilizer for plant production. The transformation of wasted nutrients into plant fertilizers has the potential to reduce the environmental impact of food production by fully utilizing the feed, minimizing the use of non-renewable resources such as industrial fertilizers, and reducing the need for large volumes of water and land (Joyce et al., 2019). Moreover, producing marketable food close to direct consumers and high diversity of vegetables and fish in small areas are also benefits promoted by aquaponics (Proksch and Baganz, 2020).

In addition to production efficiency, aquaponics is also seen as a suitable approach to promote educational and social outcomes (König et al., 2018). For example, Graber et al. (2014) and Junge et al. (2019) showed that aquaponics is a tool for teaching natural science concepts at all school levels, enhancing academic learning and providing students with the possibility of exploring educational skills. Improving the landscape in urban centers and serving as a leisure area open to public visitation have also been described as characteristics that positively impact society and can be considered a benefit of aquaponics (König et al., 2018; Aubin et al., 2019). These outcomes can be considered ecosystem services since aquaponics systems use a natural process to produce food and indirectly generate services that cause a positive impact on society (David et al., 2020). Ecosystem services (ES) are defined as direct or indirect benefits obtained by humans from natural ecosystems, processes, or production systems (MEA, 2005). On the other hand, ecosystem disservices (ED) are described as the processes, functions, and aspects resulting in negative impacts on human well-being (Shackleton et al., 2016).

Aquaponics has been labeled an environmentally friendly food production system (König et al., 2016). However, it is highly dependent on electricity and other non-renewable resources to support its need for constant oxygenation, water recirculation, and filtration (Baganz et al., 2020). Commercial aquaponics production may occur in controlled environments such as greenhouses, using high-cost methods and complex equipment demanding electricity. Additionally, filters from aquaponics systems need to be cleaned periodically, resulting in the discharge of nutrient-rich sludge from them into the natural environment (Abusin and Mandikiana, 2020). Although some solutions to reuse the sludge have been investigated, e.g., three-loops aquaponics layouts (Yogev et al., 2016), they are not yet applied in most commercial aquaponics production systems. Aquaponics sludge may cause ecosystem disservices by causing soil pollution, nitrogen leaching, and habitat deterioration (Shah et al., 2019). All these aspects cast doubt on the real sustainability of aquaponics systems.

Understanding all the strengths and weaknesses of aquaponics is necessary to determine the magnitude and balance between its benefits and harms. Sustainability assessments on aquaculture have been widely applied to quantify its sustainability degree, identify problems, and propose solutions (Valenti et al., 2011). Thus, some authors have used life cycle analysis (LCA) to assess the sustainability of aquaponics systems (Forchino et al., 2017; Maucieri et al., 2018; Chen et al., 2020). These studies have shown that the main aquaponics issues are related to its high electricity demand and the high infrastructure and equipment costs. Among other tools for assessing food production sustainability, emergy synthesis deserve attention. This is because emergy synthesis measures the pressure of the production system on the environment by accounting for all the direct and indirect energy required to produce goods or render services (Odum, 1996). Using this method, the natural environment's effort in providing resources and diluting waste is considered under a donor side perspective by recognizing the ‘quality’ of energy and converting different units of energy flows into solar emjoules, abbreviated as sej (Brown and Ulgiati, 2004). Emergy synthesis is a robust approach to support sustainable development initiatives (Giannetti et al., 2013). Besides being applied in very different production systems, emergy synthesis has already been used to quantitatively evaluate the sustainability of aquaculture production systems (David et al., 2020).

For aquaponics, emergy synthesis could be used to calculate whether its benefits overlap the negative points and guide the management and adoption of public policies to improve urban aquaponics farm sustainability. This study aims to contribute to the advances in the field by (i) investigating the sustainability performance of aquaponics systems using emergy synthesis and (ii) including ecosystem services and disservices in the emergy synthesis to discuss possibilities to better understand, quantify and represent the co-products generated by aquaponics systems.

2. Methods

2.1. Characterization of the aquaponics farms

The farms were chosen based on the study carried out by Portella et al. (2019), who conducted a nationwide data survey to identify Brazilian aquaponics producers and their main management practices. From the database generated by that study, two aquaponics farms were selected (Farms A and B) based on the following criteria: (i) both farms are located in urban centers of the São Paulo State, Brazil; (ii) they operate as coupled aquaponics systems, which means that the water and nutrients are recycled between all units as the aquaculture, hydroponics, and biological filter units are interconnected; and (iii) a complete and reliable database about their technological processes is available.

The evaluated farms differ mainly in the production scale, materials used in the greenhouse structures, and the quantity and variety of products sold. Raw data on materials and energy supporting both farms were obtained by a distance survey on their operational practices, and in situ observation by authors through fieldwork. The period of one year was considered for both data collection and field observations. Long-term solar radiation and meteorological data were obtained from the Integrated Agrometeorological Information Center (CIIAGRO, 2020). The solar transmittance coefficient into the plastic aquaponics greenhouse was assumed to be 0.81 (Sangpradit, 2014). Regarding the infrastructure facilities and equipment used, for those that last for more than one year, the energy input was converted into yearly flow according to their service life (Vassallo et al., 2007). Both evaluated farms have a greenhouse with a retractable structure that allows for opening and closing air circulation. The water used by the farms comes from the municipal supply system, and the differences in the quantities of water used by farms are due to the different dimensions (fish and vegetable tanks) of the systems used by them. The water volume needed to initially fill the tanks, as well as replace losses and evaporation were accounted for. Although the areas of the farms range from 195 to 460 m² (Table 1), the input and output values for each system were standardized for an area of 1 m^2 to enable comparisons.

Table 1. Technical and economic characteristics of the two urban aquaponics farms studied.

Item	**Unit**	**Farm A**	**Farm B**
Greenhouse area	m²	460	195
Initial water supply	m³	10	20
Replacement water	m^3/year	76	5.1
Electricity consumption	kWh/year	408	3,228
Stocked fish	unit/year	1,600	318
Initial average weight of fish	kg/fish	0.015	0.1
Final average weight of fish	kg/fish	NA	0.65
Fish produced	kg/year	NA	190.5
Seedlings	unit/year	24,840	12,000
Feed	kg/year	1,022	209
Supplementation (Iron)	kg/year	1.46	0.36
Supplementation (Calcium)	kg/year	NA	28.11
Supplementation (Potassium)	kg/year	NA	7.36
Skilled labor	hour/day	NA	8
Non-skilled labor	hour/day	5	5

NA: Not applicable.

2.1.1. Description of Farm A

Farm A is an aquaponics farm located in the city of Araraquara (238 thousand inhabitants) in Brazil. This farm focuses on the production and commercialization of vegetables. Moreover, it offers courses on aquaponics and environmental preservation. Figure 1 presents a conceptual model representing the functioning of Farm A under a systemic perspective, including internal processes and relationships, as well as the dependence of external resources and outputs generated. The diagram presented in Figure 1 was drawn using the symbol language defined by Odum (1996). Farm activities are performed without heavy machines and equipment, and exclusively through the labor of the two owners. The main farm activities are planting seedlings, feeding fish, harvesting, and selling the vegetables produced.

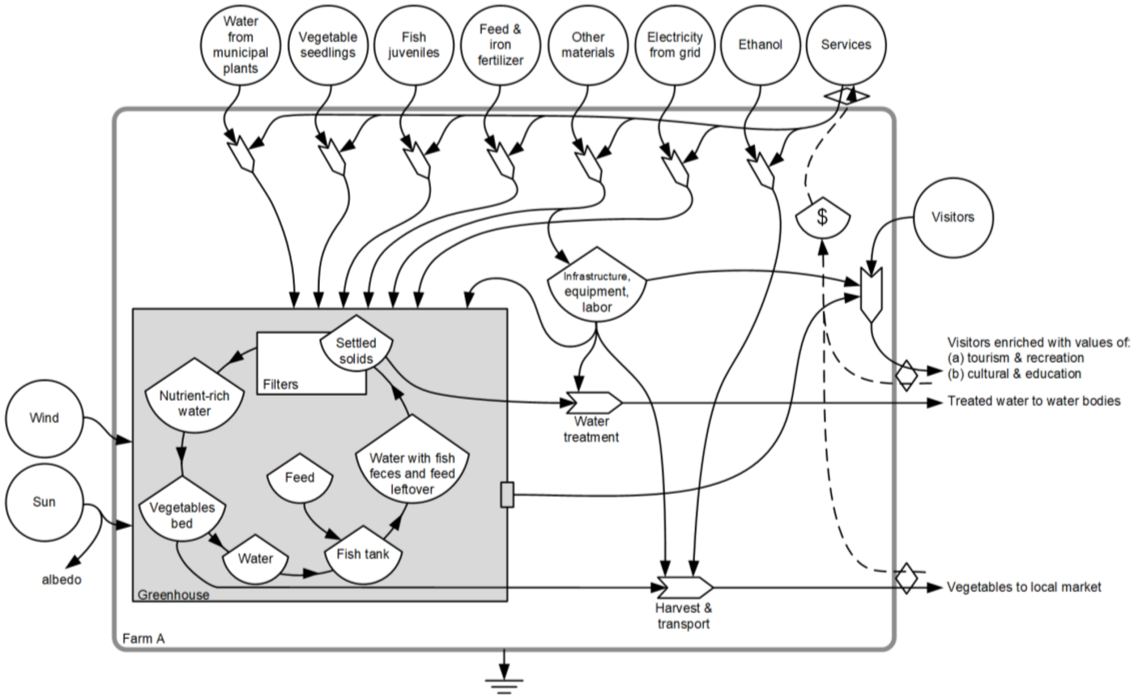

Figure 1. Energy diagram of the aquaponics system in Farm A.

The Nutrient Film Technique (NFT; Maucieri et al., 2019) is the type of hydroponic subsystem adopted, in which suspended gutters are used to accommodate the vegetables. Water is pumped from the sump to a fish tank, and then it goes by gravity through mechanical and biological filters, respectively. From the biological filter, the nutrient-rich water is pumped to the NFT gutters to nourish the vegetables and then returns to the sump by gravity. The filters are cleaned periodically, and the effluents and sludge removed are discharged to the natural environment. The electricity used to supply the aeration and pumping systems comes from the Brazilian national grid. Ethanol is the fuel used in vehicles to transport vegetables to the local market.

A variety of vegetables are produced, including lettuce, chives, parsley, watercress, and mustard, totalizing an average vegetable production of 5,520 kg/year. All vegetables are sold for 0.63 USD/unit. The Nile tilapia (*Oreochromis niloticus*) is the fish species reared; however, fish are not sold, and there is no fish harvest during the production cycles. Fish are used only to foment most of the nutrients needed by plants. Considering that the lifespan of fish reared in this situation is variable, and the adopted stocking density is low, the fish output can be considered negligible, thus we did not include the outcomes of this item in the emergy synthesis.

Farm A offers other services apart from vegetable production, such as courses and lectures on setting up and operating aquaponics systems. On average, three courses are given annually, which lasted eight hours each and reaches ~50 people. The physical space of the farm is also open for visitation and received 157 people in the assessed period. Farm A owners consider this to be the maximum capacity of their property in offering courses and receiving visitors.

2.1.2. Description of Farm B

Farm B is located in the center of São Paulo city (12.2 million inhabitants), Brazil, 279 km far from Farm A. Farm B is part of a non-governmental organization aimed to reintegrate people in social vulnerability. The system boundaries of Farm B are defined in the energy diagram presented in Figure 2, according to the symbol language defined in Odum (1996). Two different hydroponic subsystems are used in Farm B, i.e., NFT and Deep-Water Culture (DWC; Maucieri et al., 2019). In DWC subsystems, vegetables float in hanging support (rafts, panels, boards) filled with nutrient solution. Different to Farm A, Farm B has an anaerobic biodigester, which is used to treat the waste/sludge generated by the system during the production process. As a result, Farm B ceases to discard 255 L/year of sludge and 16.72 kg/year of organic matter in the environment, besides producing 47.6 m^3/year of biogas and 255 L/year of biofertilizer.

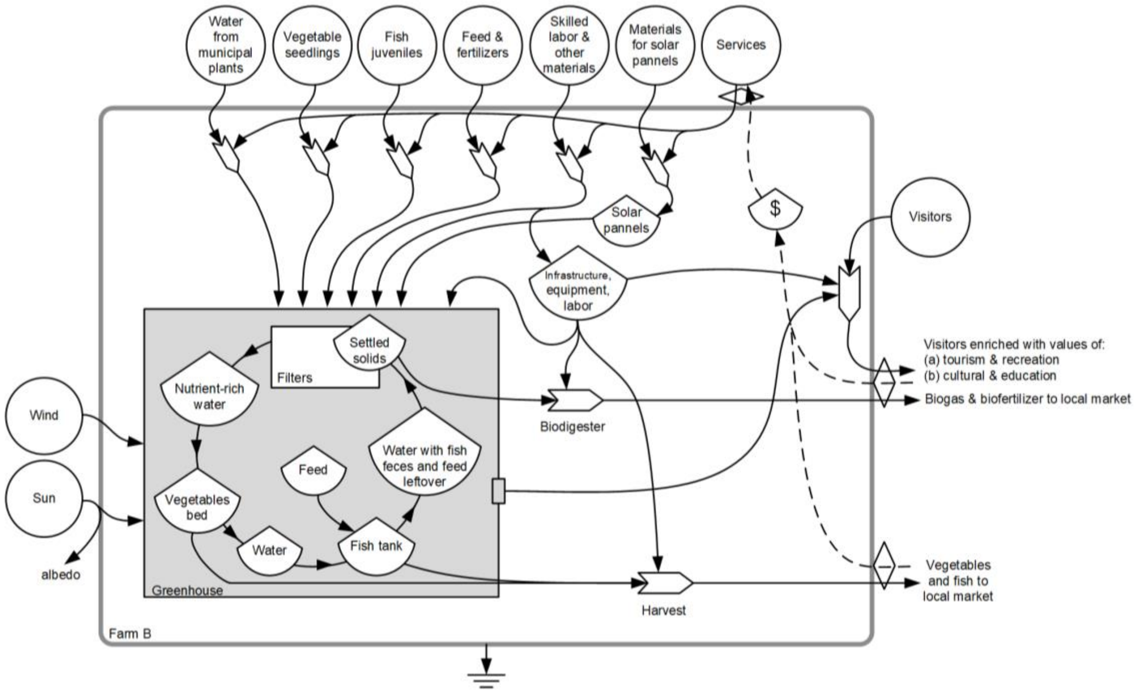

Figure 2. Energy diagram of the aquaponics system in Farm B.

Regarding the management of Farm B, two aquaponics specialists are responsible for technical reports, measurements, and improvements on the production system. Another person is responsible for monitoring the water quality parameters and the growth of fish and vegetables. The electricity used to keep the systems running is obtained from an off-grid photovoltaic system. An average of 190 kg/year of Nile tilapia is produced and marketed at 2.50 USD/kg. Lettuces, peppers, basil, chives and mint are the vegetables that are produced at an average total production of 2,640 kg/year and sold locally to farm visitors for 0.95 USD/kg. In the period analyzed, Farm B offered two courses and two workshops for students (including middle and high schools and college), social organizations, and the general community. Educational, tourist, and other visitors achieved ~213 people. Farm B managers consider this to be the maximum capacity of the property in offering courses, workshops, and receiving visitors.

2.2. Emergy synthesis

The emergy synthesis is carried out to assess the sustainability of these urban aquaponics farms previously described. The method is performed in four steps described in detail by Odum (1996) and Brown and Ulgiati (2004). First, the system boundaries are defined, and the energy diagram for each farm is drawn. The energy diagram allows us to identify, from a systemic perspective, all energy sources that support the system, internal processes, and its outputs. Second, tables with all the systems' energy inputs (renewable resources, non-renewable resources, and resources from the larger economy) and outputs are built based on the energy diagrams; this is usually called the inventory phase, similar to life cycle assessments (Puca et al., 2017). Third, all input flows are multiplied by their respective unit emergy values (UEVs), mostly taken from the literature, resulting in emergy flows in solar emjoules (sej). UEVs are conversion factors that weigh the importance of different inputs according to their energy quality based on the environmental efforts to make them available. All UEVs used in this study that originated from an outdated database are converted to the 1.20E+25 sej/year baseline (Brown et al., 2016). All system outputs are considered as co-products, receiving all emergy demanded by the system in calculating their UEVs. Fourth, this step consists of calculating emergy indicators (Table 2) and interpreting them.

In this study, the partial renewabilities of each input are considered for emergy indicator calculations to properly evaluate the system sustainability, as suggested by Ortega et al. (2002) and 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 and are described in the Supplementary Materials.

Table 2. Emergy indicators used in this study.

Indicator	**Definition**	**Formula**
Unit Emergy Value	The ratio between the total emergy demanded by the system and the outputs.	UEV=Emergy/Output
Renewability (it includes partial renewabilities)	The ratio between the renewable emergy inputs by the total emergy demanded by the system.	%R=100*(R+Mr+Sr)/Y
Emergy Yield Ratio	The ratio between the total emergy demanded by the system and the emergy inputs from the larger economy.	EYR=Y/F
Emergy Investment Ratio (it includes partial renewabilities)	The ratio between the non-renewable emergy inputs from the larger economy and the renewable and non-renewable emergy from nature.	EIR = (Mn+Sn)/(R+N+Mr+Sr)
Environmental Loading Ratio (it includes partial renewabilities)	The ratio between the total and imported non-renewable emergy and the renewable emergy inputs.	ELR=(N+Mn+Sn)/(R+Mr+Sr)
Emergy Sustainability Index (it includes partial renewabilities)	Emergy yield per unit of environmental loading.	ESI = EYR/ELR

Emergy indicators according to (Ortega et al., 2002; Brown and Ulgiati, 2004; David et al., 2021), where 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. Suffixes r and n means renewable and non-renewable fraction of material and services.

While the Unit Emergy Value (UEV) is a conversion factor, it is also an emergy indicator that assesses the ecosystem efficiency of the system. UEV measures the amount of emergy used to generate a certain amount of energy. The lower the UEV, the higher the system efficiency. The emergy yield ratio (EYR) indicates the contribution of the process to the economic sector due to local resource exploitation (Brown and Ulgiati, 2004). Renewability (%R) is the proportion of renewable resources in the total emergy used. It indicates the degree of sustainability of a productive system. The EIR identifies whether the use of resources from the larger economy is equivalent to the renewable resources in a production process (Odum, 1996; Brown and Ulgiati, 2004). The ELR indicates the environmental load due to the productive system related to N and F resources demand. ELR values lower than 2 indicate low environmental load, between 3 and 10 indicate moderate environmental load, and greater than 10 indicate high environmental load (Brown and Ulgiati, 2004). The ESI measures how much the production process contributes to the economy in relation to the environmental impact generated, i.e., it indicates the sustainability of the process (Brown and Ulgiati, 2004).

This work goes beyond the current studies by filling a gap in the scientific literature on the sustainability of one emerging aquaculture production system (aquaponics) using emergy synthesis. An innovative way to account for ecosystem services and disservices (ES&D) within emergy synthesis is also proposed and discussed as an attempt to accurately capture the environmental performance for such an important production system (Vassallo et al., 2009; Paoli et al., 2017). ES&D can be considered as co-products of aquaculture production systems, and due to their recognized importance, ES&D should be accounted for in sustainability assessments (Aubin et a., 2019; David et al., 2020). Aquaponics is an agri-aquaculture production system implemented mainly in peri-urban and urban centers. Thus, ecosystem services promoted by aquaponics farms are identified based on data previously published by Aubin et al. (2019) for aquaculture systems and Gómez-Baggethun et al. (2013) for urban agriculture production. In this present study, ecosystem services are accounted for as positive feedback to society, and they are placed in the emergy table as a subitem of the system´s outputs. Precisely, the ecosystem services of cultural & educational value, and tourism & recreation values are present in both farms. Due to the lack of databases containing emergy values for these specific environmental services, as well as all issues regarding their quantification in biophysical units, they are quantified according to their monetary value. Thus, for Farm A the annual flows of ‘cultural & educational value’ and ‘tourism & recreation value’ are calculated based on how much consumers paid for these services, multiplied by the number of people who attended the courses and visits offered. For Farm B, as this is a non-profit institution that does not charge for the services generated, the annual flows of the services were calculated based on how much they are worth (the same values charged by Farm A), multiplied by the number of people served.

Regarding disservices, as they cause negative feedback to society, the production system should reduce its generation or avoid it, as they could put human well-being and the natural environment in jeopardy. In this present work, disservices are accounted for as an emergy input by including the costs or emergy investment to reduce its potential in causing damage (Shah et al., 2019; David et al., 2020). They are placed in the emergy table as a subitem of the resources from the larger economy, as all energy and materials demanded to implement and operate treatment plants, or other operational management for disservices usually come from the larger economy. As no generic list of specific disservices to aquaculture neither to aquaponics is currently available in the scientific literature, in this work they are identified based on studies that evaluated disservices of agricultural systems (Shah et al., 2019; Yang et al., 2020) and urban productions (Gómez-Baggethun et al., 2013). Farm A generated ecosystem services, since the effluent disposal in the natural environment is a negative aspect that can cause damage to society. Thus, the emergy required to effluent treatment using a biodigester is accounted for as a disservice (represented by the 'water treatment' process in Figure 1). No disservices generated by Farm B were identified, since it already treats its effluents trough biodigester process. To measure the impact of ecosystem services and disservices inclusion on the emergy synthesis of aquaponics systems, the emergy indicators of Table 1 were calculated with and without ES&D.

