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EMERGÉTICA DE ESTUFA AGRÍCOLA CONSTRUÍDA COM BASE DE EUCALIPTO E ARCOS DE BAMBU

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RESUMO: Agricultura sustentável é vital para produção de alimentos saudáveis. Emergia é uma ferramenta biofísica que avalia sustentabilidade, que mensura, em uma única métrica, o trabalho da natureza e do ser humano na geração de seus produtos e serviços. O presente estudo analisou emergeticamente a construção e manutenção de estufa agrícola artesanal em Botucatu-SP; por meio da mensuração da quantidade de recursos renováveis, não renováveis, provenientes da economia e o fluxo emergético nos sistemas de produção, que possibilitaram o cálculo dos seguintes Índices Emergéticos: Rendimento emergético (EYR = 2,44), Investimento emergético (EIR = 0,70), Carga ambiental/Impacto ambiental (ELR = 1,82), Índice de sustentabilidade (ESI = 1,34) e Renovabilidade (%R = 35,48). A estufa analisada se mostrou sustentável a médio prazo (ESI = 1,34), mesmo tendo em sua composição dois materiais classificados como não sustentáveis, o bambu tratado (ESI = 0,72) e o eucalipto tratado (ESI = 0,23). O item que tem maior contribuição para a emergia da estufa (8,68E+12 seJ m -2 ano -1) é a mão de obra (45,14%) por se tratar de um processo construtivo artesanal. Os resultados também indicam que esse modelo de estufa tem uma contribuição moderada para o desenvolvimento econômico local, com baixíssimo impacto ambiental.

Palavras-chaves: emergia, sustentabilidade, cultivo protegido.

EMERGETIC OF AN AGRICULTURAL GREENHOUSE BUILT WITH EUCALYPTUS BASE AND BAMBOO ARCHÉS

ABSTRACT: Sustainable agriculture is vital for the production of healthy food. Emergy is a biophysical tool for sustainability assessment that measures, as a single metric, the work of nature and human beings in the generation of their products and services. The present study analyzed, through emergy, the construction and maintenance of an artisanal agricultural greenhouse in the city of Botucatu, SP, by measuring the amount of renewable, nonrenewable, and economic resources and the emergy flow in production systems, which made it possible to calculate the following emergy indices: the emergy yield (EYR = 2.44), the emergy investment (EIR = 0.70), the environmental load/environmental impact (ELR = 1.82), the sustainability index (ESI = 1.34) and the renewability (%R = 35.48). The greenhouse analyzed proved to be sustainable in the medium term (ESI = 1.34), even having two materials classified as unsustainable: treated bamboo (ESI = 0.72) and treated eucalyptus (ESI = 0.23). The item that has the greatest contribution to the emergy of the greenhouse (8.68E+12 seJ m -2 yr -1) is labor (45.14%) because it is a handcrafted construction process. The results also indicate that this greenhouse model makes a moderate contribution to local economic development, with very low environmental impact.

Keywords: emergy, sustainability, protected cultivation.

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1 INTRODUCTION

Greenhouses are structures that allow the internal temperature to be controlled so that it can be higher than the temperature in an external environment. In addition, they contribute to the protection of the plant against pest attacks and reduce the risk of bad weather. climate and protection from wind, rain and solar radiation to provide a controlled environment for the best development of the plant.

Greenhouse structures can be built with different materials: aluminum, steel, wood or bamboo. Aluminum has greater durability because of its high resistance to corrosion. On the other hand, it is a more expensive material and is more suitable for greenhouses with glass or rigid plastic coverings. The steel is suitable for both rigid coverings and coverings with plastic film. It has a long lifespan (decades), high acquisition cost and average maintenance cost related to anticorrosive protection. Wood and bamboo are the most accessible raw materials, are suitable for covering with plastic film and have the shortest useful life compared with metal materials (BUCKLIN, 2020).

The use of bamboo in the construction of greenhouse structures or crops in bioconstructions is very interesting from an economic point of view because the inputs used in conventional greenhouses can reach an inaccessible value for most family farmers (SILVA; LIMA; OLIVEIRA, 2011).

A production system is analyzed economically initially on fixed costs, variable costs, and market observations and then applies a desired profit margin, with the intention of achieving competitiveness through the final price. Generally, the contribution of natural resources and ecosystems is not measured in the production of a given product or service (ORTEGA, 2005).

Energy-based systems analysis, proposed by Odum (1996), is an analysis tool that can measure these environmental contributions, which are conventionally not considered. This methodology combines a single metric, the work of nature, with that of human beings in the generation of services and products.

The development of agriculture and national supply depends directly on information and knowledge, and these two variables are essential conditions for improving public policies, in their formulation, execution and evaluation; with this, the creation of opportunities for productive investments and the study of researchers are expanded, strengthening democracy (CONAB, 2010).

The study of an agricultural production structure, in this case, materials such as eucalyptus and bamboo, as well as the analysis of the sustainability of these structures through emergy analysis, are fundamental to the development of production systems.

2 MATERIALS AND METHODS

This study was developed in the municipality of Botucatu, between January and March 2021, in the central-western region of the state of São Paulo, 224.8 km from the capital of São Paulo, with easy access via the Marechal Rondon and Castelo Branco highways. According to the Köppen method, the climate of the region is of the Cfa type, characterized as a warm temperate (mesothermal) humid climate (CUNHA; MARTINS, 2009). The altitude of the municipality varies from 756 m to 920 m. The average annual rainfall is 1,501.4 mm, with the first quarter being the rainiest, with approximately 652.6 mm, which corresponds to 43.5% of the total; the least rainy quarter is between July and September, with a precipitation of 166.8 mm, accounting for 11.1% of the annual rainfall. The average annual temperature of the municipality is 20.3°C, and the average annual relative humidity is 73.9%.

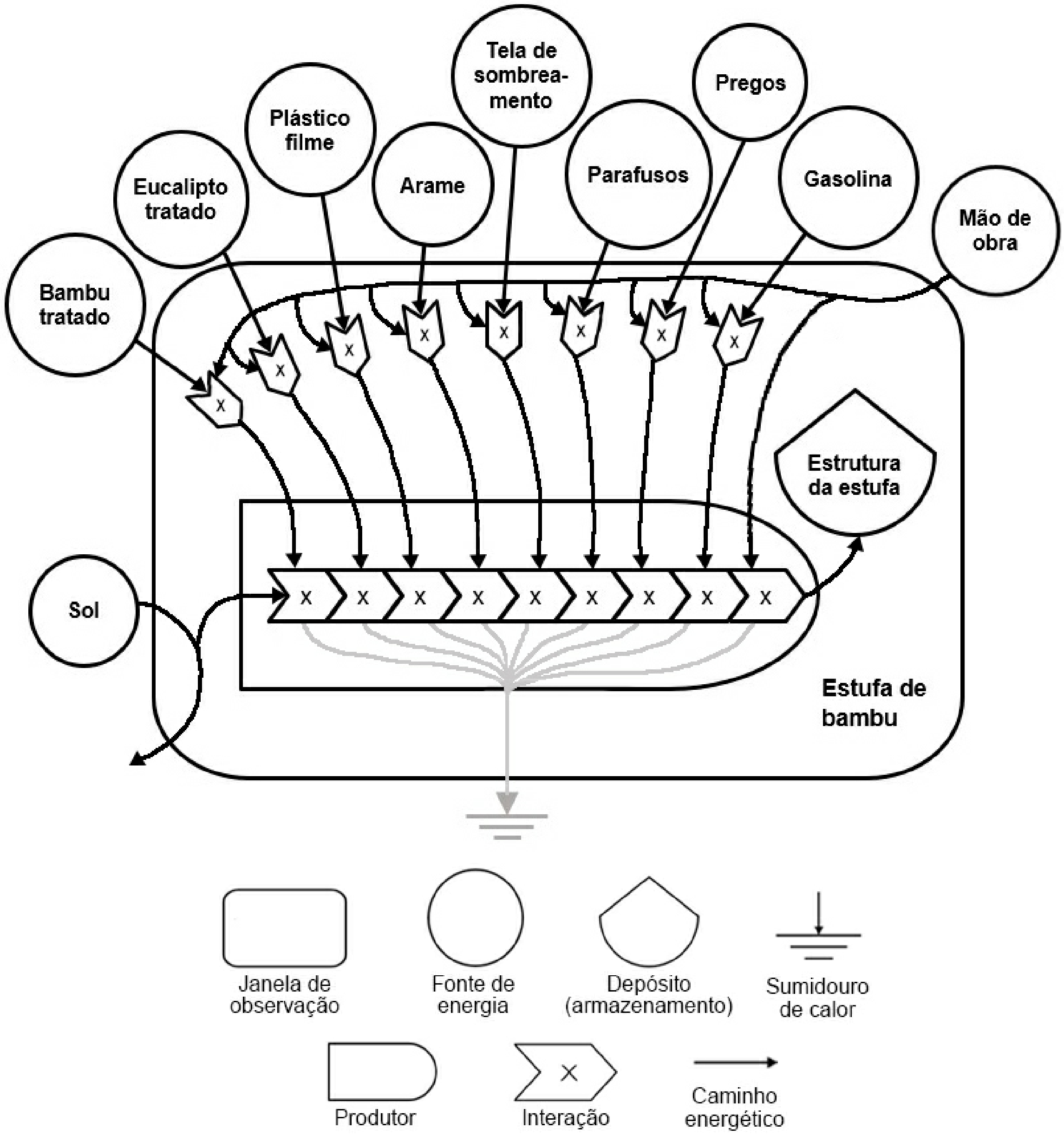
The solar radiation that falls on the municipality is 5.05 kWh m^{-2} day^{-1} (average of the last 22 years), and the average wind speed throughout the year is 1.07 ms^{-1} (average of the last 30 years). Long-term meteorological data (1971--2006) were obtained from the Meteorological Station of the Department of Soil Science and Environmental Resources – FCA/UNESP, Botucatu, SP. The solar radiation and wind speed data were obtained from the