2.3. Scenario analysis

Scenario analysis is an important tool to support strategic decision-makers (Postma and Liebl, 2005). Besides, it allows to evaluate how variations in input data affect results, helping farmers to determine actions that could be done in practice to improve the sustainability of aquaculture systems (Häyhä et al., 2011; Li et al., 2011). In the present study, a scenario analysis is performed to assess the effect of changing different input resources (quantity or kind) on emergy indicators. Variables considered within the scenario analyses are those ones that fit the following criteria: (i) inputs that show high representativeness in the total emergy demanded by aquaponics farms; (ii) inputs from non-renewable sources or with low renewability that can be replaced by inputs with higher renewability; (iii) reducing or replacing some inputs that would result in a lower amount of ecosystem disservice generation. The main aim of this scenario analysis is to propose practical alternatives based on the authors' knowledge and the technical-scientific literature to improve the sustainability of the investigated aquaponics systems.

3. Results

3.1. Emergy synthesis of aquaponics Farms A and B

Farm A demanded 6.3 times less emergy density than Farm B to keep the system running for one year (Tables 3 and 4, respectively). The resources from the larger economy had the highest proportion of emergy inputs in both farms. The materials were the most responsible for this high representation (93% for Farm A and 99% for Farm B). The renewable fraction of the materials used for infrastructure represents 32% of the emergy demanded by Farm A and 37% by Farm B. There is no contribution of natural non-renewable resources (N) for the evaluated farms.

Table 3. Emergy table of Farm A.

Note	Item	Unit	Amount (unit/m² yr)	UEV (sej/unit)	Emergy (sej/m² yr)	Emergy (%)
Renewable natural resources (R)						
	Sun	J	1.67E+07	1.00E+00	1.67E+07	<0.1
	Wind	J	1.47E+06	8.00E+02	1.18E+09	<0.1
Total (R)					1.20E+09	
Non-renewable natural resources (N)						
	None	-	-	-	-	
Resources from the larger economy (F)						
	Renewable materials (Mr)					
	Ethanol	L	5.89E+04	4.80E+04	2.83E+09	<0.1
	Water	m³	9.33E-02	1.92E+12	1.79E+11	0.1
	Electricity from grid	J	2.17E+06	1.12E+05	2.43E+11	0.2
	Materials for greenhouse and production tanks					
	Cement	g	6.47E-01	3.04E+12	1.97E+12	1.5
	Sand	g	3.00E+03	1.70E+09	5.09E+12	3.9
	Steel screws	g	2.91E+01	1.36E+10	3.96E+11	0.3
	Wood	kg	1.89E+01	1.82E+12	3.44E+13	26.5
	Non-renewable materials (Mn)					
	Ethanol	J	2.51E+05	4.80E+04	1.20E+10	<0.1
	Water	m³	9.33E-02	1.92E+12	1.79E+11	0.1
	Electricity from grid	J	1.02E+06	1.12E+05	1.14E+11	0.1
	Vegetable seedlings	J	9.60E+06	5.96E+04	5.72E+11	0.4
	Fish juveniles	J	1.09E+06	7.15E+05	7.81E+11	0.6
	Feed	J	3.22E+04	9.96E+04	3.21E+09	<0.1
	Iron fertilizer	kg	3.18E-03	1.84E+12	5.85E+09	<0.1
	Materials for greenhouse and production tanks					
	Cement	g	5.85E+00	3.04E+12	1.78E+13	13.7
	Sand	g	1.25E+03	1.70E+09	2.13E+12	1.6
	Steel screws	g	8.29E+01	1.36E+10	1.13E+12	0.9
	Wood	kg	1.11E+01	1.82E+12	2.02E+13	15.6
	Plastic	g	8.95E+03	4.19E+09	3.75E+13	28.9
	Renewable labor and services (Sr)					
	Non-skilled labor	J	1.97E+00	3.27E+06	6.45E+06	<0.1
	Non-renewable labor and services (Sn)					
	Infrastructure and equipment	USD	1.08E+00	5.60E+12	6.02E+12	4.6

	Non-skilled labor	J	1.10E+01	3.27E+06	3.60E+07	<0.1
	Fees and taxes	USD	1.63E-01	5.60E+12	9.13E+11	0.7
	Ecosystem disservices (D)					
	Materials for a biodigester (Considered as Mn)					
	Plastic	g	1.77E+01	4.19E+09	7.41E+10	0.1
Total (N+F) *					1.30E+14	
Total (N+F) **					1.30E+14	
Total emergy (Y)						
Without ecosystem disservices (Y = R+N+F) *					1.30E+14	
With ecosystem disservices (Y = R+N+F) **					1.30E+14	
Outputs (O)						
27	Vegetables	kg	1.20E+01			
	Ecosystem services (ES)					
	Cultural and education value	USD	3.83E+01			
	Tourism and recreation value	USD	3.84E+00			

Detailed calculation procedures are presented in Table A of supplementary materials.
* F = Mr+Mn+Sr+Sn
** F = Mr+Mn+Sr+Sn**+D**

Table 4. Emergy table of Farm B.

Note	Item	Unit	Amount (unit/m² yr)	UEV (sej/unit)	Emergy (sej/m² yr)	Emergy (%)
Renewable natural resources (R)						
	Sun	J	1.51E+07	1.00E+00	1.51E+07	0.0
	Wind	J	1.61E+06	8.00E+02	1.29E+09	0.0
Total (R)					1.30E+09	
Non-renewable natural resources (N)						
	None	-	-	-	-	
Resources from the larger economy (F)						
	Renewable materials (Mr)					
	Water	m³	6.44E-02	1.92E+12	1.24E+11	0.0
	Materials for greenhouse and production tanks					
	Iron	g	7.88E+04	3.56E+09	2.80E+14	34.1
	Cement	g	6.47E+00	3.04E+12	1.97E+13	2.4
	Sand	g	3.00E+03	1.70E+09	5.09E+12	0.6
	Steel screws	g	2.91E+02	1.36E+10	3.96E+12	0.5
	Non-renewable materials (Mn)					
	Water	m³	6.44E-02	1.92E+12	1.24E+11	0.0
	Vegetable seedlings	J	9.85E+06	5.96E+04	5.87E+11	0.1
	Fish juveniles	J	3.41E+06	7.15E+05	2.44E+12	0.3
	Feed	J	1.56E+04	9.96E+04	1.55E+09	0.0
	Iron fertilizer	kg	1.88E-03	1.84E+12	3.45E+09	0.0

Calcium oxide fertilizer	kg	1.44E-01	1.28E+12	1.84E+11	0.0
Potassium sulfate fertilizer	kg	3.77E-02	2.23E+12	8.41E+10	0.0
Materials for greenhouse and production tanks					
Iron	g	4.63E+04	3.56E+09	1.65E+14	20.1
Cement	g	5.85E+01	3.04E+12	1.78E+14	21.7
Sand	g	1.25E+03	1.70E+09	6.29E+11	0.1
Steel screws	g	8.29E+02	1.36E+10	1.13E+13	1.4
Plastic	g	9.39E+03	4.19E+09	3.93E+13	4.8
Materials for the solar panels					
Photoactive materials	g	1.41E+02	4.38E+11	6.17E+13	7.5
Glass	g	2.19E+03	6.08E+09	1.33E+13	1.6
Copper	g	8.70E+01	7.75E+10	6.74E+12	0.8
Aluminum	g	1.41E+02	4.35E+09	6.16E+11	0.1
Steel	g	3.33E+02	9.42E+10	3.14E+13	3.8
Ethylene Vinyl Acetate	g	7.27E+01	4.73E+09	3.44E+11	0.0
Materials for the biodigester					
Plastic	g	1.71E+01	4.19E+09	7.16E+10	0.0
Renewable labor and services (Sr)					
Non-skilled labor	J	4.66E+00	3.27E+06	1.52E+07	0.0
Skilled labor	J	7.45E+00	2.10E+07	1.56E+08	0.0
Non-renewable labor and services (Sn)					
Infrastructure and equipment	USD	1.53E+01	5.60E+12	4.39E+11	0.1
Non-skilled labor	J	2.60E+01	3.27E+06	8.49E+07	0.0
Skilled labor	J	4.16E+01	2.10E+07	8.72E+08	0.0
Ecosystem disservices (D)					
None	-	-	-	-	
Total (N+F) *				8.21E+14	
Total (N+F) **				8.21E+14	
Total emergy (Y)					
Without ecosystem disservices (Y = R+N+F) *				8.21E+14	
With ecosystem disservices (Y = R+N+F) **				8.21E+14	
Outputs (O)					
Vegetables	J	1.35E+01			
Fish	J	2.04E+07			
Biogas	J	1.02E-01			
Biofertilizer	L	1.39E+00			
Ecosystem services (ES)					
Cultural and educational value	USD	5.32E+01			
Tourism and recreation value	USD	2.28E+01			

Detailed calculation procedures are presented in Table B of supplementary materials.

* F = Mr+Mn+Sr+Sn
** F = Mr+Mn+Sr+Sn**+D**

Including ecosystem disservices in emergy accounting does not influence emergy indicators (Table 5). Farm B presents slightly higher renewability (37%) and ESI (0.6) than Farm A (33% and 0.5, respectively). Both farms showed the same value of EYR, while Farm B has a slightly higher performance for EIR and ELR.

Table 5. Emergy indicators with and without ecosystem disservices (ED) for the evaluated aquaponics farms.

Indicator		**Farm A**		**Farm B**	
		Without D	**With D**	**Without D**	**With D**
%R	Renewability	32.6	32.6	37.7	37.7
EYR	Emergy yield ratio	1.0	1.0	1.0	1.0
EIR	Emergy investment ratio	2.1	2.1	1.7	1.7
ELR	Environmental loading ratio	2.1	2.1	1.7	1.7
ESI	Emergy sustainability index	0.5	0.5	0.6	0.6

D: Ecosystem disservices.

Farm B presented a larger variety of output products compared to Farm A (Table 6). UEVs indicate higher efficiency for Farm A in producing vegetables and generating ecosystem services than Farm B as a lower amount of emergy is demanded by Farm A to deliver the same amount of these outputs. Although producing vegetables, fish, biogas and biofertilizer depends on the aquaponics technology adopted, the ecosystem services production depend on the valuation of the courses and visitation and on the physical capacity of each farm to receive people.

Table 6. Unit emergy values (UEVs), considering ecosystem disservices (ED), of the outputs produced by the evaluated aquaponics farms.

Outputs	**Farm A**	**Farm B**
Vegetables (sej/kg)	1.08E+13	6.06E+13
Fish (sej/J)	-	4.02E+07
Biogas (sej/J)	-	8.01E+15
Biofertilizer (sej/L)	-	5.89E+14
Cultural and educational value (sej/USD)	3.39E+12	1.54E+13
Tourism and recreation value (sej/USD)	3.38E+13	3.60E+13

3.2. *Scenario analysis*

Scenario analyses were performed to simulate changes that potentially would improve the emergy indicators of both farms. Water from the municipal grid supply, a resource from the larger economy, was replaced by rainwater, a renewable resource. In this simulation, all the infrastructure needed to collect rainwater, such as gutters, and pipes were considered for Farms A and B. Wood for constructing the greenhouse of Farm A was replaced by iron. The simulation of these variables indicates improvement in the emergy indicators of both farms (Table 7), in which replacing wood by iron in Farm A showed high influence on the new simulated indicators.

Table 7. Emergy indicators of the scenario analyses for Farms A and B.

Indicator	**Original values**		**Simulated values**		
	Farm A	**Farm B**	**Water - Farm A**	**Water - Farm B**	**Wood - Farm A**
%R (%)	32.6	37.7	38.6	37.7	48.0
EYR	1.0	1.0	1.0	1.0	1.0
EIR	2.1	1.7	1.6	1.7	1.1
ELR	2.1	1.7	1.6	1.7	1.1
ESI	0.5	0.6	0.6	0.6	0.9

Detailed calculation procedures are presented in Tables C to H of supplementary materials.

4. Discussion

This study intended to assess the sustainability of two urban aquaponics farms in Brazil. It is important to emphasize that both farms used management and structures well accepted and adopted in the world aquaponics field. Thus, the results obtained in this paper can be extrapolated and applied to different situations and assist in the sustainable development of this production system worldwide.

Emergy synthesis of aquaculture production has shown this activity as highly dependent on resources from the larger economy, in which the feed input has the highest influence (David et al., 2020). The materials used to implement the productive systems (infrastructure) were the items with the highest emergy demand for both farms evaluated in this study, a non-expected result from an aquaculture point of view. However, the emergy synthesis of a soil-based vegetable production have shown that greenhouse construction demanded about 57% of the total emergy input (Asgharipour et al., 2020). Economic and life cycle assessment (LCA) studies of aquaponics have also revealed that its infrastructure represents the highest monetary costs and causes the most significant environmental impacts (Forchino et al., 2017; Baganz et al., 2020; Chen et al., 2020; Ghamkhar et al., 2020). These results indicate that regardless of the sustainability assessment method adopted (LCA or emergy synthesis), the employed materials are the main environmental weakness of the current urban aquaponics systems. Therefore, aquaponics seems to reduce the existing issue of low efficiency in the feeding management of traditional aquaculture, because it converts the feed waste into vegetable biomass and minimizes the disposal of nutrient-rich effluents into the natural environment.

The emergy indicators including disservices calculated for the two evaluated aquaponics farms present better performance than most values found for traditional aquaculture production in ponds (Cavalett et al., 2006; Zhang et al., 2011), horticulture (Asgharipour et al., 2020), and soil-based vegetable production (Nakajima and Ortega, 2015) (Table 8). Farm B presented higher renewability than Farm A, probably due to the high renewable fraction and lifetime of iron used in the Farm B greenhouse construction. At Farm A, wood was the primary material used in the greenhouse construction, and consequently, it was responsible for the lower renewability of Farm A mainly due to its low lifetime compared to iron (5 vs. 10 years, for wood and iron respectively). From an emergy perspective, this means that aquaponics systems such as the one used by Farm B tend to be more sustainable in the long run, even though Farm A has shown similar results. This is because production systems with high renewability are more likely to be successful when non-renewable resources become limited (Lefroy and Rydberg, 2003; Brown and Ulgiati, 2004).

Table 8. Comparison of emergy indicators among the results of this study and previous studies of traditional aquaculture and soil-based vegetal production.

Reference	**Type of production**	**Indicator**				
		%R (%)	EYR	EIR	ELR	ESI
This study, Farm A	Aquaculture, aquaponics	33	1.0	2.1	2.1	0.5
This study, Farm B	Aquaculture, aquaponics	38	1.0	1.7	1.7	0.6
Cavalett et al. (2006)	Aquaculture, pond fish farming	22	1.3	3.2	3.6	0.4
Zhang et al. (2011)	Aquaculture, cage fish farming	72	1.8	-	0.4	4.6
Zhang et al. (2011)	Aquaculture, pond fish farming	27	1.0	-	2.7	0.4
Zhang et al. (2012)	Aquaculture, semi-natural pond fish farming	65	2.2	-	0.6	4.0
Asgharipour et al. (2020)	Horticulture in greenhouse, soil-based	17	1.0	67.9	76.0	0.2
Nakajima and Ortega (2015)	Organic horticulture, soil-based	42	1.7	1.4	1.4	1.3
Nakajima and Ortega (2015)	Conventional horticulture, soil-based	17	1.2	4.7	4.8	0.2
Nakajima and Ortega (2015)	Agroecological horticulture, soil-based	55	2.2	0.8	0.8	2.8

The EYR obtained by both farms can be considered low, which means that both farms are highly dependent on resources from the larger economy. This dependence seems to be a trend for traditional aquaculture and vegetable production in soil, which presented values similar to those found in the present study (Table 8). Numerically, this means that the lower EIR value of Farm B indicates better efficiency in using renewable resources (since the evaluated Farms do not demand N resources), where resources are continuously renewed and can supply the production system over a long time. The high EIR value of Farm A indicates that the input of resources from the larger economy is larger than the input of renewable resources. High values (> 1) of EIR are generally characteristic of intensive aquaculture systems due to the high need for resources from the larger economy to keep the system running (David et al., 2018).

The ELR showed the same values found for EIR in both farms. This result is related to the non-use of natural non-renewable resources (N) from nature by the evaluated farms. Usually, soil loss (organic matter) is accounted for as an N resource in the emergy synthesis of agricultural production and pond fish farming, but the aquaponics systems have no soil loss, and no other N resource was identified in this study. The ELR of both evaluated aquaponics farms indicated low environmental load, leading to better results for Farm B. This low environmental pressure is similar to values obtained in integrated (Cavalett et al., 2006) and semi-natural aquaculture systems (Zhang et al., 2012), and organic and agroecological horticulture (Nakajima and Ortega, 2015). The lower ELR of Farm B emphasizes the importance of using renewable materials to build the productive structures of aquaponics systems.

The ESI value <1 presented by both farms are similar to other aquaculture and horticulture systems (Table 8), except for organic and agroecological horticulture, cage and semi-natural pond fish farming. It suggests that evaluated farms provide a low emergy return in relation to their high environmental load generated (Cavalett et al., 2006; Zhang et al., 2012). Aquaculture systems that use a high degree of intensification have shown low ESI values due to high stress generated in the environment to provide the necessary resources to keep production systems running (Odum, 2001; Vassallo et al., 2007; Zhang et al., 2011; Garcia et al., 2014; David et al., 2018).

The emergy indicators obtained for the investigated farms suggest that the sustainability of aquaponics systems relies on materials used in their infrastructure. In general, the aquaponics farms seem to be located at a hierarchical scale similar to those more urbanized or high-tech systems that depend exclusively on F resources. This indicates that, although mimicking natural biological nutrient cycles and maximizing efficiency in resource use, aquaponics strongly relies on F resources that are non-sustainable at principle, unless F resources are produced without adding fossil or other non-renewable energy sources.

The high UEVs of the products indicate the low efficiency of the aquaponics farms in using the emergy invested in producing food. Nakajima and Ortega (2015) used emergy synthesis to assess conventional, organic, and agroecological systems of vegetable production and found UEVs of 4.29E+12, 4.34E+12, and 2.41E+12 sej/kg, respectively, values much lower than those obtained in the present study for the vegetable production (1.09E+13 sej/kg for Farm A, and 6.06E+13 sej/kg for Farm B). However, despite the lower efficiency in incorporating energy in its products, the aquaponics system adds economic value to the vegetables and fish produced as they are usually pesticide-free and antibiotic-free. Furthermore, it is possible to state that in emergy terms, aquaponics also adds quality energy to the generated products and thus value in more general terms. Aquaponics may cater to a consumer market that demands high-quality fish and vegetables and is willing to pay for the added-value ecological benefits of aquaponics products (Greenfeld et al., 2020). The low efficiency of both farms is even more evident when analyzing the UEVs for fish production. Farm B had low efficiency in fish production when compared to traditional aquaculture systems, such as cages (Garcia et al., 2014; David et al., 2018). Cage fish farming produces tilapias with UEVs ranging from 2.82E+05 (David et al., 2018) to 1.35E+06 sej/J (Garcia et al., 2014), lower than the UEV of 4.02E+07 sej/J of tilapias produced by Farm B. As Farm A does not produce fish for sale, it was not possible to assess its efficiency in tilapia production. These results could be explained by the fact that both farms are not exclusively focused on fish production and their maximum productive capacity is probably not being achieved. Furthermore, in the emergy synthesis of traditional vegetable and fish production (Garcia et al., 2014; Nakajima and Ortega, 2015; David et al., 2018), the emergy costs related to the transport of products from the rural area to the final consumer in the urban area were not considered. Including this emergy cost, which in most cases does not exist in urban aquaponics farms, would possibly equate the UEVs between urban farm products and those produced in rural areas.

More than producing food, both farms promote educational and tourism values by offering workshops, courses, lectures and visits. Farm A was more efficient than Farm B in generating ecosystem services due to its higher capacity in offering courses and receiving visitors. Some studies have shown that aquaponics systems have been considered a production model to promote environmental and financial education (Graber et al., 2014; König et al., 2018; Junge et al., 2019). Besides food production, adding other services to aquaponics systems seems to be a strategy to improve its economic sustainability. The generation of these services can be considered an indirect way to improve the efficiency of the aquaponic systems, as there is no need for an extra emergy input to obtain them, mainly regarding infrastructure. Aquaponics systems in urban centers, depending on the production scale, can also generate ecosystem services such as carbon sequestration, microclimate regulation, and landscape quality improvement. However, due to the small scale of farms and the lack of reliable available data from producers, these ecosystem services were not included in this present study. The inclusion of ecosystem services in emergy synthesis could generate data to help create more accurate public policies (Hein et al., 2013), recognizing the total benefits obtained from aquaponic systems. Public support can be practicable through the payment for ecosystem services (Schirpke et al., 2018; Rodríguez-Morales et al., 2020), offering producers discounts on fees, taxes, or adding value to products through sustainable certifications. Encouraging aquaponics farms in urban centers may be a strategic to obtain multiple benefits (food and environmental services).