NASA program "Prediction of World Energy Resources".

This work analyzed a specific model of an agricultural greenhouse developed in the municipality of Botucatu-SP, with bamboo and eucalyptus treated as basic materials for its construction.

The realization of a critical inventory of important processes, stocks and flows that cross the system boundaries and the variations in internal energy stocks can be obtained through mathematical modeling (ODUM, 1996). To this end, the construction of a diagram allows us to understand the logic of the system. Figure 1 shows the diagram used to measure greenhouse emergy.

Figure 1. Energy flow diagram for the construction and maintenance of the bamboo greenhouse.



Source: prepared by the authors.

The input energy flow to the system was estimated for the structural installations and materials used in these systems according to their useful life (ASGHARIPOUR *et al.*, 2020). The lifespans of the greenhouse plastic cover, treated bamboo and treated eucalyptus base were estimated at 3 years, 6 years and 12 years, respectively.

All the materials and services considered significant for the analyzed systems present in the “Emergency Calculation Tables” were converted into emergy flows by multiplying their quantities by the appropriate UEVs, adapted to the conditions of Botucatu.

However, whenever the acquired input that makes up the production system does not have an adequate UEV in the literature to quantify its emergy, the emergy contained in the monetary value spent to acquire the input is used. To calculate the emergy contained in the real monetary unit (R$), data from Brazil's total emergy (Y) were used as a basis, which was 2.19E+25 seJ in 2018 (most recent data found), and the Brazilian GDP (gross domestic product) was 3.37 trillion dollars (3.37E+12 US$) in the same year. Dividing the country's total emergy by its GDP results in the country's Emdollar (EMR), which in this case is equal to 6.50E+12 seJ US$ $^{-1}$. To obtain the emergy per real unit, the EMR was then divided by the average value of the dollar for the year 2020, which was R$5.16, data extracted from the website of the Central Bank of Brazil on the Quotes and Bulletins page. The resulting value was 1.26E+12 if R$ $^{-1}$.

Equations for calculating the emergy of real currency:

Real Currency Emergy (seJ R$ $^{-1}$) =
(Brazil EMR, 6.50E+12 seJ US$ $^{-1}$) ÷ (exchange rate, 5.16 R$ US$ $^{-1}$) = 1.26E+12 seJ R$ $^{-1}$ (1)

Brazilian Emdollar (EMR) (seJ US$-1) =
(total emergy, 2.19E+25 seJ) ÷ (GDP, 3.37E+12 US$) = 6.50E+12 seJ US$ $^{-1}$ (2)

To calculate wind energy, it was initially necessary to know some information, such as the altitude of the location and temperature. With these two pieces of data, it is possible to infer the wind density; in this case, the altitude is 825 m, and the average temperature in the city of Botucatu-SP is 20.03 °C, which results in a density of 1.466 kg/m3. From this information, together with the wind speed value, it is possible to calculate the kinetic energy and then the emergy value by multiplying the kinetic energy value by the wind transformity value (1.50 E+03 seJ $^{-1}$), as described by Odum (1996). Thus, we find, for the context of the location where the work was developed, that the wind emergy is 5.34 E+0 seJ s $^{-1}$.

The equations for calculating wind emergy are as follows:

Wind kinetic emergy (seJ s $^{-1}$) =
(energy, 3.59 E-3 J s $^{-1}$) × (transform, 1.50 E+03 seJ J $^{-1}$) = 5.34E+0 seJ s $^{-1}$ (3)

Wind kinetic energy (J s $^{-1}$) =
(air density, 1.466 kg m $^{-3}$) × (drag coefficient, 0.002) × (wind speed, 1.07 ms $^{-1}$) × 3.59 E-3 J s $^{-1}$ (4)

Being:

Wind transform, kinetic: 1.50 E+03 seJ J $^{-1}$ (ODUM, 1996)
Density of air = 1.466 kg m $^{-3}$
Drag coefficient: 0.002 (ASGHARIPOUR *et al.*, 2020)

In the case of labor, the Transformity used was 1.15E+07 seJ J $^{-1}$, which is a specific value calculated by Bonilla *et al.* (2010) for human labor in Brazil. This attention to the national context was also taken into account for the percentage of renewability of this item, which, in the case of Brazil, is 50%. This is different from other countries, such as Australia (49%) and China (26%) (BONILLA *et al.*, 2010). Since this study is focused on community and/or family garden farmers, the value of labor is considered a local resource since it is a work that is developed primarily by family members. The Tr converted to UEV per hour of work is equal to 6.02E+12 seJ h $^{-1}$.

The equation for calculating the UEV of the workforce is as follows:

UEV of labor (seJ h $^{-1}$) =
(energy, 523250 J h $^{-1}$) × (Tr, 1.15E+07 seJ J $^{-1}$) = 6.02E+12 seJ h $^{-1}$ (5)

Individual energy per hour worked (J h $^{-1}$) = [(3000 kcal day $^{-1}$)/(24 hours day $^{-1}$)] × (conversion, 4186 J/kcal) = 523250 J h $^{-1}$ (ODUM, 1996) (6)

For calculations related to treated water from Sabesp, the transformity used was a value of 1.19E+9 seJ L $^{-1}$. Renewability was 59.00%, as many chemical products, large masonry infrastructures and machinery are used in the treatment process.

2.1 Calculation of Emergy Indices

Thermodynamic performance indicators are calculated via algebraic relationships of the emergy present in the different natures of the resources (R, N or F) that make up the system studied.

In this study, the following energy indices were calculated: energy yield (EYR), energy investment (EIR), environmental load/environmental impact (ELR), sustainability index (ESI) and renewability (%R). The indices were calculated in accordance with the methods presented in Table 1.

Table 1. Energy indicators and their formulas

Indicators	Expression	Meaning
Emergy performance (EYR)	$EYR = \frac{Y}{F} = \frac{R+N+F}{F}$	Ratio between total emergy and resources of the economy
Emergy investment (EIR)	$EIR = \frac{F}{N+R}$	Ratio between the economy's resources and renewable plus nonrenewable resources
Environmental impact (ELR)	$ELR = \frac{N+FN}{R+FR}$	Ratio between nonrenewable resources (local and acquired) and renewable resources (local and acquired)
Sustainability index (ESI)	$ESI = \frac{EYR}{ELR}$	Ratio between energy efficiency and environmental impact
Emergy Renewability (%R)	$\%R = \frac{(R\ +FR)*100}{Y}$	Ratio of renewable resources to total emergy

Source: Odum (1996) and Brown and Ulgiati (2004).

2.2 Bamboo greenhouse

The greenhouse (Figure 2) used has a structure measuring three and a half meters long by three meters wide, totaling 10.5 m² of area, with a base of round eucalyptus measuring 8 to 10 cm in diameter and 2.1 m long, fastened with nails (24 × 60 mm); arches made of bamboo slats (*Bambusa tuldoides*) and interlocked with the same material crossing the arches; polyethylene plastic film with a thickness of 150 microns and dimensions of 8 × 4 m; and a shading screen with a weave that filters 50% of the solar radiation. The bamboo was fixed to the eucalyptus with screws (4.0 × 40 mm), and the ties were made with galvanized wire number 20 (0.89 mm). This model was developed by a local artisan, Carlos Lira, and is made from materials that are easily found in the region (collected bamboo and other materials purchased in stores). Its dimensions can be adapted to different contexts, and its width can vary from 3 to 4 m due to the morphological characteristics of the bamboo species used. The construction method is simple, and in this case, the construction was carried out by a single person. The construction method has been disseminated in the municipality in recent years through courses and workshops. In November 2019, in one of these 12-hour courses, the author learned the construction technique for this greenhouse.

Figure 2. Construction of the bamboo greenhouse.

Source: prepared by the authors.

Bamboo tuldoides, popularly called common bamboo, is widely cultivated in subtropical climates and can reach a height of 15 m, a useful length of 10 m, an internal length of 35--45 cm, a culm diameter of 6 cm on average, and a thickness of 0.7--1.5 cm. It has medium resistance to weevils. Used in light constructions, fences, for tutoring some arable crops, handicrafts, musical instruments (SILVA; LIMA; OLIVEIRA, 2011).

To ensure greater durability when bamboo is used in permanent constructions, it is essential that its culm be treated by introducing preservative substances into its cellular structure (AZZINI; BERALDO, 2001).