Identifying and valuing the ecosystem disservices allowed us to define and measure a strategy to solve the problem before it harms society. Filter cleaning and consequent sludge disposal on the natural environment have been reported as one of the main natural pressures from aquaponics systems (Yogev et al., 2016). This study included the payment for ecosystem disservices regarding the sludge disposal by accounting the emergy demanded for implementing a simple biodigester on Farm A. Since devices such as biodigesters and bioreactors have been tested and have obtained good results for sludge treatments (Khiari et al., 2020), this can be a technically feasible measure to avoid discharging the effluent of aquaponics systems into the natural environment. The use of biodigester by Farm B is a successful example of this strategy because besides demanding less emergy than the treatment process of effluents in Farm A, the biodigester avoided effluent disposal and enabled Farm B to generate biogas and biofertilizer. The use of biodigesters can be considered a strategy to indirectly improve the system efficiency due to generating co-products useful to society; energy obtaining from biogas in this case. Avoiding the generation of ecosystem disservices is a mandatory practice to avoid the negative impacts on society and the natural environment.

Scenario analyses were performed to technically and practically simulate feasible changes that would improve the emergy indicators of both farms. Substituting the water source and replacing the water from the municipal supply system with rainwater resulted in a significant improvement on emergy indicators of Farm A and did not change the indicators of Farm B. Although aquaponics is not a system dependent on a constant water supply, the improvement on indicators was because rainwater is a renewable item with a UEV lower than water treated by the municipal system. Replacing a non-renewable water source with a renewable one shows that this is one of the means to make aquaponics systems more sustainable. Replacing wood with iron when constructing greenhouses also resulted in a considerable improvement in the emergy indicators. This result indicates that adopting materials with high renewability and lifespan is recommended when designing and building aquaponics farms. Simulating these variables (water source and material to build the greenhouse) reveals the potential to obtain better emergy indicators. On the other hand, it is also necessary to think about strategies that improve the system's efficiency, for instance, increasing the productivity of fish and vegetables to achieve its maximum efficiency.

5. Conclusion

We presented the first emergy synthesis of urban aquaponics farms and gave relevant insights to discuss its environmentally sustainable character. The primary purpose of this study was to investigate and compare the sustainability of two urban aquaponics farms using emergy synthesis. The synthesis results showed that the aquaponics farms are highly dependent on resources from the larger economy due to the high emergy demanded by materials (> 60%) to build the greenhouses. Despite having lower efficiencies in converting emergy into fish and/or vegetables than traditional agricultural or aquicultural systems found in the literature, both evaluated aquaponic systems presented promising emergy indicators. It should be noted that urban farms are designed to meet the specific needs of urban centers, using buildings´ dead spots to produce food.

Emergy indicators obtained in this study from simulation can provide subsidies for aquaponics farmers to achieve more sustainable production. Replacing water from municipal treatment plants with rainwater and wood used in the greenhouse infrastructure by iron improved the indicators by up to 40% and proved to be important practical strategies that would bring higher sustainability.

Including disservices should be a standard practice in emergy synthesis to adequately assess production systems. This practice prevents high impacts on system’s downstream and would avoid misinterpretations in labeling it as more sustainable without considering a systemic perspective regarding their burden on the environment. Considering ecosystem services allowed to identify that evaluated farms do not focus exclusively on food production, but also on generating educational and tourism values. Recognizing the importance in accounting for ecosystem services could have practical implications for developing public policies such as the payment for ecosystem services, which would support the permanence of these production systems more aligned with sustainability, as suggested by Agenda 2030.

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Supplementary Materials

Table A. Calculations for Farm A (460 m^2).

Note	Item	Value	Unit	Reference
1	**Sun**			
	Insolation	2.05E+07	J/m²/year	CIIAGRO (2020)
	Solar transmittance coefficient	81.60%	%	Sangpradit (2014)
	Annual flow	1.67E+07	J/m²/year	
	UEV	1.00E+00	sej/J	By definition
	Emergy	1.67E+07	sej/m²/year	
2	**Wind**			
	Density of air	1.30E+00	kg/m³	
	Drag coefficient	1.00E-03		
	Wind velocity	3.30E+00	m/s	CIIAGRO (2020)
	Time	3.15E+07	s	
	Annual flow	1.47E+06	J/m²/year	
	UEV	8.00E+02	sej/J	Brown and Ulgiati (2016)
	Emergy	1.18E+09	sej/m²/year	
3	**Ethanol**			
	Consumption	4.80E+02	L/year	
	Conversion	2.97E+05	J/L	
	Renewable fraction	19.00%	%	Agostinho and Siche (2014)
	Annual flow	5.89E+04	J/m²/year	
	UEV	4.80E+04	sej/J	Agostinho and Siche (2014)
	Emergy	2.83E+09	sej/m²/year	
4	**Water**			
	Quantity	8.59E+01	m³	
	Renewable fraction	50.00%	%	Giannetti et al. (2015)
	Annual flow	9.33E-02	m³/m²/year	
	UEV	1.92E+12	sej/m³	Liu et al. (2019)
	Emergy	1.79E+11	sej/m²/year	
5	**Electricity from grid**			

	Consumption	4.08E+02	kWh/year	
	Conversion	3.60E+06	J/kWh	
	Renewable fraction	68.00%	%	Giannetti et al. (2015)
	Annual flow	2.17E+06	J/m²/year	
	UEV	1.12E+05	sejJ/J	Giannetti et al. (2015)
	Emergy	2.43E+11	sej/m²/year	
6	**Cement**			
	Quantity	5.98E+04	g	
	Renewable fraction	9.96%	%	Asgharipour et al. (2020)
	Annual flow	6.47E-01	g/m²/year	
	UEV	3.04E+12	sej/g	Pulselli et al. (2009)
	Emergy	1.97E+12	sej/m²/year	
7	**Sand**			
	Quantity	3.91E+07	g	
	Renewable fraction	70.49%	%	Asgharipour et al. (2020)
	Annual flow	3.00E+03	g/m²/year	
	UEV	1.70E+09	sej/g	Campbell et al. (2005)
	Emergy	5.09E+12	sej/m²/year	
8	**Steel screws**			
	Quantity	5.15E+05	g	
	Renewable fraction	26.00%	%	This study
	Annual flow	2.91E+01	g/m²/year	
	UEV	1.36E+10	sej/g	Odum (2002)
	Emergy	3.96E+11	sej/m²/year	
9	**Wood**			
	Quantity	6.90E+04	kg	
	Renewable fraction	63.00%	%	De Oliveira et al. (2018)
	Annual flow	1.89E+01	kg/m²/year	
	UEV	1.82E+12	sej/kg	Odum (1996)
	Emergy	3.44E+13	sej/m²/year	
10	**Ethanol**			
	Consumption	4.80E+02	L/year	
	Conversion	2.97E+05	J/L	
	Non-renewable fraction	8.10E-01	%	Agostinho and Siche (2014)
	Annual flow	2.51E+05	J/m²/year	
	UEV	4.80E+04	sej/J	Agostinho and Siche (2014)
	Emergy	1.20E+10	sej/m²/year	
11	**Water**			
	Quantity	8.59E+01	m³	
	Non-renewable fraction	50.00%	%	Giannetti et al. (2015)
	Annual flow	9.33E-02	m³/m²/year	
	UEV	1.92E+12	sej/m³	Liu et al. (2019)

	Emergy	1.79E+11	sej/m²/year	
12	**Electricity from grid**			
	Consumption	4.08E+02	kWh/year	
	Conversion	3.60E+06	J/kWh	
	Non-renewable fraction	32.00%	%	Giannetti et al. (2015)
	Annual flow	1.02E+06	J/m²/year	
	UEV	1.12E+05	sej/J	Giannetti et al. (2015)
	Emergy	1.14E+11	sej/m²/year	
13	**Vegetable seedlings**			
	Seedlings	2.76E+02	kg	
	Conversion	1.60E+07	J/kg	Nan et al. (2020)
	Energy	4.42E+09	J	
	Annual flow	9.60E+06	J/m²/year	
	UEV	5.96E+04	sej/J	Zhang et al. (2007)
	Emergy	5.72E+11	sej/m²/year	
14	**Fish juveniles**			
	Stocked fish	1.60E+03	unit/year	
	Fish weight	1.50E+01	g	
	Conversion to kcal	5.00E+00	kcal/g	
	Conversion from kcal to J	4.19E+03	J/kcal	
	Annual flow	1.09E+06	J/m²/year	
	UEV	7.15E+05	sej/J	Brown and Bardi (2001)
	Emergy	7.81E+11	sej/m²/year	
15	**Feed**			
	Consumed feed	1.02E+03	kg/year	
	Feed energy	1.45E+04	J/kg	
	Annual flow	3.22E+04	J/m²/kg	
	UEV	9.96E+04	sej/J	Brown and Bardi (2001)
	Emergy	3.21E+09	sej/m²/year	
16	**Iron fertilizer**			
	Quantity	1.46E+00	kg	
	Annual flow	3.18E-03	kg/m²/year	
	UEV	1.84E+12	sej/kg	Odum (1996)
	Emergy	5.85E+09	sej/m²/year	
17	**Cement**			
	Quantity	5.98E+04	g	
	Non-renewable fraction	90.04%	%	Asgharipour et al. (2020)
	Annual flow	5.85E+00	g/m²/year	
	UEV	3.04E+12	sej/g	Pulselli et al. (2009)
	Emergy	1.78E+13	sej/m²/year	
18	**Sand**			
	Quantity	3.91E+07	g	

	Non-renewable fraction	29.51%	%	Asgharipour et al. (2020)
	Annual flow	1.25E+03	g/m²/year	
	UEV	1.70E+09	sej/g	Campbell et al. (2005)
	Emergy	2.13E+12	sej/m²/year	
19	**Steel screws**			
	Quantity	5.15E+05	g	
	Non-renewable fraction	74.00%	%	Asgharipour et al. (2020)
	Annual flow	8.29E+01	g/m²/year	
	UEV	1.36E+10	sej/g	Odum (2002)
	Emergy	1.13E+12	sej/m²/year	
20	**Wood**			
	Quantity	6.90E+04	kg	
	Non-renewable fraction	37.00%	%	De Oliveira et al. (2018)
	Annual flow	1.11E+01	kg/m²/year	
	UEV	1.82E+12	sej/kg	Odum (1996)
	Emergy	2.02E+13	sej/m²/year	
21	**Plastic**			
	Annual flow	8.95E+03	g/m²/year	
	UEV	4.19E+09	sej/g	Odum (2002)
	Emergy	3.75E+13	sej/m²/year	
22	**Non-skilled labor**			
	Man-hours	5.00E+00	hours/day	
	Conversion to kcal	2.85E-01	kcal/year	
	Conversion to J	4.19E+03	J/kcal	
	Renewable fraction	15.20%	%	Giannetti et al. (2015)
	Annual flow	1.97E+00	J/m²/year	
	UEV	3.27E+06	sej/J	Oliveira et al. (2018)
	Emergy	6.45E+06	sej/m²/year	
23	**Infrastructure and equipment**			
	Depreciation	1.08E+00	USD/m²/year	
	UEV	5.60E+12	sej/USD	Giannetti et al. (2018)
	Emergy	6.02E+12	sej/m²/year	
24	**Non-skilled labor**			
	Man-hours	5.00E+00	hours/day	
	Conversion to kcal	2.85E-01	kcal/year	
	Conversion to J	4.19E+03	J/kcal	
	Non-renewable fraction	84.80%	%	Giannetti et al. (2015)
	Annual flow	1.10E+01	J/m²/year	
	UEV	3.27E+06	sej/J	Oliveira et al. (2018)
	Emergy	3.60E+07	sej/m²/year	
25	**Fees and taxes**			
	Annual flow	1.63E-01	USD/m²	

	UEV	5.60E+12	sej/USD	Giannetti et al. (2018)
	Emergy	9.13E+11	sej/m²/year	
26	**Plastic**			
	Annual flow	1.77E+01	g/m²/year	
	UEV	4.19E+09	sej/g	Odum (2002)
	Emergy	7.41E+10	sej/m²/year	
27	**Vegetables**			
	Total production	5.52E+03	kg/year	
	Annual flow	1.20E+01	kg/m²/year	
28	**Cultural and education value**			
	Annual flow	3.83E+01	USD/m²/year	
29	**Tourism and recreation value**			
	Annual flow	3.84E+00	USD/m²/year	

Table B. Calculations for Farm B (195 m^2).

Note	Item	Value	Unit	Reference
1	**Sun**			
	Insolation	1.85E+07	J/m²/year	
	Solar transmittance coefficient	81.60%	%	
	Annual flow	1.51E+07	J/m²/year	
	UEV	1.00E+00	sej/J	By definition
	Emergy	1.51E+07	sej/m²/year	
2	**Wind**			
	Density of air	1.30E+00	kg/m3	
	Drag coefficient	1.00E-03		
	Wind velocity	3.40E+00	m/s	CIIAGRO (2020)
	Time	3.15E+07	s	
	Annual flow	1.61E+06	J/m²/year	
	UEV	8.00E+02	sej/J	Brown and Ulgiati (2016)
	Emergy	1.29E+09	sej/m²/year	
3	**Water**			
	Quantity	2.51E+01	m³	
	Renewable fraction	50.00%	%	Giannetti et al. (2015)
	Annual flow	6.44E-02	m³/m²/year	
	UEV	1.92E+12	sej/m³	Liu et al. (2019)
	Emergy	1.24E+11	sej/m²/year	
4	**Iron**			
	Quantity	2.44E+08	g	
	Renewable fraction	63.00%	%	Oliveira et al. (2018)

	Annual flow	7.88E+04	g/m²/year	
	UEV	3.56E+09	sej/g	Odum (2002)
	Emergy	2.80E+14	sej/m²/year	
5	**Cement**			
	Quantity	2.54E+05	g	
	Renewable fraction	9.96%	%	Asgharipour et al. (2020)
	Annual flow	6.47E+00	g/m²/year	
	UEV	3.04E+12	sej/g	Pulselli et al. (2009)
	Emergy	1.97E+13	sej/m²/year	
6	**Sand**			
	Quantity	1.66E+07	g	
	Renewable fraction	70.49%	%	Asgharipour et al. (2020)
	Annual flow	3.00E+03	g/m²/year	
	UEV	1.70E+09	sej/g	Campbell et al. (2005)
	Emergy	5.09E+12	sej/m²/year	
7	**Steel screws**			
	Quantity	2.18E+06	g	
	Renewable fraction	26.00%	%	This study
	Annual flow	2.91E+02	g/m²/year	
	UEV	1.36E+10	sej/g	Odum (2002)
	Emergy	3.96E+12	sej/m²/year	
8	**Water**			
	Quantity	2.51E+01	m³	
	Non-renewable fraction	50.00%	%	Giannetti et al. (2015)
	Annual flow	6.44E-02	m³/m²/year	
	UEV	1.92E+12	sej/m³	Liu et al. (2019)
	Emergy	1.24E+11	sej/m²/year	
9	**Vegetable seedlings**			
	Seedlings	1.20E+02	kg	
	Conversion	1.60E+07	J/kg	
	Energy	1.92E+09	J	
	Annual flow	9.85E+06	J/m²/year	
	UEV	5.96E+04	sej/J	Zhang et al. (2007)
	Emergy	5.87E+11	sej/m²/year	
10	**Fish juveniles**			
	Stocked fish	3.18E+02	unit/year	
	Fish weight	1.00E+02	g	
	Conversion to kcal	5.00E+00	kcal/g	
	Conversion from kcal to J	4.19E+03	J/kcal	
	Annual flow	3.41E+06	J/m²/year	

	UEV	7.15E+05	sej/J	Brown and Bardi (2001)
	Emergy	2.44E+12	sej/m²/year	
11	**Feed**			
	Consumed feed	2.09E+02	kg/year	
	Feed energy	1.45E+04	J/kg	
	Annual flow	1.56E+04	J/m²/year	
	UEV	9.96E+04	sej/J	Brown and Bardi (2001)
	Emergy	1.55E+09	sej/m²/year	
12	**Iron fertilizer**			
	Quantity	3.66E-01	kg	
	Annual flow	1.88E-03	kg/m²/year	
	UEV	1.84E+12	sej/kg	Odum (1996)
	Emergy	3.45E+09	sej/m²/year	
13	**Calcium oxide fertilizer**			
	Quantity	2.81E+01	kg	
	Annual flow	1.44E-01	kg/m²/year	
	UEV	1.28E+12	sej/kg	Odum (1996)
	Emergy	1.84E+11	sej/m²/year	
14	**Potassium sulfate fertilizer**			
	Quantity	7.36E+00	kg	
	Annual flow	3.77E-02	kg/m²/year	
	UEV	2.23E+12	sej/kg	Brandt-Williams (2002)
	Emergy	8.41E+10	sej/m²/year	
15	**Iron**			
	Quantity	2.44E+08	g	
	Non-renewable fraction	37.00%	%	Oliveira et al. (2018)
	Annual flow	4.63E+04	g/m²/year	
	UEV	3.56E+09	sej/g	Odum (2002)
	Emergy	1.65E+14	sej/m²/year	
16	**Cement**			
	Quantity	2.54E+05	g	
	Non-renewable fraction	90.04%	%	Asgharipour et al. (2020)
	Annual flow	5.85E+01	g/m²/year	
	UEV	3.04E+12	sej/g	Pulselli et al. (2009)
	Emergy	1.78E+14	sej/m²/year	
17	**Sand**			
	Quantity	1.66E+07	g	
	Non-renewable fraction	29.51%	%	Asgharipour et al. (2020)
	Annual flow	1.25E+03	g/m²/year	
	UEV	1.70E+09	sej/g	Campbell et al. (2005)

	Emergy	6.29E+11	sej/m²/year	
18	**Steel screws**			
	Quantity	2.18E+06	g	
	Non-renewable fraction	74.00%	%	Asgharipour et al. (2020)
	Annual flow	8.29E+02	g/m²/year	
	UEV	1.36E+10	sej/g	Odum (2002)
	Emergy	1.13E+13	sej/m²/year	
19	**Plastic**			
	Annual flow	9.39E+03	g/m²/year	
	UEV	4.19E+09	sej/g	Odum (2002)
	Emergy	3.93E+13	sej/m²/year	
20	**Photoactive materials**			
	Annual flow	1.41E+02	g/m²/year	
	UEV	4.38E+11	sej/g	Brown and Ulgiati (2010)
	Emergy	6.17E+13	sej/m²/year	
21	**Glass**			
	Annual flow	2.19E+03	g/m²/year	
	UEV	6.08E+09	sej/g	Brown and Ulgiati (2010)
	Emergy	1.33E+13	sej/m²/year	
22	**Copper**			
	Annual flow	8.70E+01	g/m²/year	
	UEV	7.75E+10	sej/g	Cohen et al. (2007)
	Emergy	6.74E+12	sej/m²/year	
23	**Aluminum**			
	Annual flow	1.41E+02	g/m²/year	
	UEV	4.35E+09	sej/g	Cohen et al. (2007)
	Emergy	6.16E+11	sej/m²/year	
24	**Steel**			
	Annual flow	3.33E+02	g/m²/year	
	UEV	9.42E+10	sej/g	Cohen et al. (2007)
	Emergy	3.14E+13	sej/m²/year	
25	**Ethylene Vinyl Acetate**			
	Annual flow	7.27E+01	g/m²/year	
	UEV	4.73E+09	sej/g	Brown et al. (2011)
	Emergy	3.44E+11	sej/m²/year	
26	**Plastic**			
	Annual flow	1.71E+01	g/m²/year	
	UEV	4.19E+09	sej/g	Odum (2002)
	Emergy	7.16E+10	sej/m²/year	
27	**Non-skilled labor**			

	Man-hours	5.00E+00	hours/day	
	Conversion to kcal	2.85E-01	kcal/year	
	Conversion to J	4.19E+03	J/kcal	
	Renewable fraction	15.20%	%	Giannetti et al. (2015)
	Annual flow	4.66E+00	J/m²/year	
	UEV	3.27E+06	sej/J	Oliveira et al. (2018)
	Emergy	1.52E+07	sej/m²/year	
28	**Skilled labor**			
	Man-hours	8.00E+00	hours/day	
	Conversion to kcal	2.85E-01	kcal/year	
	Conversion to J	4.19E+03	J/kcal	
	Renewable fraction	15.20%	%	Giannetti et al. (2015)
	Annual flow	7.45E+00	J/m²/year	
	UEV	2.10E+07	sej/J	Oliveira et al. (2018)
	Emergy	1.56E+08	sej/m²/year	
29	**Infrastructure and equipment**			
	Annual flow	1.53E+01	USD/m²/year	
	UEV	5.60E+12	sej/USD	Giannetti et al. (2018)
	Emergy	4.39E+11	sej/m²/year	
30	**Non-skilled labor**			
	Man-hours	5.00E+00	hours/day	
	Conversion to kcal	2.85E-01	kcal/year	
	Conversion to J	4.19E+03	J/kcal	
	Non-renewable fraction	84.80%	%	Giannetti et al. (2015)
	Annual flow	2.60E+01	J/m²/year	
	UEV	3.27E+06	sej/J	Oliveira et al. (2018)
	Emergy	8.49E+07	sej/m²/year	
31	**Skilled labor**			
	Man-hours	8.00E+00	hours/day	
	Conversion to kcal	2.85E-01	kcal/year	
	Conversion to J	4.19E+03	J/kcal	
	Non-renewable fraction	84.80%	%	Giannetti et al. (2015)
	Annual flow	4.16E+01	J/m²/year	
	UEV	2.10E+07	sej/J	Oliveira et al. (2018)
	Emergy	8.72E+08	sej/m²/year	
32	**Vegetables**			
	Total production	2.64E+03	kg/year	
	Annual flow	1.35E+01	kg/m²/year	
33	**Fish**			
	Harvested fish	2.93E+02	unit/year	

	Fish weight	6.50E+02	g/unit	
	Conversion to kcal	5.00E+00	kcal/g	Brown and Bardi (2001)
	Conversion from kcal to J	4.19E+03	J/kcal	Brown and Bardi (2001)
	Annual flow	2.04E+07	kg/m^2/year	
34	**Biogas**			
	Biogas production	47.6	m^3/year	
	Average methane percent in the biogas	64.8%	%	Ciotola et al. (2011)
	Average annual daily methane yield	30.84	m^3/year	
	Energy content of methane	3.77E+07	J/m^3	Ciotola et al. (2011)
	Annual flow	1.02E-01	J/m^2/year	
35	**Biofertilizer**			
	Annual flow	1.39E+00	L/m^2/year	
36	**Cultural and educational value**			
	Annual flow	5.32E+01	USD/m^2/year	
37	**Tourism and recreation value**			
	Annual flow	2.28E+01	USD/m^2/year	

Table C. Emergy table for the scenario analysis of water resource of Farm A.