The bamboo was treated on the same property where it was built, using the sap replacement technique, in a barrel containing a solution with 100 L of water, 900 g of potassium or sodium dichromate, 850 g of copper sulfate, and 620 g of boric acid. For the process to occur more efficiently, the bamboo poles were placed in the barrel for a period of up to 6 hours after collection and remained in their natural growth position for 3 weeks. In the fourth week, the orientation of the poles was reversed (at this point, the tips were placed in contact with the solution). Before use, the poles remained to dry for 30 days. This method was carried out according to the instructions of the artisan who designed this greenhouse model;

the process of sap replacement or radial transport is widespread in the treatment for the preservation of round wood (GALVÃO; MAGALHÃES; MATTOS, 2004). This replacement technique is recommended to obtain a good level of bamboo resistance (TIBURTINO *et al.*, 2016).

3 RESULTS AND DISCUSSION

3.1 Emergy analysis of the bamboo treatment

Before the greenhouse was constructed, the collected bamboo was treated with the aim of increasing the useful life of the material. As the treatment took place entirely in a shaded location, solar radiation was considered zero.

The 200-liter plastic drum in which the bamboo sticks were placed for treatment has a mass of 8.40 kg and is made of high-density polyethylene (HDPE). This material has an estimated useful life of 50 years and a density of 0.96 g cm^{-3}.

The evaporation of water present in the solution was considered null because a layer of engine oil was added to the solution to prevent this process.

The transpiration of bamboo poles is based on the mass reduction that the species experiences between wet and dry materials. The mass of the wet stems of the species *B. tuldoides*, freshly harvested, ranged from 126.8 kg to 67.7 kg after treatment and drying. The mass reduction was 53.39%. Therefore, the amount of water that was transported throughout the process was 59.10 kg.

Twenty 6.45-meter-long sticks of *B. tuldoides were collected and treated,* totaling 129 meters. The emergy fluxes of this process are presented in Table 2. The total emergy obtained was 2.36E+14 seJ, and the emergy per linear meter of treated bamboo was 1.83E+12 seJ m^{-1}; considering the useful life of treated bamboo of 6 years, the emergy per linear meter each year was 3.05E+11 seJ m^{-1} $year^{-1}$. Since this is an unmanaged clump with more than 10 years of life, the renewability (%R) of the bamboo *in natura* was considered to be 100%; after treatment, this index reached 30.77%, and the total emergy of the material increased 4.27 times (Table 3).

Equations related to the calculations of the emergy of treated bamboo are as follows:

Emergy per linear meter of treated bamboo (seJ m^{-1}) = (total emergy, 2.36E+14 seJ) ÷ (meters of treated bamboo, 129 m) = 1.83E+12 seJ m^{-1} (7)

Emergy per linear meter of treated bamboo each year (seJ m^{-1} yr^{-1}) = (total emergy, 2.36E+14 seJ) ÷ (meters of treated bamboo, 129 m) ÷ (useful life, 6 yr) = 3.05E+11 seJ m^{-1} yr^{-1} (8)

%R: Renewability of treated bamboo (%) = [(R, 7.25E+13 seJ) + (FN, 7.02E+10 seJ)] × 100 ÷ (2.36E+14 seJ) = 30.77% (9)

Emergy of treated bamboo relative to untreated bamboo =
(2.36E+14 seJ) ÷ (5.53E+13 seJ) = 4.27 (10)

Table 2. Energy flows involved in bamboo treatment (flows in 6 years)

No.	Item	%R	Value	Un	UEV	Emergy flow	Ref. (UEV)	%
	Local renewable resources (R)							
1	Wind	100.00	2.44E+07	J	1.50E+03	3.66E+10	4	0.02
2	Perspiration	100.00	2.80E+05	J	4.81E+04	1.35E+10	4	0.01
3	Bamboo	100.00	1.28E+09	J	4.32E+04	5.53E+13	4	23.45
4	Labor (50.00%)	50.00	2.85E+00	h	6.02E+12	1.71E+13	1	7.27
	Local nonrenewable resource (N)							
5	Labor (50.00%)	50.00	2.85E+00	h	6.02E+12	1.71E+13	1	7.27
	Renewable Economy Resources (FR)							
6	Treated water (59.00%)	59.00	5.90E+01	L	1.19E+09	7.02E+10		0.03
	Nonrenewable resources of the economy (FN)							
7	Treated water (41.00%)	59.00	4.10E+01	L	1.19E+09	4.88E+10		0.02
8	HDPE drum	0.00	1.28E+06	J	2.72E+05	3.48E+11		0.15
9	Gasoline	0.00	1.24E+08	J	1.94E+05	2.41E+13	2	10.21
10	Engine oil	0.00	2.00E-01	L	2.49E+12	4.98E+11	4	0.21
11	Copper sulfate	0.00	8.50E+02	g	8.64E+10	7.34E+13		31.15
12	Boric acid	0.00	6.20E+02	g	3.80E+08	2.36E+11	3	0.10
13	Sodium dichromate	0.00	3.76E+01	R$	1.26E+12	4.74E+13		20.11
	Total (R)					7.25E+13		30.74
	Total (N)					1.71E+13		7.27
	Total (F)					1.46E+14		61.98
	Total (FR)					7.02E+10		0.03
	Total (FN)					1.46E+14		61.95
	Total Emergy (Y)	30.77	1.29E+02	m	1.83E+12	**2.36E+14**	5	
	Total Emergy per Year (Y/year)	30.77	1.29E+02	m	**3.05E+11**	**3.93E+13**	5	