Note	Item	Unit	Amount (unit/m^2/yr)	UEV (sej/unit)	Emergy (sej/m^2/yr)
Renewable natural resources (R)					
1	Sun	J	1.67E+07	1.00E+00	1.67E+07
2	Wind	J	1.47E+06	8.00E+02	1.18E+09
3	Rainwater	m^3	1.87E-01	2.34E+04	4.37E+03
Total (R)					1.20E+09
Non-renewable natural resources (N)					
	None	-	-	-	-
Resources from the larger economy (F)					
	Renewable materials (Mr)				
4	Ethanol	L	5.89E+04	4.80E+04	2.83E+09
5	Electricity from grid	J	2.17E+06	1.12E+05	2.43E+11
	Materials for the greenhouse and production tanks				
6	Cement	g	1.29E+00	3.04E+12	3.94E+12
7	Sand	g	5.99E+03	1.70E+09	1.02E+13
8	Steel screws	g	5.82E+01	1.36E+10	7.92E+11
9	Wood	kg	3.15E+01	1.82E+12	5.73E+13
	Non-renewable materials (Mn)				
10	Vegetable seedlings	J	9.60E+06	5.96E+04	5.72E+11
11	Fish juveniles	J	1.09E+06	7.15E+05	7.81E+11

12	Electricity from grid	J	1.02E+06	1.12E+05	1.14E+11
13	Feed	J	3.22E+04	9.96E+04	3.21E+09
14	Iron fertilizer	kg	3.18E-03	1.84E+12	5.85E+09
15	Ethanol	L	2.51E+05	4.80E+04	1.20E+10
	Materials for the greenhouse and production tanks				
16	Wood	kg	1.85E+01	1.82E+12	3.37E+13
17	Cement	g	1.17E+01	3.04E+12	3.20E+13
18	Sand	g	2.51E+03	1.70E+09	1.26E+12
19	Steel screws	g	1.66E+02	1.36E+10	1.67E+12
20	Plastic	g	9.01E+03	4.19E+09	3.77E+13
	Renewable services (Sr)				
21	Non-skilled labor	J	1.97E+00	3.27E+06	6.45E+06
	Non-renewable services (Sn)				
22	Infrastructure and equipment	USD	1.18E+00	5.60E+12	6.63E+12
23	Non-skilled labor	J	1.10E+01	3.27E+06	3.60E+07
24	Fees and taxes	USD	1.63E-01	5.60E+12	9.13E+11
	Ecosystem disservices (ED)				
	Materials for a biodigester (Considered as Mn)				
25	Plastic	g	1.77E+01	4.19E+09	7.41E+10
Total (N+F) *					1.88E+14
Total (N+F) **					1.88E+14
Total emergy (Y)					
Without ecosystem disservices (Y = R+N+F) *					1.88E+14
With ecosystem disservices (Y = R+N+F) **					1.88E+14
Outputs (O)					
26	Vegetables	kg	1.20E+01		
	Ecosystem services (ES)				
27	Cultural and education value	USD	3.83E+01		
28	Tourism and recreation value	USD	3.84E+00		

* F = Mr+Mn+Sr+Sn
** F = Mr+Mn+Sr+Sn**+D**

Table D. Calculations for the scenario analysis of the water of the Farm A.

Note	Item	Value	Unit	Reference
3	**Rainwater**			
	Quantity	8.59E+01	m³	
	Annual flow	1.87E-01	m³/m²/year	
	UEV	2.34E+04	sej/m³	Odum (2004)
	Emergy	4.37E+03	sej/m²/year	
20	**Plastic**			
	Annual flow	9.01E+03	g/m²/year	

	UEV	4.19E+09	sej/g	Odum (2002)
	Emergy	3.77E+13	sej/m^2/year	
25	**Plastic**			
	Annual flow	1.77E+01	g/m^2/year	
	UEV	4.19E+09	sej/g	Odum (2002)
	Emergy	7.41E+10	sej/m^2/year	

Table E. Emergy table for the scenario analysis of water resource of Farm B.

Note	Item	Unit	Amount (unit/m^2/yr)	UEV (sej/unit)	Emergy (sej/m^2/yr)
Renewable natural resources (R)					
1	Sun	J	1.51E+07	1.00E+00	1.51E+07
2	Wind	J	1.61E+06	8.00E+02	1.29E+09
3	Rainwater	m^3	1.29E-01	2.34E+04	3.01E+03
Total (R)					1.30E+09
Non-renewable natural resources (N)					
	None	-	-	-	-
Resources from the larger economy (F)					
	Renewable materials (Mr)				
	Materials for the greenhouse and production tanks				
4	Iron	g	7.88E+04	3.56E+09	2.80E+14
5	Cement	g	6.47E+00	3.04E+12	1.97E+13
6	Sand	g	3.00E+03	1.70E+09	5.09E+12
7	Steel screws	g	2.91E+02	1.36E+10	3.96E+12
	Non-renewable materials (Mn)				
8	Vegetable seedlings	J	9.85E+06	5.96E+04	5.87E+11
9	Fish juveniles	J	3.41E+06	7.15E+05	2.44E+12
10	Feed	J	1.56E+04	9.96E+04	1.55E+09
11	Iron fertilizer	kg	1.88E-03	1.84E+12	3.45E+09
12	Calcium oxide fertilizer	kg	1.44E-01	1.28E+12	1.84E+11
13	Potassium sulfate fertilizer	kg	3.77E-02	2.23E+12	8.41E+10
	Materials for the greenhouse and production tanks				
14	Iron	g	4.63E+04	3.56E+09	1.65E+14
15	Cement	g	5.85E+01	3.04E+12	1.78E+14
16	Sand	g	1.25E+03	1.70E+09	6.29E+11
17	Steel screws	g	8.29E+02	1.36E+10	1.13E+13
18	Plastic	g	9.69E+03	4.19E+09	4.11E+13
	Materials for the solar panels				
19	Photoactive materials	g	1.41E+02	4.38E+11	6.17E+13

20	Glass	g	2.19E+03	6.08E+09	1.33E+13
21	Copper	g	8.70E+01	7.75E+10	6.74E+12
22	Aluminum	g	1.41E+02	4.35E+09	6.16E+11
23	Steel	g	3.33E+02	9.42E+10	3.14E+13
24	Ethylene Vinyl Acetate	g	7.27E+01	4.73E+09	3.44E+11
	Materials for the biodigester				
25	Plastic	g	1.71E+01	4.19E+09	7.16E+10
	Renewable services (Sr)				
26	Non-skilled labor	J	4.66E+00	3.27E+06	1.52E+07
27	Skilled labor	J	7.45E+00	2.10E+07	1.56E+08
	Non-renewable services (Sn)				
28	Infrastructure and equipment	USD	1.53E+01	5.60E+12	4.39E+11
29	Non-skilled labor	J	2.60E+01	3.27E+06	8.49E+07
30	Skilled labor	J	4.16E+01	2.10E+07	8.72E+08
	Ecosystem disservices (ED)				
	None	-	-	-	-
Total (N+F) *					8.21E+14
Total (N+F) **					8.21E+14
Total emergy (Y)					
Without ecosystem disservices (Y = R+N+F) *					8.21E+14
With ecosystem disservices (Y = R+N+F) **					8.21E+14
Outputs (O)					
31	Vegetables	J	1.35E+01		
32	Fish	J	2.04E+07		
33	Biogas	J	1.02E-01		
34	Biofertilizer	L	1.39E+00		
	Ecosystem services (ES)				
35	Cultural and educational value	USD	5.32E+01		
36	Tourism and recreation value	USD	2.28E+01		

* F = Mr+Mn+Sr+Sn
** F = Mr+Mn+Sr+Sn**+D**

Table F. Calculations for the scenario analysis of the water of Farm B.

Note	Item	Value	Unit	Reference
3	**Rainwater**			
	Quantity	2.51E+01	m³	
	Annual flow	1.29E-01	m³/m²/year	
	UEV	2.34E+04	sej/m³	Odum (2004)
	Emergy	3.01E+03	sej/m²/year	
18	**Plastic**			

	Annual flow	9.69E+03	g/m^2/year	
	UEV	4.19E+09	sej/g	Odum (2002)
	Emergy	4.11E+13	sej/m^2/year	
25	**Plastic**			
	Annual flow	1.81E+01	g/m^2/year	
	UEV	4.19E+09	sej/g	Odum (2002)
	Emergy	7.46E+10	sej/m^2/year	

Table G. Emergy table for the scenario analysis of the material of Farm A.

Note	Item	Unit	Amount (unit/m^2/yr)	UEV (sej/unit)	Emergy (sej/m^2/yr)
Renewable natural resources (R)					
1	Sun	J	1.67E+07	1.00E+00	1.67E+07
2	Wind	J	1.47E+06	8.00E+02	1.18E+09
Total (R)					1.20E+09
Non-renewable natural resources (N)					
	None	-	-	-	-
Resources from the larger economy (F)					
	Renewable materials (Mr)				
3	Ethanol	L	5.89E+04	4.80E+04	2.83E+09
4	Water	m^3	9.33E-02	1.92E+12	1.79E+11
5	Electricity from grid	J	2.17E+06	1.12E+05	2.43E+11
	Materials for the greenhouse and production tanks				
6	Cement	g	1.29E+00	3.04E+12	3.94E+12
7	Sand	g	5.99E+03	1.70E+09	1.02E+13
8	Steel screws	g	5.82E+01	1.36E+10	7.92E+11
9	Iron	g	7.88E+04	3.56E+09	2.80E+14
	Non-renewable materials (Mn)				
10	Water	m^3	9.33E-02	1.92E+12	1.79E+11
11	Vegetable seedlings	J	9.60E+06	5.96E+04	5.72E+11
12	Fish juveniles	J	1.09E+06	7.15E+05	7.81E+11
13	Electricity from grid	J	1.02E+06	1.12E+05	1.14E+11
14	Feed	J	3.22E+04	9.96E+04	3.21E+09
15	Iron fertilizer	kg	3.18E-03	1.84E+12	5.85E+09
16	Ethanol	L	2.51E+05	4.80E+04	1.20E+10
17	Iron	g	4.63E+04	3.56E+09	1.65E+14
18	Cement	g	1.17E+01	3.04E+12	3.20E+13
19	Sand	g	2.51E+03	1.70E+09	1.26E+12
20	Steel screws	g	1.66E+02	1.36E+10	1.67E+12
21	Plastic	g	2.69E+04	4.19E+09	1.13E+14

	Renewable services (Sr)				
22	Non-skilled labor	J	1.97E+00	3.27E+06	6.45E+06
	Non-renewable services (Sn)				
23	Infrastructure and equipment	$	1.08E+00	5.60E+12	6.02E+12
24	Non-skilled labor	J	1.10E+01	3.27E+06	3.60E+07
25	Fees and taxes	$	1.63E-01	5.60E+12	9.13E+11
	Ecosystem disservices (ED)				
	Materials for a biodigester (Considered as Mn)				
26	Plastic	g	1.77E+01	4.19E+09	7.41E+10
Total (N+F) *					6.16E+14
Total (N+F) **					6.16E+14
Total emergy (Y)					
Without ecosystem disservices (Y = R+N+F) *					6.16E+14
With ecosystem disservices (Y = R+N+F) **					6.16E+14
Outputs (O)					
27	Vegetables	kg	1.20E+01		
	Ecosystem services (ES)				
28	Cultural and education value	$	3.83E+01		
29	Tourism and recreation value	$	3.84E+00		

* F = Mr+Mn+Sr+Sn

** F = Mr+Mn+Sr+Sn**+D**

Table H. Calculations for the scenario analysis of the material of Farm A.

Note	Item	Value	Unit	Reference
10	**Iron**			
	Quantity	5.75E+08	g	
	Renewable fraction	63.00%	%	Oliveira et al. (2018)
	Annual flow	7.88E+04	g/m²/year	
	UEV	3.56E+09	sej/g	Odum (2002)
	Emergy	2.80E+14	sej/m²/year	
18	**Iron**			
	Quantity	5.75E+08	g	
	Non-renewable fraction	37.00%	%	Oliveira et al. (2018)
	Annual flow	4.63E+04	g/m²/year	
	UEV	3.56E+09	sej/g	Odum (2002)
	Emergy	1.65E+14	sej/m²/year	

Chapter 4

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

This chapter is based on:

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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.

Keywords: Aquaculture; BFT; Emergy synthesis; Sustainability; Tilapia farming.

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 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, 2005). 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, 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 Figure 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 production (Table 1).

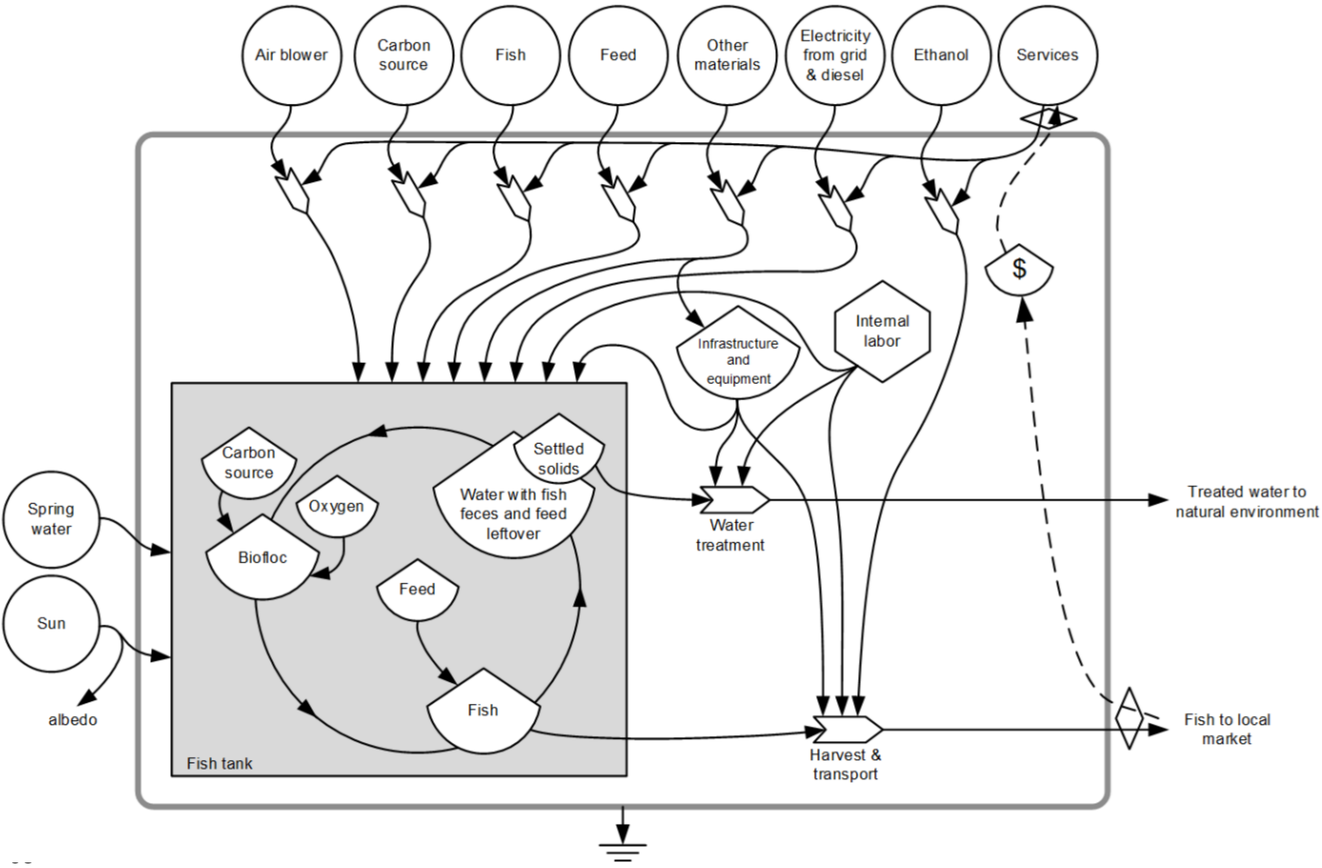

Figure 1. Energy diagram of the biofloc-based system to produce Nile tilapia fingerlings.

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	114000
Initial average weight of fish	g/fish	1
Final average weight of fish	g/fish	5
Cycle	unit/year	5
Fish produced	unit/year	1500000
Carbon source (sugar)	kg/year	700
Feed	kg/year	7000
Feed conversion ratio	-	1.2
Taxes and feed	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

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 m³ 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 m³ 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 35ºC. After this process, the heater was only needed when the water temperature was lower than 27ºC. 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 hours per day to operate the system manually.

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 appendices. 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 emergy 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 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.

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.

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 source, photovoltaic electricity is known as a sustainable alternative source to replace electricity from hydroelectric and thermoelectric. Considering that photovoltaic panel is 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/m²/year to produce 6000 kg/m²/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.

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

Note	Item	Unit	Amount (unit/m² yr)	UEV (sej/unit)	Emergy (sej/m² yr)	Emergy (%)*
Renewable resources (R)						
1	Sun	J	1.67E+07	1.00E+00	1.67E+07	<0.1
2	Springwater	m³	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	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/m²/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 ratio; %R: Renewability; EYR: Emergy yield ratio; Emergy investment ratio; ELR: Emergy loading ratio; ESI: Emergy sustainability index.

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 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 g 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 photovoltaic 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) and the grid-connected solar photovoltaic system could be easily applicable option for small-scale farmers. However, we encourage investigations of other renewable options of electricity sources on the sustainability of BFT production, such 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. Evaluating the use and sustainability of more efficient aerator systems is highly recommended, for example, compressor or centrifugal blowers that consume less energy and are up to 60% more efficient in promoting 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 photovoltaic as an electricity source did not improve the BFT farm's sustainability.

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Supplementary data

Calculations for BFT farm.