Source: [1] Bonilla *et al*. (2010), [2]Brown; Protano. ; Ulgiati, (2011), [3]Cuadra and Rydberg (2000), [4] Odum (1996), [5] calculated in this study, and prepared by the authors.

Table 3. Energy indices associated with bamboo treatment (flows in 6 years)

Emergy indices	Value	Interpretation of index value based on Brown and Ulgiati (2004)
EYR	1.61	(1<EYR<2) Small contribution to economic development.
EIR	1.63	The lower the EIR, the greater the competitiveness of the system.
ELR	2.25	(2<ELR<3) Production system with low environmental load (impact).
ESI	0.72	(ESI<1) The analyzed system is not sustainable.
%R	30.77	The higher the %R, the greater the renewability of the analyzed system.

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

Source: Brown and Ulgiati (2004) and prepared by the authors.

The energy yield (EYR) was 1.61, and values between (1<EYR<2) indicate that the contribution is small to the development of the economy. The energy investment (EIR) was 1.63, which is dimensionless and indicates that the lower the EIR is, the greater the competitiveness. The environmental impact (ELR), with a value of 2.25, is considered a system with low environmental load (impact). The sustainability index (ESI) is 0.72, indicating that the system is not sustainable because copper sulfate and sodium dichromate are used to treat bamboo (components with the highest energy values in the process, together corresponding to 51.26% of the total energy), which are nonrenewable economic resources.

3.2 Emergy analysis of eucalyptus treatment

With respect to treated eucalyptus, no emergy studies have been conducted with this material, so the study of emergy in intensive eucalyptus cultivation in the state of São Paulo (ROMANELLI *et al*., 2008) was used as a basis, which showed a transformity of 9.50E+03 seJ $^{-1}$ and a renewability of 58.00%, and a sap replacement treatment similar to that used in bamboo, which is an appropriate method for preserving round wood (GALVÃO; MAGALHÃES; MATTOS, 2004).

To determine water loss through transpiration throughout the treatment, we used MONTEIRO *et al*. (2021), which indicates that the weight reduction of eucalyptus is 15 to 20% through drying, we considered 18% for this study; therefore, 157.2 kg of treated eucalyptus lost 34.50 liters of water through transpiration throughout the process.

The emergy flows of this eucalyptus treatment process are presented in Table 4. The total emergy contained in 157.2 kg of treated eucalyptus was 2.10E+14 seJ; considering the useful life of the treated eucalyptus of 12 years, we have a transformity of 5.69E+03 seJ J $^{-1}$ year $^{-1}$.

After treatment, the eucalyptus, which initially had a renewability (%R) of 58%, now has 16.29% of this index, which represents a reduction of 3.56 times (Table 5). As with the treated bamboo, this reduction is due mainly to the large energy contribution that the chemical products used as preservation agents and classified as FNs had for the process, with 35.04% copper sulfate and 22.62% sodium dichromate. The environmental impact index (ELR) had a value of 5.14, which is considered a production system with moderate environmental load (impact); the sustainability index (ESI) was 0.23, indicating that the system is not sustainable.

Table 4. Energy flows involved in the treatment of eucalyptus (flows in 12 years)