Note	Item	Value	Unit	Reference
1	**Sun**			
	Insolation	2.05E+07	J/m²/year	CIIAGRO (2020)
	Solar transmittance coefficient	81.60%	%	Sangpradit (2014)
	Annual flow	1.67E+07	J/m²/year	
	UEV	1.00E+00	sej/J	By definition
	Emergy	1.67E+07	sej/m²/year	
2	**Spring water**			
	Quantity	8.00E+05	L	
	Annual flow	8.81E+02	L/m²/year	
	UEV	3.27E+05	sej/L	Bastianoni and Marchettini (2000)
	Emergy	2.88E+08	sej/year	
3	**Electricity**			
	Consumption	9.12E+04	kWh/year	
	Conversion	1.25E+07	J/kWh	
	Renewable fraction	68.00%	%	Giannetti et al. (2015)
	Annual flow	8.54E+08	J/m²/year	
	UEV	1.12E+05	sej/J	Giannetti et al. (2015)
	Emergy	9.56E+13	sej/year	
4	**Ethanol**			
	Consumption	5.00E+02	L/year	
	Conversion	2.97E+05	J/L	
	Renewable fraction	19.00%	%	Agostinho and Siche (2014)
	Annual flow	3.11E+04	J/m²/year	
	UEV	4.80E+04	sej/J	Agostinho and Siche (2014)
	Emergy	1.49E+09	sej/m²/year	
5	**Carbon source**			
	Quantity	7.00E+02	kg	
	Renewable fraction	33%	%	Pereira and Ortega (2010)
	Annual flow	2.54E-01	kg/m²/year	
	UEV	4.87E+12	sej/kg	Brown and Ulgiati (2004)
	Emergy	1.24E+12	sej/year	
6	**Iron**			

	Quantity	1.14E+07	g	
	Renewable fraction	63.00%	%	Oliveira et al. (2018)
	Annual flow	7.88E+02	g/m²/year	
	UEV	3.56E+09	sej/g	Odum (2002)
	Emergy	2.80E+12	sej/m²/year	
7	**Sand**			
	Quantity	7.72E+07	g	
	Renewable fraction	70.49%	%	Asgharipour et al. (2020)
	Annual flow	3.00E+03	g/m²/year	
	UEV	1.70E+09	sej/g	Campbell et al. (2005)
	Emergy	5.09E+12	sej/m²/year	
8	**Electricity**			
	Consumption	9.12E+04	kWh/year	
	Conversion	1.25E+07	J/kWh	
	Non-renewable fraction	32.00%	%	Giannetti et al. (2015)
	Annual flow	4.02E+08	J/m²/year	
	UEV	2.20E+05	sej/J	Giannetti et al. (2015)
	Emergy	8.84E+13	sej/year	
9	**Ethanol**			
	Consumption	5.00E+02	L/year	
	Conversion	2.97E+05	J/L	
	Non-renewable fraction	81.00%	%	Agostinho and Siche (2014)
	Annual flow	1.32E+05	J/m²/year	
	UEV	4.80E+04	sej/J	Agostinho and Siche (2014)
	Emergy	6.36E+09	sej/m²/year	
10	**Diesel**			
	Consumption	5.00E+02	L/year	
	Conversion	3.60E+07	J/L	
	Annual flow	1.98E+07	J/m²/year	
	UEV	4.59E+03	sej/J	Giannetti et al. (2019)
	Emergy	9.10E+10	sej/year	
11	**Feed**			
	Consumed feed	7.00E+03	kg/year	
	Feed energy	1.45E+04	J/kg	
	Total feed energy	1.02E+08	J/kg	
	Annual flow	1.12E+05	J/m²/year	

	UEV	9.96E+04	sej/J	Brown and Bardi (2001)
	Emergy	1.11E+10	sej/year	
12	**Carbon source**			
	Quantity	7.00E+02	kg	
	Non-renewable fraction	67.00%	%	Pereira and Ortega (2010)
	Annual flow	5.17E-01	kg/m²/year	
	UEV	4.87E+12	sej/kg	Brown and Ulgiati (2004)
	Emergy	2.52E+12	sej/year	
13	**Iron**			
	Quantity	1.14E+07	g	
	Non-renewable fraction	37.00%	%	Oliveira et al. (2018)
	Annual flow	4.63E+02	g/m²/year	
	UEV	3.56E+09	sej/g	Odum (2002)
	Emergy	1.65E+12	sej/m²/year	
14	**Sand**			
	Quantity	7.72E+07	g	
	Renewable fraction	29.51%	%	Asgharipour et al. (2020)
	Annual flow	1.25E+03	g/m²/year	
	UEV	1.70E+09	sej/g	Campbell et al. (2005)
	Emergy	2.13E+12	sej/m²/year	
15	**Concrete**			
	Quantity	7.83E+07	g	
	Annual flow	4.31E+03	g/m²/year	
	UEV	1.38E+09	sej/g	Pulselli et al. (2008)
	Emergy	5.93E+12	sej/m²/year	
16	**Pipes**			
	Quantity	2.41E+07	kg	
	Annual flow	2.65E+03	kg/m²/year	
	UEV	4.19E+09	sej/kg	Odum (2002)
	Emergy	1.11E+13	sej/m²/year	
17	**Plastic**			
	Annual flow	9.73E+00	g/m²/year	
	UEV	4.19E+09	sej/g	Odum (2002)
	Emergy	4.08E+10	sej/m²/year	
18	**Human labor**			
	Man-hours	3.00E+01	hours/day	

	Conversion to kcal	2.85E-01	kcal/year	
	Conversion to J	4.19E+03	J/kcal	
	Renewable fraction	7.00%	%	Allegretti et al. (2018)
	Annual flow	2.76E+00	J/m²/year	
	UEV	3.27E+06	sej/J	Oliveira et al. (2018)
	Emergy	9.03E+06	sej/year	
19	**Infrastructure and equipment**			
	Depreciation	1.50E+04	$/year	
	Annual flow	1.65E+01	$/m²/year	
	UEV	5.60E+12	sej/$	Giannetti et al. (2018)
	Emergy	9.25E+13	sej/year	
20	**Human labor**			
	Man-hours	3.00E+01	hours/day	
	Conversion to kcal	2.85E-01	kcal/year	
	Conversion to J	4.19E+03	J/kcal	
	Non-renewable fraction	93.00%	%	Allegretti et al. (2018)
	Annual flow	3.33E+04	J/m²/year	
	UEV	3.27E+06	sej/J	Oliveira et al. (2018)
	Emergy	1.09E+11	sej/year	
21	**Taxes and fees**			
	Annual flow	1.93E+00	$/m²/year	
	UEV	5.60E+12	sej/$	Giannetti et al. (2018)
	Emergy	1.08E+13	sej/year	
22	**Effluent treatment by biodigester**			
	Annual flow of plastic	8.96E+00	g/m²/year	
	UEV	4.19E+09	sej/g	Odum (2002)
	Emergy	3.75E+10	sej/year	
23	**Fish fingerlings**			
	Harvested fish	1.50E+06	unit/year	
	Fish weight	5.00E+00	g	
	Conversion to kcal	5.00E+00	kcal/g	Brown and Bardi (2001)
	Conversion from kcal to J	4.18E+03	J/kcal	Brown and Bardi (2001)
	Annual flow	1.57E+11	J	

Emergy table for the sensitivity analysis of replacing the hydroelectric electricity source by photovoltaic.

Note	**Item**	**Unit**	**Amount (unit/m² yr)**	**UEV (sej/unit)**	**Emergy (sej/m² yr)**	**Emergy (%)**
Renewable resources (R)						
1	Sun	J	1.67E+07	1.00E+00	1.67E+07	0.0
2	Spring water	m³	8.81E+02	3.27E+05	2.88E+08	0.0
Total (R)					3.05E+08	
Non-renewable resources (N)						
	None	-	-	-	-	
Resources from the larger economy (F)						
	Renewable materials (Mr)					
3	Ethanol	L	3.11E+04	4.80E+04	1.49E+09	0.0
4	Carbon source	kg	2.54E-01	4.87E+12	1.24E+12	0.5
5	Iron	g	7.88E+02	3.56E+09	2.80E+12	1.1
6	Sand	g	3.00E+03	1.70E+09	5.09E+12	2.0
	Non-renewable materials (Mn)					
7	Ethanol	L	1.32E+05	4.80E+04	6.36E+09	0.0
8	Diesel	J	1.98E+07	4.59E+03	9.10E+10	0.0
9	Feed	J	1.02E+08	9.96E+04	1.12E+05	0.0
10	Carbon source	kg	5.17E-01	4.87E+12	2.52E+12	1.0
11	Iron	g	4.63E+02	3.56E+09	1.65E+12	0.7
12	Sand	g	1.25E+03	1.70E+09	2.13E+12	0.9
13	Concrete	g	4.31E+03	1.38E+09	5.93E+12	2.4
14	Pipes	g	2.65E+03	4.19E+09	1.11E+13	4.4
15	Plastic	g	9.73E+00	4.19E+09	4.08E+10	0.0
	Materials for the solar panels					
16	Photoactive materials	g	1.41E+02	4.38E+11	6.17E+13	24.7
17	Glass	g	2.19E+03	6.08E+09	1.33E+13	5.3
18	Copper	g	8.70E+01	7.75E+10	6.74E+12	2.7
19	Aluminum	g	1.41E+02	4.35E+09	6.16E+11	0.2
20	Steel	g	3.33E+02	9.42E+10	3.14E+13	12.6
21	Ethylene Vinyl Acetate	g	7.27E+01	4.73E+09	3.44E+11	0.1
	Renewable services (Sr)					
22	Human labor	J	2.76E+00	3.27E+06	9.03E+06	0.0

	Non-renewable services (Sn)					
23	Infrastructure and equipment	$	1.65E+01	5.60E+12	9.25E+13	37.0
24	Human labor	J	3.33E+04	3.27E+06	1.09E+11	0.0
25	Taxes and fees	$	1.93E+00	5.60E+12	1.08E+13	4.3
	Ecosystem disservices (D)					
26	Effluent treatment by biodigester	g	8.96E+00	4.19E+09	3.75E+10	0.0
Total (N+F)					2.50E+14	
Total emergy (Y)						
(Y = R+N+F+D)					2.50E+14	
Outcome (O)						
27	Fish fingerlings	J	1.57E+11			

Calculations for the sensitivity analysis of the replacement of hydroelectric electricity source by photovoltaic.

Note	Item	Value	Unit	Reference
1	**Sun**			
	Insolation	2.05E+07	J/m²/year	CIIAGRO (2020)
	Solar transmittance coefficient	81.60%	%	Sangpradit (2014)
	Annual flow	1.67E+07	J/m²/year	
	UEV	1.00E+00	sej/J	By definition
	Emergy	1.67E+07	sej/m²/year	
2	**Spring water**			
	Quantity	8.00E+05	L	
	Annual flow	8.81E+02	L/m²/year	
	UEV	3.27E+05	sej/L	Bastianoni and Marchettini (2000)
	Emergy	2.88E+08	sej/year	
3	**Ethanol**			
	Consumption	5.00E+02	L/year	
	Conversion	2.97E+05	J/L	
	Renewable fraction	19.00%	%	Agostinho and Siche (2014)
	Annual flow	3.11E+04	J/m²/year	
	UEV	4.80E+04	sej/J	Agostinho and Siche (2014)
	Emergy	1.49E+09	sej/m²/year	
4	**Carbon source**			

	Quantity	7.00E+02	kg	
	Renewable fraction	33%	%	Pereira and Ortega (2010)
	Annual flow	2.54E-01	kg/m²/year	
	UEV	4.87E+12	sej/kg	Brown and Ulgiati (2004)
	Emergy	1.24E+12	sej/year	
5	**Iron**			
	Quantity	1.14E+07	g	
	Renewable fraction	63.00%	%	Oliveira et al. (2018)
	Annual flow	7.88E+02	g/m²/year	
	UEV	3.56E+09	sej/g	Odum (2002)
	Emergy	2.80E+12	sej/m²/year	
6	**Sand**			
	Quantity	7.72E+07	g	
	Renewable fraction	70.49%	%	Asgharipour et al. (2020)
	Annual flow	3.00E+03	g/m²/year	
	UEV	1.70E+09	sej/g	Campbell et al. (2005)
	Emergy	5.09E+12	sej/m²/year	
7	**Ethanol**			
	Consumption	5.00E+02	L/year	
	Conversion	2.97E+05	J/L	
	Non-renewable fraction	81.00%	%	Agostinho and Siche (2014)
	Annual flow	1.32E+05	J/m²/year	
	UEV	4.80E+04	sej/J	Agostinho and Siche (2014)
	Emergy	6.36E+09	sej/m²/year	
8	**Diesel**			
	Consumption	5.00E+02	L/year	
	Conversion	3.60E+07	J/L	
	Annual flow	1.98E+07	J/m²/year	
	UEV	4.59E+03	sej/J	Giannetti et al. (2019)
	Emergy	9.10E+10	sej/year	
9	**Feed**			
	Consumed feed	7.00E+03	kg/year	
	Feed energy	1.45E+04	J/kg	
	Total feed energy	1.02E+08	J/kg	
	Annual flow	1.12E+05	J/m²/year	
	UEV	9.96E+04	sej/J	Brown and Bardi (2001)

	Emergy	1.11E+10	sej/year	
10	**Carbon source**			
	Quantity	7.00E+02	kg	
	Non-renewable fraction	67.00%	%	Pereira and Ortega (2010)
	Annual flow	5.17E-01	kg/m²/year	
	UEV	4.87E+12	sej/kg	Brown and Ulgiati (2004)
	Emergy	2.52E+12	sej/year	
11	**Iron**			
	Quantity	1.14E+07	g	
	Non-renewable fraction	37.00%	%	Oliveira et al. (2018)
	Annual flow	4.63E+02	g/m²/year	
	UEV	3.56E+09	sej/g	Odum (2002)
	Emergy	1.65E+12	sej/m²/year	
12	**Sand**			
	Quantity	7.72E+07	g	
	Renewable fraction	29.51%	%	Asgharipour et al. (2020)
	Annual flow	1.25E+03	g/m²/year	
	UEV	1.70E+09	sej/g	Campbell et al. (2005)
	Emergy	2.13E+12	sej/m²/year	
13	**Concrete**			
	Quantity	7.83E+07	g	
	Annual flow	4.31E+03	g/m²/year	
	UEV	1.38E+09	sej/g	Pulselli et al. (2008)
	Emergy	5.93E+12	sej/m²/year	
14	**Pipes**			
	Quantity	2.41E+07	kg	
	Annual flow	2.65E+03	kg/m²/year	
	UEV	4.19E+09	sej/kg	Odum (2002)
	Emergy	1.11E+13	sej/m²/year	
15	**Plastic**			
	Annual flow	9.73E+00	g/m²/year	
	UEV	4.19E+09	sej/g	Odum (2002)
	Emergy	4.08E+10	sej/m²/year	
16	**Photoactive materials**			
	Annual flow	1.41E+02	g/m²/year	
	UEV	4.38E+11	sej/g	Brown and Ulgiati (2010)

	Emergy	6.17E+13	sej/m²/year	
17	**Glass**			
	Annual flow	2.19E+03	g/m²/year	
	UEV	6.08E+09	sej/g	Brown and Ulgiati (2010)
	Emergy	1.33E+13	sej/m²/year	
18	**Copper**			
	Annual flow	8.70E+01	g/m²/year	
	UEV	7.75E+10	sej/g	Cohen et al. (2007)
	Emergy	6.74E+12	sej/m²/year	
19	**Aluminum**			
	Annual flow	1.41E+02	g/m²/year	
	UEV	4.35E+09	sej/g	Cohen et al. (2007)
	Emergy	6.16E+11	sej/m²/year	
20	**Steel**			
	Annual flow	3.33E+02	g/m²/year	
	UEV	9.42E+10	sej/g	Cohen et al. (2007)
	Emergy	3.14E+13	sej/m²/year	
21	**Ethylene Vinyl Acetate**			
	Annual flow	7.27E+01	g/m²/year	
	UEV	4.73E+09	sej/g	Brown et al. (2011)
	Emergy	3.44E+11	sej/m²/year	
22	**Human labor**			
	Man-hours	3.00E+01	hours/day	
	Conversion to kcal	2.85E-01	kcal/year	
	Conversion to J	4.19E+03	J/kcal	
	Renewable fraction	7.00%	%	Allegretti et al. (2018)
	Annual flow	2.76E+00	J/m²/year	
	UEV	3.27E+06	sej/J	Oliveira et al. (2018)
	Emergy	9.03E+06	sej/year	
23	**Infrastructure and equipment**			
	Depreciation	1.50E+04	$/year	
	Annual flow	1.65E+01	$/m²/year	
	UEV	5.60E+12	sej/$	Giannetti et al. (2018)
	Emergy	9.25E+13	sej/year	
24	**Human labor**			
	Man-hours	3.00E+01	hours/day	

	Conversion to kcal	2.85E-01	kcal/year	
	Conversion to J	4.19E+03	J/kcal	
	Non-renewable fraction	93.00%	%	Allegretti et al. (2018)
	Annual flow	3.33E+04	J/m²/year	
	UEV	3.27E+06	sej/J	Oliveira et al. (2018)
	Emergy	1.09E+11	sej/year	
25	**Taxes and fees**			
	Annual flow	1.93E+00	$/m²/year	
	UEV	5.60E+12	sej/$	Giannetti et al. (2018)
	Emergy	1.08E+13	sej/year	
26	**Effluent treatment by the biodigester**			
	Annual flow of plastic	8.96E+00	g/m²/year	
	UEV	4.19E+09	sej/g	Odum (2002)
	Emergy	3.75E+10	sej/year	
27	**Fish fingerlings**			
	Harvested fish	1.50E+06	unit/year	
	Fish weight	5.00E+00	g	
	Conversion to kcal	5.00E+00	kcal/g	Brown and Bardi (2001)
	Conversion from kcal to J	4.18E+03	J/kcal	Brown and Bardi (2001)
	Annual flow	1.57E+11	J	

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Chapter 5

Tilapia farming based on periphyton as a natural food source.

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Tilapia farming based on periphyton as a natural food source

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Abstract

Nutrient-rich effluents from aquaculture can be reused to enhance the development of natural food to feed fish in periphyton-based systems. A periphyton-based system is a strategy to increase fish farming efficiency, reducing feed use and effluent disposal. This study aimed to evaluate different types of feeding management in periphyton- based systems to produce Nile tilapia in ponds. To do this, two new production models were compared: (P100–0) Nile tilapia fed 100% of the recommended amount of feed sharing effluent with a tilapia production in a periphyton-based system with no feed input, and (P50–0) Nile tilapia fed 50% of feed plus periphyton sharing effluent with a tilapia production in a periphyton-based system with no feed input. Fish fed only feed showed higher growth performance than those fed partially feed plus periphyton. On the other hand, fish only periphyton-based fed grew similarly when using effluent from a system fed only feed and fed partially feed plus periphyton. Biomass gain and productivity were significantly higher in P100–0 than in P50–0, and no differences in the feed conversion ratio and survival were found. For both production models, fish feed fed and periphyton-based fed corresponded, respectively, to 75% and 25% of the total productivity of each production model. The tilapia growth performance indicates that the proposed production models are promising strategies for using natural food in a periphyton-based system and reusing effluents from monocultures, especially when inputting a high amount of nutrients as in P100–0.

Keywords: Effluent recycle; Natural food; Nile tilapia; Periphyton; Ponds.

1. Introduction

Feed is the most expensive input and is mainly responsible for the low sustainability of aquaculture (Ayroza et al., 2011; David et al., 2020). Feed can constitute up to 70% of the total production cost of intensive monocultures (Ayroza et al., 2011). Besides that, feed is not fully utilized by fish which generates effluent rich in nitrogen and phosphorus (Boyd et al., 2020). Depending on the system and management adopted, these nutrients are discarded in the natural environ- ment without treatment, causing environmental problems such as eutrophication of water bodies and biodiversity loss (Valenti et al., 2018). To avoid these problems, aquaculture systems should advance toward more sustainable production models that optimize feed use. Thus, the nutrient-rich effluents from aquaculture should be reused to produce a second crop or enhance the development of natural food to feed fish, for example, in periphyton-based systems (Garcia et al., 2016; Boyd et al., 2020).

Periphyton-based aquaculture uses artificial substrates to grow periphyton as a natural food strategy to increase fish farming efficiency in ponds and cage systems. Periphyton is a microorganism community composed of algae, bacteria, fungi, protozoa, zooplankton, and other invertebrates (Azim et al., 2005). This community develops naturally on submerged substrates introduced into the water column (Azim and Asaeda, 2005). Moreover, periphyton has often been reported as the major contributor to primary production in pond systems due to its composition based mostly on green microalgae (Saikia and Das, 2009). The use of periphyton has led to reducing the dependence on feed (Garcia et al., 2016) as it converts the inorganic nutrients present in the water column, usually from feed leftovers and fish feces, into natural food available to fish (van Dam and Verdegem, 2005). Additionally, periphyton microorganisms recycle the nutrients discharged into the water, maintain water quality (Milstein et al., 2013), and improve aquaculture production sustainability (David et al., 2018). Nile tilapia has been the species often cultured in periphyton-based systems. This species is an opportunistic omnivore with a tendency toward herbivory feeding behavior (Beveridge and Baird, 2000). Moreover, tilapia has morphological adaptations that allow it to take advantage of the periphyton (Sanderson et al., 1996; Sibbing and Witte, 2005).

Periphyton-based systems have mainly been applied to previous studies as a strategy to decrease the use of feed. For example, Garcia et al. (2016) showed that periphyton could replace feed by at least 50% without harming Nile tilapia growth in cages. So far, there has been no report on using effluent from aquaculture as a nutrient source to pro- mote natural food development to nourish farmed fish. Thus, an alternative to not using the feed is to take advantage of the nutrient-rich effluent of a traditionally fed monoculture to foment periphyton development in a production model that shares effluent. Integrating a periphyton-based system to a monoculture would be a way to treat effluent, avoid its discharge into the natural environment, and produce fish without direct use of feed. In addition, fish reared only using natural food (periphyton) could receive differentiated labeling and possibly be sold to a niche market of more sustainable products. Thus, this study aimed to evaluate different types of feeding management in periphyton- based systems to produce Nile tilapia in ponds. To do this, two new production models were compared: (i) Nile tilapia fed 100% of the recommended amount of feed sharing effluent with tilapia production in a periphyton-based system with no feed input, and (ii) Nile tilapia fed 50% of feed plus periphyton sharing effluent with tilapia production in a periphyton-based system with no feed input.

2. Material and Methods

2.1. Experimental design and feeding management

The experiment was carried out for 112 days in experimental ponds, under real culture conditions at the Fisheries Institute, Votuporanga, SP, Brazil (20º 27′ 50″ S, 50º 03′ 53″ W). The experimental design was authorized by the Ethics Committee on Animal Use (CEUA FCAV/Unesp – Protocol No. 011730/19).

The study was designed using four feeding managements combined in two production models with three replicates each (Figure 1). In the first production model (P100-0), there was a feeding management in which fish were fed only feed (F100), sharing the effluent with a second feeding management where fish were periphyton-based fed with no feed input (F0-100). In the second production model (P50-0), there was a feeding management in which fish were fed feed every other day (50% of feed) plus periphyton (F50), sharing the effluent with a fish production fed at a periphyton-based system (F0-50). To do this, six ponds of 1.5 m depth and 104 m² (8 x 13 m) were used and divided in half by a 5 mm mesh net. Different feeding management was adopted in each half of a pond (52 m²) as described above. A control treatment using only substrate with periphyton, without fish, was also included in this trial. However, in this control treatment, the periphyton was consumed by insect larvae, which made the results unreliable to be presented. The consumption of periphyton by insect larvae, mainly chironomids, is also reported by other authors who evaluated periphyton development without the presence of fish (Azim et al., 2005).

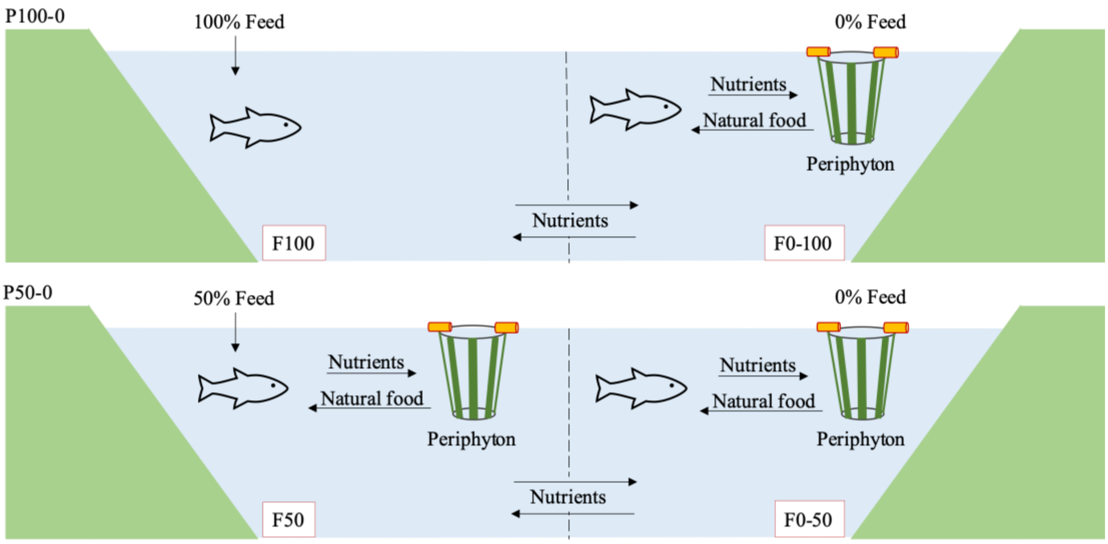

Figure 1. Feeding management adopted during the trial. P100-0: on the left side, fish were fed only feed (F100) sharing effluent with the right side where fish were periphyton-based fed with no feed input (F0-100). P50-0: on the left side, fish were fed feed every other day (50% of feed) plus periphyton (F50), sharing the effluent with the right side in which fish were fed at a periphyton-based system (F0-50).

Sex-reversed male Nile tilapia (*Oreochromis niloticus*) with an average weight of 137.7 ± 2.7 g were obtained from a local fish farm and stocked at the density of 1.8 fish/m² in F100 and F50, and at 0.96 fish/m² in F100-0 and F50-0. The low density (<1 fish/m^2) was adopted in treatments fed only with natural food (periphyton) as an attempt to possibly meet the requirements imposed by organic standards (Milstein et al., 2005; IFOAM, 2014).

Concerning the feed management, the feed portions were previously weighed according to the feed manufacturer's recommendation, ranging from 5% of the live weight of the fish at the beginning of the experiment to 2% at the end. Commercial feed containing 32% of crude protein and 6% of ether extract was offered until apparent satiation three times a day (9:30h, 12:30h, and 15:30h). Fish from F100 were fed daily and from F50 every other day. Feed was offered carefully and slowly to ensure that it was entirely consumed by the fish and did not disperse in the pond. Daily feed intake was calculated as the difference between the amount of feed recommended and the feed left in the tray. The presence and absence of substrate and the amount of nutrients input in the ponds through the feed determined the production model differences.

2.2. Pond preparation

Before the beginning of the trial, the ponds were sun-dried, and then agricultural lime (CaCO3) was applied to each pond bottom at 200 kg/ha. Organic poultry manure was used as a fertilizer at a proportion of 200 kg/ha. After seven days of the lime and fertilizer application, the ponds were filled with water from a farm dam. The water supply was monitored monthly during the experiment, and the concentrations of total nitrogen and phosphorus were 1.21 ± 0.64 and 0.07 ± 0.03 mg/L, respectively. There was no water renewal in the ponds during the experimental period; only 5% replacement of the pond volume every two weeks to compensate for losses due to seepage and evaporation. Moreover, no artificial aeration was used during the study.

For periphyton colonization, nine modules of bamboo substrates were added into the experimental units of the F0-100, F50, and F0-50. The number of modules was calculated to increase 50% (26 m^2) of the surface area of each experimental unit (Figure 2). Each substrate module comprised 10 bamboo stems (1x0.06 m) and cone-shaped assembled with floats. All substrates were installed 21 days before the beginning of the experiment, which is sufficient time to obtain a stable periphytic community (Garcia et al., 2016).

Figure 2. Scheme illustrating the distribution of bamboo substrates in experimental ponds for Nile tilapia production. P100-0: on the left side, fish were fed only feed (F100) sharing effluent with the right side where fish were periphyton-based fed with no feed input (F0-100). P50-0: on the left side, fish were fed feed every other day (50% of feed) plus periphyton (F50), sharing effluent with the right side in which fish were fed in a periphyton-based system (F0-50).

2.3. Characterization of the periphyton

On days 0, 60, and 112 of the trial, three stems of bamboo substrates were collected from each experimental unit to obtain samples of the colonized periphyton. The periphyton was carefully removed from the bamboo using a brush and distilled water. The samples were dried in an oven for 72 hours at 60 °C until constant weight to obtain the periphyton dry matter (DM) per substrate area (mg/cm²). In the first 60 days, the DM increased equally from 0.25 mg/cm^2 to 1.1 mg/cm^2 in all types of feeding managements and remained stable until the end of the experiment. The DM was submitted to analyze to determine the crude protein and ether extract content of the periphyton. As periphyton DM was low, the periodic samples from the same feeding management were pooled. Periphyton crude protein content was determined using Leco Nitrogen/Protein in Organic Samples, model FP528, and ether extract by the acid hydrolysis method, both following the AOAC (2000) methodology. Periphyton from F50, F0-100, and F0-50 contained 25.7 ± 1.5%, 26.4 ± 0.3%, and 23.2 ± 1.2% of crude protein, respectively. Regarding the ether extract content, periphyton presented approximately 0.2% regardless of the feeding management.

2.4. *Water quality*

The physical-chemical parameters of the water were monitored in all experimental units. However, throughout the experimental period, the treatments that shared the same pond showed similar values for all parameters. Thus, the water quality results were pooled and presented for each production model (P100-0 and P50-0).

Daily water temperature and dissolved oxygen were measured at 50 cm depth using a multiparameter YSI professional. These measurements were taken in the morning (8:00h) and in the afternoon (16:00h). Transparency and pH were measured biweekly at 12:00h, using a Secchi disk and pH meter (model Hanna HI-98129), respectively. On a monthly basis, three water samples were collected and frozen to determine nitrogen compounds and the total phosphorus. All chemical parameters were determined according to the APHA methodology (2005), total ammonia nitrogen (4500-NH_3-F. Phenate Method), N-nitrate (4500-NO_3-E. Cadmium Reduction Method), N-nitrite (4500-NO2-B. Colorimetric Method), total nitrogen (4500-N_{org}-B. Macro-Kjeldahl Method), and total phosphorus (4500-P D. Stannous Chloride Method).

2.5. *Fish growth and body composition*

Fish were weighed (20% of the fish of each experimental unit, n=17) biweekly to adjust the amount of feed. At the end of the experiment, all fish from each experimental unit were weighed and the following parameters were calculated: final weight (g), specific growth rate (%/day) (SGR = [(ln final weight − ln initial weight)/time] × 100), feed conversion ratio (FCR = feed consumption/weight gain), biomass gain (g) (BG = final biomass – initial biomass), survival (%) = [(final number of fish/initial number of fish) x 100], and productivity (kg/m²) (productivity = final fish biomass/experimental unit area).

To analyze the fish body composition, at the end of the experiment, three fish samples were randomly collected from each experimental unit (totaling 12 fish per feeding management) and frozen. The fish samples were ground in a meat grinder (CAF, model 22S), homogenized, and lyophilized for determining the percentage of dry matter

(DM), crude protein (CP) (Leco Nitrogen/Protein in Organic Samples, model FP528), and ether extract (EE) (by the acid hydrolysis method), according to the AOAC (2000) methodology.

2.6. Statistical analysis

The normality (Shapiro-Wilk's test) and homogeneity of variance (Levene's test) were tested for all data. Water quality parameters and most of the fish growth parameters (i.e., feed conversion ratio, biomass gain, survival, and productivity) were compared between the production models (P100-0 and P50-0) using the student's *t-test*. For the final fish weight and specific growth rate, due to the difference in stocking densities adopted among the treatments fed feed (F100 and F50) and unfed feed (F0-100 and F0-50), the data from F100 was compared to F50 and from F0-100 compared to F0-50, both using the student's *t-test*. The data of fish composition were analyzed by one-way ANOVA, followed by Tukey's test to detect differences among the means values of each type of feeding management. All data were analyzed at a 5% significance level.

3. Results

3.1. Water quality

Overall, the water quality in both production models was very similar, with a significant difference only detected in dissolved oxygen in the morning, transparency, and total phosphorous (t-test, $P<0.05$). Both dissolved oxygen in the morning and transparency were significantly higher in P50-0 than in P100-0, while the inverse was observed for total phosphorus (Table 1).

Table 1. Means (± SD) of water quality parameters measured in each production model during 112 days of the experimental period.

Parameter	**Period**	**Production model**		*****P*****-value**
		P100-0	**P50-0**	
Temperature (°C)	Morning	28.84 ± 0.12	28.79 ± 0.10	0.601
	Afternoon	31.95 ± 0.19	32.07 ± 0.10	0.371
Dissolved Oxygen (mg/L)	Morning	4.03 ± 0.63 b	5.79 ± 0.70 a	0.032
	Afternoon	7.23 ± 0.18	9.17 ± 1.60	0.105
Transparency (cm)		26.38 ± 3.04 b	32.80 ± 2.13 a	0.040
pH		6.56 ± 0.02	6.60 ± 0.02	0.056
Ammonia (mg/L)		0.18 ± 0.03	0.13 ± 0.01	0.065
Nitrite (mg/L)		0.30 ± 0.09	0.30 ± 0.06	1.000
Nitrate (mg/L)		0.29 ± 0.03	0.27 ± 0.14	0.766
Total Nitrogen (mg/L)		1.49 ± 0.25	1.59 ± 0.21	0.608
Total Phosphorus (mg/L)		0.13 ± 0.01 a	0.10 ± 0.01 b	0.033

* Means followed by different letters in the same line indicate statistical difference by Student's *t-test* at 5% significance level. P100-0: production model in which fish were fed only feed sharing effluent with the production of fish periphyton-based fed with no feed input. P50-0: the production model in which fish were fed feed every other day (50% of feed) plus periphyton sharing effluent with the production of fish periphyton-based fed.

3.2. Fish growth and body composition

Comparing the production models, biomass gain, and productivity were significantly higher in P100-0 than in P50-0, and no difference for the feed conversion ratio and survival were found (Table 2). For both production models, fish fed with feed and periphyton-based fed corresponded, respectively, to 75% and 25% of the total productivity of each model. Fish from F100 presented a final weight 38.8% and specific growth rate (SGR) 36% higher than F50. Meanwhile, fish fed with no feed grew similarly in F0-100 and F0-50, as no significant differences for the final weight and SGR were found.

Table 2. Productive parameters (mean ± SD) found for each production model and treatment after 112 days of the experimental period.

Parameter	**P100-0**		**P50-0**		***P*-value***
Feed conversion ratio	1.37 ± 0.20		1.46 ± 0.39		0.759
Biomass gain (kg)	47.18 ± 7.40	a	20.15 ± 5.86	b	0.007
Survival (%)	99.14 ± 0.29		99.33 ± 1.15		0.792
Productivity (kg/m^2)	0.48 ± 0.04	a	0.30 ± 0.04	b	0.006
	F100		**F50**		***P*-value****
Final weight (g)	513.04 ± 52.00	a	314.84 ± 31.31	b	0.004
Specific growth rate (%/day)	1.18 ± 0.11	a	0.75 ± 0.07	b	0.004
	F0-100		**F0-50**		***P*-value*****
Final weight (g)	318.22 ± 75.59		196.76 ± 44.59		0.074
Specific growth rate (%/day)	0.72 ± 0.20		0.30 ± 0.18		0.060

P100-0: production model in which fish were fed only feed sharing effluent with the production of fish periphyton-based fed with no feed input. P50-0: production model in which fish were fed feed every other day (50% of feed) plus periphyton sharing effluent with the production of fish periphyton-based fed. F100: treatment in which fish were fed only feed. F50: treatment in which fish were fed feed every other day (50% of feed) plus periphyton. F0-100: treatment in which fish were periphyton-based fed, sharing effluent with F100. F0-50: treatment in which fish were periphyton-based fed, sharing effluent with F50.

Means followed by different letters in the same line indicate statistical difference by Student's *t-test* at 5% significance level.

* Student's t-test comparing the production models as both were under the same experimental conditions, varying only the feeding management.

** Student's t-test comparing the fed feed treatments as both were under the same experimental conditions (fish density at 1.8 fish/m^2), varying only the feeding management.

*** Student's t-test comparing the unfed feed treatments as both were under the same experimental conditions (fish density at 0.96 fish/m^2), varying only the effluent source. F0-100 shared effluent with F100 and F0-50 with F50.

No significant differences were observed in fish crude protein content among all treatments (ANOVA one-way, $P>0.05$) (Figure 4). Regarding the ether extract content, only fish grown in F0-50 presented a significantly lower result than all the other feeding managements.

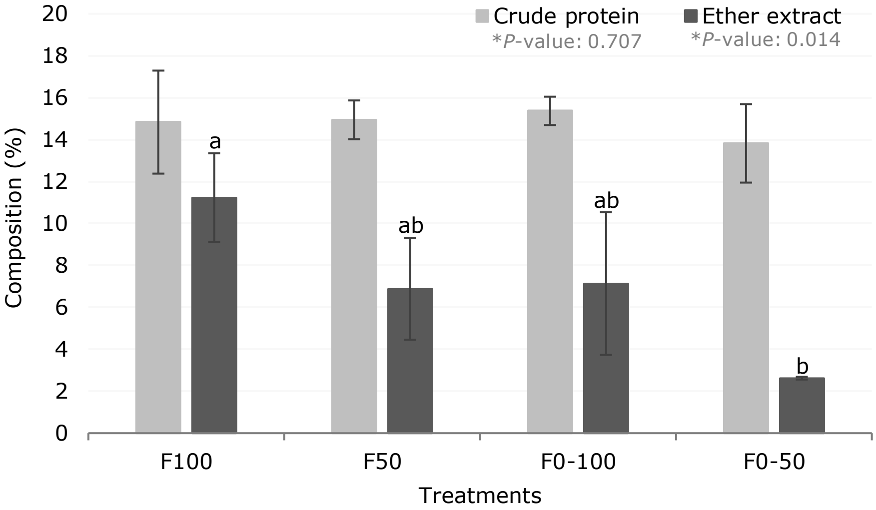

Figure 4. Centesimal composition (%) of tilapia carcass at different feeding managements. F100: feeding management in which fish were fed only feed. F0-100: feeding management where fish were periphyton-based fed with no feed input. F50: feeding management in which fish were fed feed every other day. F0-50: feeding management in which fish were periphyton-based fed.

4. Discussion

All water quality parameters remained within the desired levels for tilapia culture over the experimental period (El-Sayed, 2020). The difference between the average DO values in the morning, higher in P50-0, is probably related to the greater surface area of the substrate colonized by the periphyton and its green algae community that produces oxygen, combined with the lower fish biomass compared to P100-0. Other reasons are the differences in the nutrient input and the accumulation of organic matter between the models. The decomposition of organic matter tends to reduce the DO in the pond’s water (Tammam et al., 2020). Accumulation of organic matter usually occurs due to the continuous addition of feed leftover and fish feces, lower in P50-0 than P100-0. The average value of transparency followed this same pattern, presenting a higher value for P50-0, where the nutrient input was lower, and there were more substrates than in the P100-0. These results corroborate the findings from Asaduzzaman et al. (2009). These authors showed that using substrates for periphyton increases water transparency in the production of tilapia (*O. niloticus*) and freshwater prawns

(*Macrobrachium rosenbergii*) in ponds due to nutrient absorption and particulate material accumulation.

Approximately twice as much phosphorus and nitrogen were introduced through the feed in the P100-0 compared to P50-0. Despite that, only the total phosphorus in the water was significantly higher at P100-0 (Table 1), indicating that the periphyton could not incorporate all phosphorus load. On the other hand, the periphyton in both models cycled the nitrogen, keeping the levels of nitrogenous compounds similar between them over the experimental period, even with more nitrogen input and without water renewal. This similarity can be attributed to the effect of periphyton on nitrification (Asaduzzaman et al., 2009). Periphyton is usually composed, besides other microorganisms, by nitrifying bacteria and algae that contribute to processing the nitrogenous waste in ponds (Langis et al., 1988; Ramesh et al., 1999). These results indicate that the periphyton was more efficient in processing nitrogen than phosphorus under the evaluated conditions.

The tilapia growth performance indicates that the proposed production models are promising strategies for using natural food in a periphyton-based system and reusing effluents from monocultures. This is because the partial or total feed restriction plus periphyton maintained high survival rates (>99%) for cultivated fish. In addition, both production models presented FCR (1.37 for P100-0 and 1.46 for P50-0) similar or even lower than conventional production systems, such as tilapia in ponds (1.7, Rodrigues et al., 2019) and cages (1.84, Garcia et al., 2016). Another interesting fact that boosts the results of this study is that, even with no water renewal or artificial aeration, satisfactory growth performances were achieved at a higher fish density (1.8 fish/m²) than that usually used in periphyton-based culture. Other authors have applied periphyton-based systems to produce Nile tilapia in extensive and semi-intensive pond systems, with fish densities ranging from 1.1 to 1.4 fish/m² (van Dam and Verdegem, 2005). Additionally, only a feed reduction of 30 to 40% has been tested (van Dam and Verdegem, 2005; Milstein et al., 2005; Milstein et al., 2013). Compared to these studies, the proposed production models (P100-0 or P50-0) seems to be efficient to produce fish non-fed and reduce the dependence of this input in aquaculture system.

The proximal fish composition has important implications for human consumption. Fish is usually recognized as a high-quality protein and fat acid source (Pinho et al., 2021). Therefore, guaranteeing the fish nutritional quality is an essential market requirement (Gould et al., 2019). Tilapia periphyton-based fed (F0-100) or partially fed with periphyton (F50) presented a similar composition to those fed only with feed (F100). Although there was no statistical difference, considering the absolute averages, fish from F0-100 and F50 showed 40% less EE than F100 while maintaining the same protein content. The high-calorie content in the feed (mainly due to the ether extract levels, ~ 6% *vs.* 0.2% of EE in the periphyton) may have caused the higher accumulation of EE in fish from F100. To the best of our knowledge, our study is the first to report the proximate composition of fish grown using periphyton as natural food. These results highlight the possibility of using periphyton as a natural food source in aquaculture without compromising the quantity of macronutrients in the composition of farmed fish.

The superior growth performance on both sides (F100 and F0-100) of the production model with higher nutrient input (P100-0) than both sides of P50-0 indicates a positive correlation between the input of nutrients in the system and the growth of fish produced in a periphyton-based system. From a practical perspective, the productive results obtained show that both production models could be immediately applied by producers who use monocultures to comply with legal requirements and possibly obtain extra income. This is because producers using monoculture pond systems are required to set aside large areas for filtration systems and decantation basins to reduce the concentration of nutrients in farm effluents (Boyd et al., 2020). Adopting periphyton-based systems can recover a large proportion of lost nutrients in ponds, avoiding the disposal of nutrient-rich effluents and consequent environmental problems (Saikia, 2011; David et al., 2018; Rodrigues et al., 2019). Therefore, from an economical and sustainable point of view, adopting integrated production models to reuse the nutrient-rich effluent, and generate a product possibly eligible for some type of certification would be more beneficial for tilapia producers than investing in filtration systems or decantation basins.

5. Conclusion

The natural food available in the periphyton-based system allowed the total and partial feed restriction of Nile tilapia culture in ponds. The results suggest that the higher input of nutrients in the production models P100-0 allowed to obtain higher fish growth performance than in P50-0. Additionally, proximal tilapia compositions were similar to those fed with periphyton or feed, mainly in protein content. Thus, sharing effluents between a fed monoculture with non-fed fish in a periphyton-based system may bring new perspectives for more efficient production due to better nutrient use, possibly resulting in economic and environmental advantages.

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Chapter 6

Growth performance of Nile tilapia reared in cages in a farm dam submitted to a feed reduction strategy in a periphyton-based system.

This chapter is based on:

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Growth performance of Nile tilapia reared in cages in a farm dam submitted to a feed reduction strategy in a periphyton-based system

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Abstract

The periphyton-based system is a low-cost and sustainable strategy for small-scale producers who have limited technology and budgets. This study aimed to evaluate the effects of different feed restriction levels (50% and 67%), using periphyton as a natural food source, on the growth performance of Nile tilapia reared under real culture conditions in cages placed in a farm dam. Three treatments were tested: F100 - fish fed daily only on feed; F50 - fish fed every other day, plus periphyton; and F33 - fish fed every two days, plus periphyton. Considering the results of fish growth in F50 and F33 compared to F100 and the low amount of periphyton dry matter, it is reasonable to state that the fish under feed restriction did not take advantage of the periphyton due to its low availability. This low availability of the periphyton is possibly associated with the water N:P ratio and its variation over the experimental period. Therefore, periphyton-based systems are not indicated for conditions with a low N:P ratio or subject to great variations in this ratio.