N.	Item	%R	Value	Un	UEV	Emergy flow	Ref. (UEV)	%
				Local renewable resources (R)				
1	Wind	100.00	1.86E+04	J	1.50E+03	2.79E+07	4	0.00
2	Perspiration	100.00	1.64E+05	J	4.81E+04	7.89E+09	4	0.00
3	Labor (50.00%)	50.00	2.85E+00	h	6.02E+12	1.71E+13	1	8.18
				Local nonrenewable resource (N)				
4	Labor (50.00%)	50.00	2.85E+00	h	6.02E+12	1.71E+13	1	8.18
				Renewable Economy Resources (FR)				
5	Eucalyptus (58.00%)	58.00	1.78E+09	J	9.50E+03	1.69E+13	5	8.07
6	Treated water (59.00%)	59.00	5.90E+01	L	1.19E+09	7.02E+10		0.03
				Nonrenewable resources of the economy (FN)				
7	Eucalyptus (42.00%)	58.00	1.29E+09	J	9.50E+03	1.22E+13	5	5.84
8	Treated water (41.00%)	59.00	4.10E+01	L	1.19E+09	4.88E+10		0.02
9	HDPE drum	00,00	1.28E+06	J	2.72E+05	3.48E+11		0.17
10	Gasoline	00,00	1.24E+08	J	1.94E+05	2.41E+13	2	11.48
11	Engine oil	00,00	2.00E-01	L	2.49E+12	4.98E+11	4	0.24
12	Copper sulfate	00,00	8.50E+02	g	8.64E+10	7.34E+13		**35.04**
13	Boric acid	00,00	6.20E+02	g	3.80E+08	2.36E+11	3	0.11
14	Sodium dichromate	00,00	3.76E+01	R$	1.26E+12	4.74E+13		**22.62**
Total (R)						1.72E+13		8.19
Total (N)						1.71E+13		8.18
Total (F)						1.75E+14		83.63
Total (FR)						1.70E+13		8.10
Total (FN)						1.58E+14		75.53
Total Emergy (Y)		16.29	3.07E+09	J	6.83E+04	**2.10E+14**	6	
Total Emergy per Year (Y/year)		16.29	3.07E+09	J	**5.69E+03**	**1.75E+13**	6	

Source: [1] Bonilla *et al*. (2010), [2]Brown *et al*. (2011), [3]Cuadra and Rydberg (2000), [4] Odum (1996), [5] Romanelli *et al*. (2008), [6] calculated in this study and elaborated by the authors.

Table 5. Energy indices associated with eucalyptus treatment (flows in 12 years)

Emergy indices	Value	Interpretation of index value based on Brown and Ulgiati (2004)
EYR	1.20	(1<EYR<2) Small contribution to economic development.
EIR	5.11	The lower the EIR, the greater the competitiveness of the system.
ELR	5.14	(3<ELR<10) Production system with moderate environmental load (impact).
ESI	0.23	(ESI<1) The analyzed system is not sustainable.
%R	6.29	The higher the %R, the greater the renewability of the analyzed system.

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

Source: Brown and Ulgiati (2004) and prepared by the authors.

3.3 Greenhouse emergy analysis (construction and maintenance)

After the emergy of these fundamental elements for the construction of the greenhouse (treated eucalyptus and bamboo) was obtained, the main energy and material flows involved in the manufacturing and maintenance of this greenhouse were accounted for.

To prepare these emergy calculation tables (Tables 6 and 7), a useful life of 12 years for the greenhouse was considered, since this time represents the estimated durability of the most durable item used in construction, which is the basis of the entire structure, the treated eucalyptus. The analysis revealed a total emergy of 1.04E+14 seJ m $^{-2}$, which corresponds to an annual emergy for the construction and maintenance of the greenhouse of 8.68E+12 seJ m $^{-2}$ year $^{-1}$ and a renewability %R of 35.48. Compared with the emergy of 3.07E+12 seJ m $^{-2}$ year $^{-1}$ and a %R of 7.98% reported by Asgharipour *et al*. (2020) In large greenhouses (average size of 1685 m²) built with metal arches and an estimated useful life of 40 years for vegetable production in Jiroft, Iran, one is 2.83 times larger than the other. The %R of the bamboo greenhouse was 4.45 times greater. The environmental impact index is also noteworthy because it is 7.13 times greater in the metal greenhouse (ELR = 9.77). The energy investment is the most discrepant, being 282421.58 times higher in the metal greenhouse (ELR = 196488.34) because it is a greenhouse in which 99.99% of the energy involved in its construction comes from resources from the economy (F).

Table 6. Energy flows in the construction and maintenance of the bamboo greenhouse (flows in 12 years)

No.	Item	%R	Value	Un	UEV	Emergy flow	Ref. (UEV)	%
	Local renewable resources (R)							
1	Solar radiation	100.0	8.07E+08	J	1.00E+00	8.07E+08		0.00
2	Treated bamboo (30.74%) (x2)	30.76	5.16E+01	m	1.83E+12	9.45E+13	7	8.65
3	Treated eucalyptus (8.19%)	16.29	2.51E+08	J	6.83E+04	1.72E+13	7	1.57
4	Labor (50.00%)	50.00	4.10E+01	h	6.02E+12	2.47E+14	2	22.57
	Local nonrenewable resources (N)							
5	Treated bamboo (7.28%) (x2)	30.76	1.22E+01	m	1.83E+12	2.24E+13	7	2.05
6	Treated eucalyptus (8.78%)	16.29	2.51E+08	J	6.83E+04	1.72E+13	7	1.57
7	Labor (50.00%)	50.00	4.10E+01	h	6.02E+12	2.47E+14	2	22.57
	Renewable Economy Resources (FR)							
8	Treated bamboo (0.03%) (x2)	30.76	5.04E-01	m	1.83E+12	9.22E+11	7	0.08
9	Treated eucalyptus (8.10%)	16.29	2.49E+08	J	6.83E+04	1.70E+13	7	1.55
10	Wire (79.90%) (x2)	79.90	6.20E+02	g	1.47E+10	9.11E+12	6	0.83
11	Steel screw (97.90%)	79.90	1.76E+02	g	1.36E+10	2.39E+12	1	0.22
	Nonrenewable resources of the economy (FN)							
12	Treated bamboo (61.96%) (x2)	30.76	1.04E+02	m	1.83E+12	1.91E+14	7	17.43
13	Treated eucalyptus (75.53%)	16.29	2.32E+09	J	6.83E+04	1.58E+14	7	14.49
14	Wire (20.10%) (x2)	79.90	1.56E+02	g	1.47E+10	2.29E+12	6	0.21
15	Steel screw (20.10%)	79.90	4.42E+01	g	1.36E+10	6.01E+11	1	0.06
16	Shading screen (x2)	0.00	2.78E+03	g	2.16E+09	6.00E+12	3	0.55
17	Carbon steel nails	0.00	8.80E+02	g	2.77E+09	2.44E+12		0.22
18	Plastic film (x4)	0.00	1.28E+04	g	3.72E+08	4.76E+12	4	0.44
19	Gasoline (x4)	0.00	4.87E+08	J	1.11E+05	5.40E+13	5	4.94
Total (R)						3.58E+14		32.79
Total (N)						2.86E+14		26.19
Total (F)						4.48E+14		41.03
Total (FR)						2.94E+13		2.69
Total (FN)						4.19E+14		38.34
Total Emergy (Y)		35.48	1.05E+01	m²	1.04E+14	**1.09E+15**	7	
Total Emergy per Year (Y/year)		35.48	1.05E+01	m²	**8.68E+12**	**9.11E+13**	7	

Source: [1]Asgharipour *et al*. (2020), [2]Bonilla *et al*. (2010), [3] Mu; Feng; Chu (2012), [4] Odum (1996), [5] Odum (2000), [6] Pulselli; Simoncini; Marchettini 2009), [7] calculated in this study and prepared by the authors.

Table 7. Energy indices in the construction and maintenance of the bamboo greenhouse (flows in 12 years)

Emergy indices	Value	Interpretation of index value based on Brown and Ulgiati (2004)
EYR	2.44	(2<EYR<5) Moderate contribution to economic development.
EIR	0.70	The lower the EIR, the greater the competitiveness of the system.
ELR	1.82	(ELR<2) Production system with very low environmental load.
ESI	1.34	(1<ESI<5) Medium-term sustainable system.
%R	35.48	The higher the %R, the greater the renewability of the analyzed system.

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

Source: Brown and Ulgiati (2004) and prepared by the authors.

4 CONCLUSIONS

The number of studies using emergy as a tool for diagnosing and comparing production systems has been increasing. This tool has proven to be useful for analysis and decision-making in production processes, enabling the selection and discovery of the potential of materials and processes that generate less environmental impact and are sustainable over the long term; in addition, it challenges the use of useful life criteria for choosing materials, i.e., a material with a longer lifespan is not always the most appropriate choice from the perspective of emergy.

Labor, in general, had a large effect on the results of the analyses since the construction and maintenance of the structure studied was artisanal. Context is a fundamental aspect of this type of analysis, since a single item, in this case, labor, can significantly alter the results of the emergy indices.

There are still challenges in using emergy to analyze poorly studied systems, such as the availability of data on UEVs in the literature and making the necessary adaptations to the conditions of the analyzed system. Often, the references and/or adjustments made in other studies are not clear, making establishing the necessary relationships difficult. The tables containing the emergy flows presented in this work (Tables 2, 4 and 6) show the importance of the items of the analyzed system being decomposed and having their real percentages allocated to the resource categories to which they belong (R, N, FR and FN). In this way, the indices calculated using these data are more faithful to the realities of the system. This practice, however, is often not used in emergy analysis works, as it is common to allocate the item to the resource category in which it has the highest percentage of emergy. This method generates an error in the results that increases as it is replicated.

This study contributes to this universe of protected cultivation structures, but more studies and greater standardization of the method are needed, aiming at achieving sustainability and development for various sectors, regardless of scale, as emergy analysis has the potential to make greater contributions to humanity in search of a more harmonious relationship with the planet.

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