Keywords: Feed reduction; Natural food; Periphyton; Small-scale farmer; Tilapia production.

Feeding has been reported as the major cost in aquaculture and mainly responsible for the environmental impact caused by this activity (Ayroza, Romagosa, Ayroza, Filho, & Salles, 2011; Verdegem, 2013). The use of feed in high and inadequate quantities leads to economic losses, water quality deterioration, and environmental impact generation (Moraes, Attayde, & Henry-Silva, 2020). Alternative managements, such as periphyton-based systems, have been tested to reduce the dependence and costs on feed (Azim et al., 2004; Garcia et al., 2017; Rodrigues et al., 2019; Tammam, Wassef, Toutou, & El-Sayed, 2020). The periphyton-based system is a low-cost and sustainable strategy to produce certain species of fish (David, Pinho, & Garcia, 2018; Lu, Liu, Kerr, Shao, & Wu, 2017). Periphyton is the community of microorganisms established by microalgae, bacteria, fungi, protozoa, zooplankton, and other aquatic invertebrates (Azim & Asaeda, 2005). These microorganisms have been considered a valuable source of natural food for cultured fish (Azim & Asaeda, 2005; Milstein, Peretz, & Harpaz, 2009; Tammam et al., 2020). In cage fish farming in a tropical hydroelectric reservoir, the leftover feed enhances periphyton development in substrates by accumulating nutrients from fish culture (Moraes et al., 2020).

The use of periphyton in cages in hydroelectric reservoirs allows production of up to 52 kg/m^3 of Nile tilapia (*Oreochromis niloticus)* using 32% less feed in a period almost 20% shorter than in productions based exclusively on feed (Garcia, Romera, Sousa, Paiva-Ramos, & Onaka, 2016). Besides, the periphyton-based system can lead to increasing the annual operating income of intensive tilapia cage farming by up to 57% and the profitability index by up to 87% (Garcia et al., 2017). The aforementioned benefits of periphyton in tilapia growth combined with the possibility of reducing feeding costs make the periphyton-based system a potential alternative for producers whose cages are placed in small-scale reservoirs, such as lakes and farm dams. This is because aquaculture in these locations is limited in terms of technology and investment (Roriz, Delphino, Gardner, & Gonçalves, 2017). Based on this information and on the success of the study conducted by Garcia et al. (2016) evaluating 50% feed reduction and the use of periphyton as a complementary food source in cage farming in hydroelectric reservoirs; we hypothesized that a further reduction in the amount of feed (> 50%) for Nile tilapia reared in cages in small-scale reservoirs will benefit producers and may not harm the fish growth performance. Thus, this study aimed to evaluate the effects of different feed restriction levels (50% and 67%) using periphyton as a natural food source on the growth performance of Nile tilapia reared in cages placed in a farm dam.

The study was performed over 112 days in 12 cages (1 m^3), under real culture conditions, placed in a farm dam (1 ha, 4 m depth) at the Fisheries Institute, Votuporanga, SP, Brazil (20º 27′ 50″ S, 50º 03′ 53″ W). The experimental design was authorized by the Ethics Committee on Animal Use (CEUA FCAV/Unesp – Protocol No. 011730/19). Nile tilapia (*Oreochromis niloticus)* were stocked with an initial average weight of 137.7 ± 2.7 g at a density of 85 fish/m^3. Three treatments with four replicates each were tested, as follows: F100 - fish fed daily only on feed, following the total amount suggested by the manufacturer, with no substrate for periphyton; F50 - fish fed every other day, representing 50% of the manufacturer's recommendation, plus substrate for periphyton; and, F33 - fish fed every two days, representing 33% of the amount suggested by the manufacturer, plus substrate for periphyton.

The substrates used for periphyton colonization were made of bamboo stalks cut lengthwise, representing 70% (3.50 m^2) of the total internal area of the cage (5 m^2). The substrates were installed in the cages of treatments F50 and F33, 21 days before the beginning of the experiment, which is the time needed to obtain a stable periphytic community (Garcia et al., 2016).

The feed portions provided were previously weighed (approximately 3 to 5% of the fish weight per fed day). Commercial feed containing 32% of crude protein and 6% of ether extract was slowly and carefully offered until apparent satiation, ensuring that the fish entirely consumed the feed. In all treatments, the fish were fed at 9:30, 12:30, and 15:30h, respecting the feeding schedule of each treatment. The daily feed consumed was calculated as the difference between the amount of feed initially weighed and the feed left in the tray. Fish were weighed (20% of each experimental unit, n=17) periodically to adjust the feed amount. At the beginning and end of the experiment, all fish were weighed. Having these data, we calculated the final weight (g), weight gain (g), specific growth rate (%/day), feed conversion ratio, survival (%), and productivity (kg/m^3).

To characterize the studied environment, the water temperature and dissolved oxygen were measured daily, and transparency and pH were measured biweekly. Water samples (n=3 per sampling period) from the farm dam were collected monthly to determine total ammonia (4500-NH_3-F. Phenate Method), nitrate (4500-NO_3-E.

Cadmium Reduction Method), nitrite (4500-NO2-B. Colorimetric Method), total nitrogen (4500-N_{org}-B. Macro-Kjeldahl Method), and total phosphorus (4500-P D. Stannous Chloride Method), following the APHA (2005) methodology. All the recorded water quality values (Table 1) were within the acceptable range for tilapia farming (El-Sayed, 2020). On days 0, 60, and 112 of the trial, three periphyton samples were collected from the experimental unit of treatments F50 and F33. The periphyton was carefully removed from the bamboo stalks using a brush and distilled water. The samples were dried in an oven for 72 hours at 60 °C until constant weight to obtain the dry matter (DM) of substrate surface area (mg/cm²) and track the amount of periphyton available (Figure 1).

Table 1. Means (±SD), minimum and maximum of water quality parameters obtained from the farm dam during the 112 days of the experimental period.

Parameter	**Value**		
Temperature (°C)	29.6	±	1.6
Min - Max	24.8	-	33.4
Dissolved oxygen (mg/L)	4.0	±	0.9
Min - Max	2.2	-	6.8
Transparency (cm)	83	±	14
Min - Max	63	-	108
Ammonia (mg/L)	0.21	±	0.15
Min - Max	0.05	-	0.42
Nitrite (mg/L)	0.24	±	0.22
Min - Max	0.03	-	0.50
Nitrate (mg/L)	0.73	±	0.49
Min - Max	0.35	-	1.57
Total nitrogen (mg/L)	1.21	±	0.76
Min - Max	0.34	-	2.23
Total phosphorus (mg/L)	0.08	±	0.03
Min - Max	0.05	-	0.12
N:P		14:1	
Min - Max	6:1	-	18:1

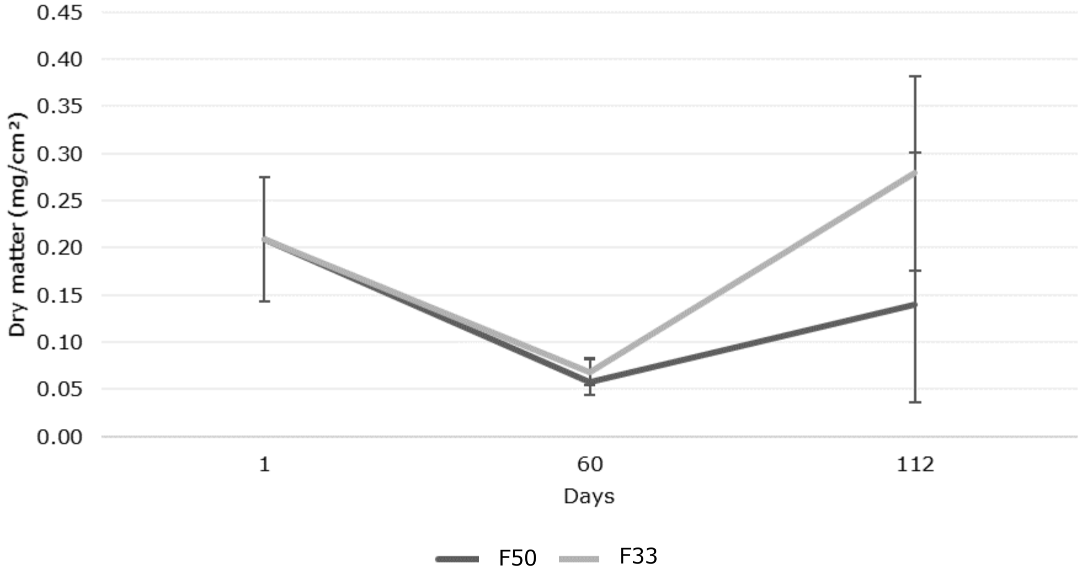

Figure 1. Variation (mean±SD) of the periphyton dry matter per unit surface area over the experimental period.

Once the premises of normality (Shapiro-Wilk's test) and homogeneity of variances (Levene's test) were fulfilled, all data concerning fish growth performance were analyzed by ANOVA (one-way). When a significant difference between the means was detected, they were compared using Tukey’s test at a significance level of 5%.

All treatments presented 100% survival. The F100 showed better results for all parameters evaluated, except for FCR, which did not significantly differ among the treatments (Table 2). Many studies have elucidated the periphyton consumption by fish (Asaduzzaman et al., 2008; Asaduzzaman, Wahab, Verdegem, Mondal, & Azim, 2009), especially when it is submitted to some level of feed restriction (Garcia et al., 2016). However, considering the results of the fish growth in F50 and F33 compared to F100, and the low variation of the periphyton DM (Figure 1), it is reasonable to state that the fish under 50% and 67% of feed restriction did not take advantage of the periphyton due to its low availability. The low consumption of periphyton is evident when we compare the weight gain of F100 with F50 and F33, which were equivalent to 50% and 33% of F100, respectively.

Table 2. Growth performance of Nile tilapia reared in cages under different feed restriction levels, using periphyton as complementary natural food.

Parameter	**Treatment**			
	F100	**F50**	**F33**	***p*-value**
Final weight (g)	566.16 ± 48.70 a	342.04 ± 31.09 b	280.77 ± 11.49 b	< 0.001
Weight gain (g)	425.32 ± 48.83 a	199.15 ± 27.16 b	139.45 ± 10.98 b	< 0.001
SGR (%/day)	1.24 ± 0.08 a	0.77 ± 0.06 b	0.61 ± 0.04 c	< 0.001
FCR	1.81 ± 0.22	1.75 ± 0.28	1.79 ± 0.14	0.954
Productivity (kg/m^3)	45.86 ± 3.94 a	27.71 ± 2.52 b	22.67 ± 0.96 b	< 0.001

* Means in the same row bearing different lowercase letters are significantly different ($p < 0.05$). SGR - specific growth rate, FCR - feed conversion ratio.

The unexpected poor growth of tilapia in F50 and F33 may be a consequence of the low periphyton colonization during the whole experimental period, in which the substrates had less than 0.30 mg/cm^2 of periphyton dry matter. This value is three times lower than that reported in the same type of substrate in a hydroelectric reservoir (Garcia et al., 2016) and ten times lower than in earth ponds (Azim, Wahab, Van Dam, Beveridge, & Verdegem, 2001). Such development and availability of the periphyton are possibly associated with the average water N:P ratio obtained in this study (14:1) and its variation over the experimental period (from 6:1 to 18:1). The average water N:P ratio is below that usually reported for periphyton-based tilapia production, around 17:1 (Azim & Asaeda, 2005) to 27:1 (Garcia et al., 2016). Thus, the amount of nitrogen and phosphorus available in the reservoir, plus supplementation through nutrients from fish feces and leftover feed, seems not to have been sufficient to guarantee the full development of the periphyton in the evaluated conditions. Therefore, periphyton-based aquaculture approaches are not indicated for conditions with a low N:P ratio or subject to great variations in this ratio. Hence, the small-scale producers of tilapia cage farming must only consider such systems in places with suitable water quality that will can take advantage of the benefits of periphyton for tilapia growth and feed reduction.

Although some authors associate the use of periphyton with an increase in fish production (Garcia et al., 2016; Tammam et al., 2020); other studies show that this management did not have any effect on production (Asaduzzaman et al., 2009; Rodrigues et al., 2019), as in the present study. The 50% reduction in feed and the use of periphyton as complementary feeding in cage farming in hydroelectric reservoirs is a valid and beneficial management until the fish reach 500 g (Garcia et al., 2016). Taking this into account, in our study, we tried to further reduce (-67%) the use of feed and allocate the cages in a farm dam to make this technology feasible for small-scale producers. However, the results showed that, in our experimental conditions, it was not possible to obtain a better or similar fish growth performance to that found by Garcia et al. (2016), not even in treatments where feed was reduced by 50%.

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Chapter 7

Short Communication, in preparation for submission.

Consumer perception regarding the certified fish market in Brazil

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Abstract

Certification protocols have been used to make aquaculture a sustainable and safe food production activity. It is clear the growing concern of consumers with sustainability, the origin of the food they are consuming, and its quality. Thus, this study aimed to describe the preferences and perceptions of the Brazilian fish consumer regarding the certified fish market. For this, a comprehensive online quantitative survey was conducted. Certification is a term known by 62% of respondents. For 51% of consumers, certification is related to product quality assurance. Almost 40% of the respondents prefer fish with any brand or certification label. The study showed that Brazil has the potential for a specific certified fish market. Most Brazilian fish consumers are aware of what certification is and the aspects involved in it. Investments in the certification of aquaculture production should be made mainly to serve Brazilian consumers with a higher level of education and financial condition, located mainly in the South and Southeast regions of Brazil.

Keywords: Aquaculture; Certification; Fisheries; Niche market; Sustainability.

1. Introduction

World fish production reached approximately 179 million tons in 2018, in which 87% of this total was destined for human consumption (FAO, 2020). Global fish consumption increased 3.1% per year from 1961 to 2017, a rate nearly twice the 1.6% annual population growth (FAO, 2020). In this context, extractive fishing and aquaculture are key food production sectors to meet the growing global demand for quality and safe fish food. Nonetheless, supplying fish has been challenging given the limitations of natural resources and natural stocks and the consequent stagnation of extractive fish production. In response, aquaculture has grown in recent years as an alternative way to produce fish without directly harming the natural fish stocks, being already the source of 52% of the fish consumed in the world (FAO, 2020).

Aquaculture exponential growth has attracted the attention of researchers, civil society, and non-governmental organizations concerned with the environmental, economic, and social impacts of this activity (Henares et al., 2019). Some problems are aggravated, especially when linked to incorrect production management, such as the irrational use of water, the release of nutrient-rich effluents in the natural environment, the introduction and spread of diseases, the use of exotic species, and the pollution from drug residues (Samuel-Fitwi et al., 2012; Fry et al., 2016; Ottinger et al., 2016). In the last decades, consumers are increasingly aware of these problems and have sought to consume products produced following guidelines aimed at environmentally correct and socially just aquaculture production (Azhar et al., 2019). For this, one way for consumers to know the origin of the fish being purchased and consumed is by identifying these products through certification seals.

Certification programs have been developed and applied to make aquaculture an environmentally sustainable and socially responsible production activity by adopting efficient standardization mechanisms that add value across the chain (Marschke and Wilkings, 2014). These standards compromise requirements covering the potential negative impacts of aquaculture, including water quality, responsible sourcing of feed, disease prevention, animal welfare, and fair treatment and pay of workers (FAO, 2011). In this context, the reduction of environmental impacts and the implementation of sustainable practices in aquaculture can favor the growth of a still incipient market, allowing small producers the opportunity to invest in production systems that offer differentiated products with added value (Mauracher et al., 2013; Risius et al., 2017). These actions can minimize the negative implications of conventional aquaculture and generate sustainable products.

Although not every domain is covered in every scheme, due to all the requirements, adjustments, and audits required by certifying companies, having their products certified can be costly for the producer, especially for small-scale ones (Marschke and Wilkings, 2014). Therefore, the cost of the certification process is transferred to the final consumer, who, in most cases, pays more to consume a certified product (Marschke and Wilkings, 2014). Hence, the certified fish market has also become a way to serve a market niche of more demanding consumers. This market has grown a lot in recent years, especially in developing countries like Brazil, where aquaculture and fish consumption have been growing at an accelerated pace (Vince and Haward, 2019).

Following the global growth trend, Brazilian aquaculture grew by 83% in fish consumption over the past 11 years, with a population increase below 10% in the same period (FAO, 2020; PEIXE BR, 2021). According to Seafood Brazil (2021), the national consumption of fish is directly linked to the success of aquaculture. In 2020, Brazil reached a production of 802,930 t in which the South region (30%) was the largest producer, followed by the North (20%), Northeast (18.35%), Southeast (16.8%), and Midwest (14.55%) (PEIXE BR, 2021). Due to this growth and international demands for fish import and export, in recent years, some Brazilian companies have been looking for certifiers in order to certify their production processes. However, despite the increase in fish consumption and the interest of companies in having their production certified, little is known regarding consumers' preferences and understanding of the certified fish market so far. Yet, it is clear the growing concern of consumers with sustainability, the origin of the food they are consuming, and its quality. Thus, this study aimed to describe the preferences and perceptions of the Brazilian fish consumer regarding the certified fish market. In addition, we investigated if there is a market niche for certified fish in Brazil and what is the socio-economic profile of this consumer. For this, a comprehensive quantitative survey was conducted.

2. Material and methods

2.1. Survey design and data collection

Brazilian fish consumers were surveyed from July to October 2020. The survey was conducted online using the Google Forms platform, disseminated through social networks and email lists, and reached 670 people distributed in all regions of Brazil (Figure 1). The number of responses obtained in each region was considered representative and according to population distribution in each Brazilian Region. The Southeast region is the most populous and the Central-west has the lowest number of inhabitants (IBGE, 2010).

The data collection strategy was designed to reach consumers of different social classes and education levels. This combination offers a strategic advantage because it allows identifying if the perception and consumption of certified fish are linked to the purchasing power of the consumer or their knowledge about certification. Moreover, we interviewed only people who regularly visit commercial establishments to buy food, mainly meat. A simple questionnaire was prepared with questions to characterize the fish consumer and their preferences and perceptions concerning the supply and consumption of certified fish in Brazil (for details, see questionnaire in Supplementary Material). For this, the questionnaire was divided into three main sections. The first section consisted of social, economic, and demographic questions to support the characterization of consumers. The inquiries referred mainly to interviewees’ income, age, gender, educational level, and place of residence. The second section of questions was designed to cover the consumers’ preferences concerning the type of meat, origin of fish, and criteria adopted when buying fish. The questions of the third section aimed to know consumers’ knowledge, preferences, and attitudes towards certified fish products.

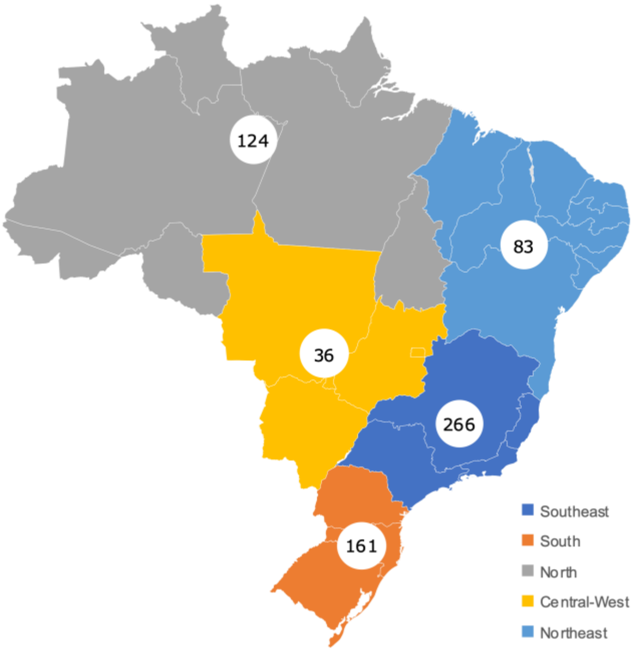

Figure 1. Number of respondents by region of Brazil.

2.2. *Data analysis*

From the 670 sets of responses obtained, 16 were not considered in the data analysis. This is because three respondents were minors (<17 years old), and 13 were not meat consumers. Thus, 654 sets of responses were considered valid and assessable.

Consumers were divided into groups according to their income and educational level using the socio-economic questions applied in Section 1 of the questionnaire. General profiles, preferences, and perceptions of the consumers were characterized by obtaining the percentage of occurrence of each response option given. When required, chi-square tests (at 5% level of significance) were employed to identify possible relationships between the different groups of consumers.

3. Results

The socio-economic characteristics of the respondents are presented in Table 1. Slightly more than half of the respondents were male, and most of them were between

25 and 50 years old. Most respondents (81%) received more than one minimum wage monthly (R$1045.00 or US$213.27) and had higher education (99%).

Table 1. Socio-economic characteristics of respondents in Brazil.

Category	**n**	**%**
Gender		
Male	331	51
Female	323	49
Age group (years)		
17 - 25	157	24
25 - 35	200	31
35 - 50	168	26
> 50	129	20
*Monthly income**		
< 1045	126	19
1045 to 3135	229	35
3135 to 6270	135	21
> 6270	164	25
Education level		
Basic education	7	1
High school	106	16
Graduate, MSc, or PhD	541	83
Occupational status		
Employed	255	39
Student	217	33
Autonomous	74	11
Retired	38	6
Unemployed	36	6

* Value in BRL Reais R$ (R$ 1.00 = US$ 4.90).

Regarding the consumers' preferences and demands, beef was the type of meat preferred by 43% of respondents, followed by fish (39%), chicken (11%), and pork (8%). The origin of the fish is a fact that had no importance for 52% of respondents, while 25% preferred fish from aquaculture and 23% from fishery. Among consumers who have preference in the fish instead other types of meat, in the South region 41% of the respondents preferred fish from fishery e and 14% preferred it from aquaculture. On the other hand, in the Southeast region 48% of the respondents preferred fish from aquaculture and 23% from fishery. In the other regions, the preferences were the same.

Although the origin does not influence the purchase of fish, 63% of the 654 respondents seek to know whether the fish purchased was fished or cultivated, and 93% prefer when the fish comes from a small-scale farmer. Among the criteria adopted when buying fish, the visual aspect, price, and form of presentation (e.g., whole fish, fillet, sliced) were the most reported (Figure 2). With respect to the factors hindering access to fish, the high price charged, and the lack of quality assurance were the main reasons informed (Figure 3).

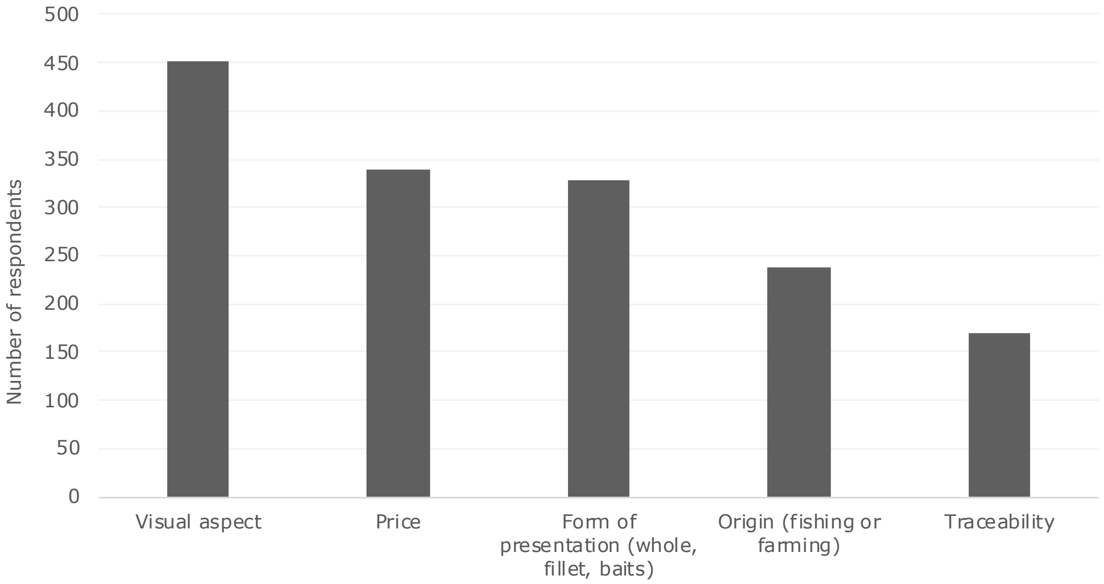

Figure 2. Criteria adopted by Brazilian consumers when buying fish.

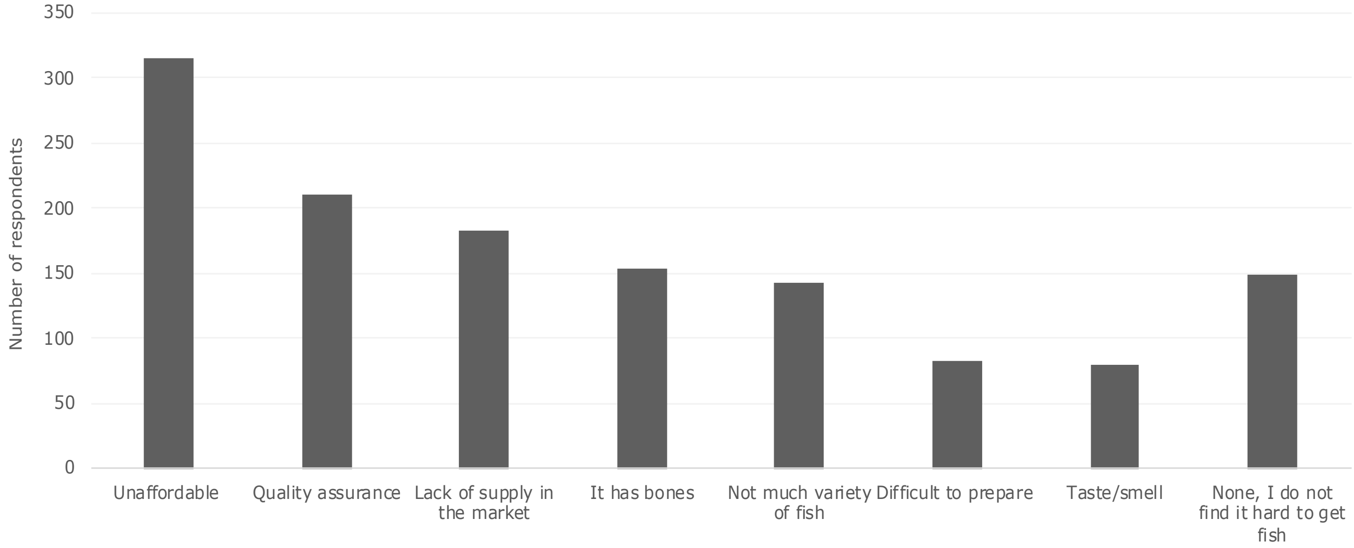

Figure 3. Main reasons that hinder the access of Brazilian consumers to fish.

Certification is a term known by 62% of respondents, and 28% of them did not understand what certification is but wanted to learn more about the subject. For 51% of consumers, certification is related to product quality assurance (traceability) (Figure 4). Whereas 31% of survey participants expect certified food to be healthier and tastier, produced in a sustainable, ecologically correct, and socially fair way, ensuring animal welfare. When asked if they prefer any brand or certification label, 37% (n=243) of respondents answered yes. Among these respondents that have a label preference, 99% have higher education and 40% are employed ($P<0.05$), and no differences were found regarding gender, age group, and economic class ($P>0.05$). Furthermore, 43% of them were from the Southeast region, 21% from the South, 17% from the North, 13% from the Northeast, and 5% from the Midwest. This distribution of consumers in the regions follows the same pattern as the total sample of respondents.

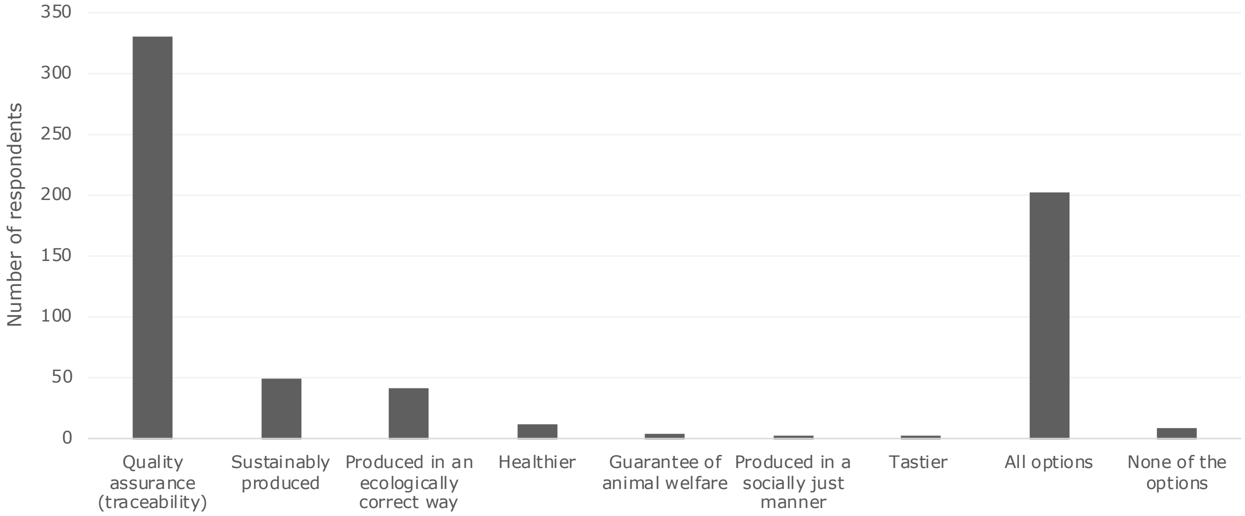

Figure 4. Aspects that Brazilian consumers of fish understand to be related to the term certification.

For aquaculture products, 97% of all respondents believe in the importance of certification for developing this sector. Of all responders, 49% would be willing to pay up to 10% more for a certified product and 26% up to 30% more than conventional products without certification (Figure 5).

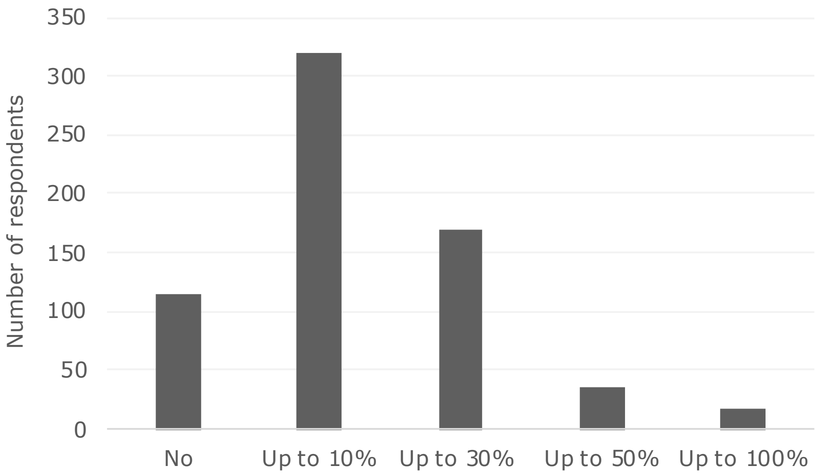

Figure 5. How much more, compare to the normal price, is the Brazilian fish consumer willing to pay for certified fish.

4. Discussion

This study aimed to determine the perceptions of Brazilian consumers concerning certified fish and whether there is a market for this type of product in Brazil. There are no recent scientific studies involving Brazilian fish consumers. Most of the current information about the certified fish market is found only on technical websites and magazines. Despite the attempt to reach consumers of all levels of education, most respondents in this study had a higher level of education and favorable financial conditions. This trend was also found by Lopes et al. (2016). An explanation for this result would be the online means of disseminating the questionnaire and the still limited ability of consumers to deal with online forms. Furthermore, it is important to highlight the continental dimensions of Brazil and the impossibility of carrying out a survey of this type on-site.

Price remains the main reason that hinders access to fish, as Lopes et al. (2016) found this same reason in a survey carried out five years ago. However, despite this limitation, consumers reported that they would buy fish instead of beef if it costs less, even though most respondents prefer beef. The potential market for fish in Brazil is evidenced when fish was reported as the second preferred meat by Brazilians, being only 4% behind beef and 18% ahead of chicken, which is the low-cost meat. This combination of results shows that despite the constant increase in fish supply, Brazil still has growth potential in aquaculture due to its growing demand. The form of presentation was also a reason reported by respondents as hindering access to fish. This result opens room for exploring the fish processing sector in Brazil, this is because, since 2016, the lack of access to different types of fish processing has been reported as an obstacle to consumption (Lopes et al., 2016). In this sense, aquaculture companies can explore other cuts for fish meat and marketing and packaging since the inadequate visual aspect of the fish was also reported as a main problem. Fish in Brazil is often in plastic bags, without any label or type of information on consumption, preparation or origin (SEBRAE, 2020).

Culturally, fish produced by aquaculture is associated with productions carried out in polluted environments, with harmful contaminants to human health, and with lower quality than fish originating from extractive fishing (Kubitza, 2015). This negative perception is even more remarkable when, due to inattention of the producer, the consumer identifies a taste of clay (off-flavor) or some other irregularity in the fish (Näslund and Johnsson, 2016), mainly in tilapia, the most produced aquaculture species in Brazil (PEIXE BR, 2021). For these reasons and the growing concern for sustainable production, most respondents answered that they are looking for certification to guarantee the quality and traceability of fish. For consumers, certifications serve to ensure that the products they buy are safe and free from fraud. Engaged in one or more certification programs, the fish farmer or company will be able to ensure that their products were obtained under the best possible management techniques, with a focus on the efficient use of resources, effluent management, social and environmental responsibility, animal welfare and health (FAO, 2011). In this sense, certifications are important incentives and tools to guarantee the quality, expand competitive markets, add value, and benefit producers and consumers (Marschke and Wilkings, 2014).

The preference of 37% of respondents for certified fish shows that these products must be sold to serve a niche market, especially for people with a higher level of education and financial stability and located in the South and Southeast regions of Brazil. This preference is linked to knowing what certification is and the willingness to pay more for this type of product. Also, knowing that consumers would prefer fish produced by small producers and believe that certification is essential for the sustainable development of aquaculture reinforces the need to develop the certified fish market in Brazil.

In addition to this study, future investigations should assess the producer's perception of certifications. In general, business owners have a negative perception of certifications, especially when they are mandatory (Kubitza, 2015). Certifications are usually associated with different regulations and may demand more tax and cost increases than real benefits for the producer. Additionally, their success fluctuates with market pressures, making it more challenging to maintain long-term commitment. The susceptibility of certification initiatives to such oscillation betrays the need for private and public regulation to work together. Certification regulations should facilitate and encourage producers to adapt and seek certification and support the development of low-cost and accessible national certifications for both producer and consumer. Additionally, more investment in publicizing the benefits of certified products should be made in order to increase the consumer market for this type of product, promoting sustainable production.

5. Conclusion

The study showed that Brazil has the potential to consume certified fish, especially if it is targeted at a specific market niche. More than 60% of Brazilian fish consumers know what certification all is about and all the aspects involved in it. Furthermore, 87% of the consumers would be willing to pay at least 10% more for certified fish. Investments in fish certification in Brazil should be made mainly to serve the consumers with a higher level of education and financial condition, located mainly in the South and Southeast regions of Brazil.

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Supplementary Material

Questionary - Market Research on Certification in Brazilian Aquaculture

1. Sex:
   a. Female
   b. Male
   c. Other
2. Which region do you live in?
   a. Midwest
   b. Northeast
   c. North
   d. Southeast
   e. South
3. Which state do you live in?
   a. Acre (AC)
   b. Alagoas (AL)
   c. Amapá (AP)
   d. Amazonas (AM)
   e. Bahia (BA)
   f. Ceará (CE)
   g. Distrito Federal (DF)
   h. Espírito Santo (ES)
   i. Goiás (GO)
   j. Maranhão (MA)
   k. Mato Grosso (MT)
   l. Mato Grosso do Sul (MS)
   m. Minas Gerais (MG)
   n. Pará (PA)
   o. Paraíba (PB)
   p. Paraná (PR)
   q. Pernambuco (PE)
   r. Piauí (PI)
   s. Rio de Janeiro (RJ)
   t. Rio Grande do Norte (RN)

    u. Rio Grande do Sul (RS)
    v. Rondônia (RO)
    w. Roraima (RR)
    x. Santa Catarina (SC)
    y. São Paulo (SP)
    z. Sergipe (SE)
    aa. Tocantins (TO)

4. Age range:
    a. Under 17 years old
    b. From 17 to 25 years old
    c. From 25 to 35 years old
    d. From 35 to 50 years old
    e. Over 50 years old
5. Average monthly income:
    a. Less than 1 minimum wage (R$ 1045.00)
    b. Between 1 and 3 minimum wages (R$ 1045.00 - 3135.00)
    c. Between 3 and 6 minimum wages (R$ 3135.00 - 6270.00)
    d. More than 6 minimum wages (R$ 6270.00)
6. Level of education:
    a. Never studied
    b. Elementary School
    c. High School
    d. Higher Education
7. Current professional situation:
    a. Autonomous
    b. Businessperson
    c. Student
    d. Employee
    e. Unemployed
    f. Retired
    g. Rural producer
8. What kind of meat do you prefer?
    a. Beef

   b. Pork
   c. Chicken
   d. Fish
   e. I do not eat meat

9. Which criteria do you take into account when buying fish?
   a. Price
   b. Visual aspect
   c. Origin (fishing or farming)
   d. Form of presentation (whole, fillet, baits)
   e. Traceability (if it has any seal, certification, if it is from a local producer)
10. If fish cost less than other meats, would you prefer it?
    a. Yes
    b. No
11. Do you know what aquaculture is?
    a. Yes
    b. No
12. Do you prefer to choose between fish from a fishery or aquaculture?
    a. I prefer fish from a fishery
    b. I prefer farmed fish
    c. I have no preference, it does not matter
13. Do you know where the fish you consume comes from?
    a. Yes, I always ask before I buy it
    b. No, because I don't think it's important
    c. No, I never thought about it
14. What are the main factors that make it hard for you to get fish?
    a. Lack of supply in the market, as it is not found very often
    b. Unaffordable
    c. Not much variety of fish
    d. Difficult to prepare
    e. It has bones
    f. Taste/smell
    g. Quality assurance
    h. None of the above, I do not find it hard to get fish

15. What do you understand by certified fish?
    a. Produced in an ecologically correct way
    b. Produced in a socially just manner
    c. Sustainably produced
    d. Healthier
    e. Tastier
    f. Quality assurance (traceability, inspection)
    g. Guarantee of animal welfare
    h. All previous options
    i. None of the above options
16. Do you know how to identify a certified product?
    a. Yes
    b. No
17. Do you know any type of certification?
    a. Yes
    b. No
    c. No, but I would like to know more about the topic
18. Do you prefer any brand or certification?
    a. Yes
    b. No
19. Would you be willing to pay extra for sustainable product? How much?
    a. No
    b. Up to 10%
    c. Up to 30%
    d. Up to 50%
    e. Up to 100%
20. Would you prefer fish produced by small local producers rather than large companies?
    a. Yes
    b. No
21. Do you know the benefits of sustainably produced products?
    a. Yes, I know they are produced responsibly, preserving the environment, respecting society and contributing to the economy

   b. I do not know

22. Do you believe in the importance of certification for the development of aquaculture?
    a. Yes
    b. No

Chapter 8

Final remarks

The main contributions of this thesis were presenting a systematic review of emergy synthesis applied for aquaculture (Chapter 2), the sustainability assessment of two modern aquaculture systems (Chapters 3 and 4), the technical feasibility of periphyton-based systems in reducing the amount of feed in tilapia farming (Chapters 5 and 6) and presenting the consumers perspective regarding sustainable and certified aquaculture products (Chapter 7).

An extensive overview of aquaculture sustainability from an emergy synthesis point of view was presented in a review article. In addition to present the results achieved so far, we identify some drawbacks of the emergy method and confirmed that some practices usually applied in aquaculture, such as monoculture exclusively feed fed, do not support the sustainable development of this activity. As a solution to the dependence on feed, integrated systems and those that seek to replace feed with a natural food source, e.g., periphyton, are encouraged. Emergy synthesis is a solid method to assess the sustainability of different type of systems and processes. Nevertheless, for aquaculture, improvements in the method are still needed to adjust it to aquaculture reality. For that, the crucial point is to integrate the specialists in emergy and aquaculture to perform reliable and consistent studies.

An important outcome of this thesis was numerically show up how sustainable aquaponics and bioflocs systems are for tilapia farming, especially in Brazil. In the past years, both systems have been labelled and commercialized as sustainable aquaculture systems. Still, the real sustainability of aquaponics and biofloc systems are questioned due to the high demand for infrastructure, equipment and electricity to make them properly work. Chapter 3 and 4 presents the first studies using emergy synthesis to address these questions. The findings of both chapters shows that aquaponics and biofloc systems are potentially sustainable to produce tilapia in Brazil. Moreover, we pointed out that adopting infrastructures with high lifetime and equipment energetically efficient are crucial to boost the sustainability of aquaponics and biofloc systems, respectively. We would like to point out that expanding the emergy assessment of such modern systems for other locations and climate conditions is essential to have a more comprehensive view of the strengths and weaknesses of systems and thus promote the sustainable development of aquaculture.

Regarding the experimental studies to investigate periphyton-based systems in different production situations, the results of tilapia growth under feed restriction reared in ponds (Chapter 5) did not corroborate to those in cages located in a farm dam (Chapter 6). The difference in the results suggests that periphyton-based systems are not suitable for all production situations, highlighting that the profile of nutrients in the water directly affects the availability of periphyton for fish nutrition and consequently its growth. We initially assumed that replacing feed for periphyton is a sustainable strategy for tilapia production, based on previous emergy assessments. However, the systems performed in Chapter 6 are not technically feasible, and thus the sustainability of periphyton-based systems in different situations remains a question to be answered in future studies.

Lastly, the consumers' perspective of sustainable/certified aquaculture products explored in Chapter 7 showed that there is a wide range of market possibilities for such products in Brazil. Thus, the findings and set of information presented in this thesis is an important step and may be useful for developing future certification protocols for sustainable aquaculture products.