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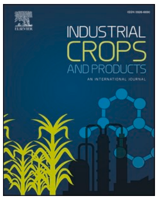

Environmental performance of bamboo-based office paper production: A comparative study with eucalyptus

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ABSTRACT

Bamboo has being used as alternative raw material for construction, reinforcing fibers, paper production, among other applications. Although its recognized potentials as raw material, there are doubts about its environmental performance compared to traditional wood-based products, including paper production, which hinders bamboo-based paper plants in large scales. This study aims to assess the environmental performance of producing office paper from bamboo. Emergy synthesis (with 'm') and global warming potential indicators are calculated and compared with the traditional eucalyptus paper-based production. Results highlights the importance in including the renewability fractions of each input resources into emergy calculations for production systems with high human-labor intensity such as the bamboo agricultural production. Office paper produced from bamboo has similar renewability (28%), moderate environmental load (3.23 vs. 2.49), and emergy unsustainability (0.34 vs. 0.60) compared to paper produced from eucalyptus, but bamboo showed lower performance for global efficiency (568 vs. 442 sej/ton$_{paper}$), emergy yield (1.09 vs. 1.49), and emergy investment (10.79 vs. 2.05). Focusing on global warming potential, office paper produced from bamboo releases 98 kgCO$_{2\ eq.}$/ton$_{paper}$ compared to 56–267 kgCO$_{2\ eq.}$/ton$_{paper}$ for eucalyptus. Notwithstanding, bamboo-based office paper demands four times more land area of agricultural production than eucalyptus, but it has a positive social aspect by requiring higher amount of direct human labor. This work shows the advantages of using eucalyptus rather than bamboo in producing office paper from an emergy and land demand perspectives, while global warming can still be considered inconclusive. Future efforts should consider a quantitative and qualitative analysis of human labor availability in both systems, as well an economic analysis to support discussions towards more sustainable office paper production from different raw materials.

1. Introduction

Bamboo is an important non-wood fiber resource used as an alternative raw material for construction, reinforcing fibers, paper production, plastic straws and other applications in several countries where the supply of wood-derived raw materials is limited (Yu et al., 2011; González et al., 2011; Mahdavi et al., 2012; Banavath et al., 2011; El Bassam, 1998; Kleinhenz and Midmore, 2001; Luan et. al., 2023). Modern industries use almost exclusively one of the numerous bamboo species (*Bambusa vulgaris*) for products such as baskets, vases, pencil and pen holders, kitchen containers, wall plaques, table mats, and lamp shades, all of which have a decorative-cum-utility value. Many nutritious and active minerals, such as vitamins, amino acids, flavine, phenolic acid, polysaccharide, trace elements, and steroids can be extracted from bamboo culm, shoot, and leaf, all of which have anti-oxidation, anti-aging, anti-bacterial, and anti-viral functions (Ogunjimni et al., 2009). Bamboo is an important source of fiber for pulping and papermaking compared with other non-wood fibers such as rice/wheat straw and reed due to its long fiber and chemical composition similar to hardwoods (Tripathi et al., 2018; Bhardwaj, 2019). Bamboo can be comparable to hardwood in several fiber characteristics, such as fiber length, aspect, and fibrous cell wall cavity ratio (Chen et al.,

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2019; Bhardwaj, 2019). According to Pego et al. (2019), bamboo fibers have long fibers with potential use in pulp and paper industries. China is a major bamboo-producing country, with its area and stocking being among the top in the world (Gu, et. al., 2019). In China, bamboo has been used for papermaking for over 1700 years, with an annual production of about 200,000 tons reaching 5 billion dollars (Li and Kobayashi, 2004). Another example is India, in which bamboo is used to produce high-quality writing and printing papers, as well for long fiber furnish in newsprint made of hardwood pulp (Bhardwaj, 2019). India has a rich diversity of bamboo resources with 136 species out of more than 1000 species found worldwide (Dwivedi et al., 2019).

Starting in the 1970's (Ciaramello, 1970; Ciaramello and Azzini, 1971a; Ciaramello and Azzini, 1971b; Azzini and Ciaramello, 1971; Barrichelo and Foelkel, 1975), Brazil has several experiences in producing paper from cellulose mixtures, incorporating bamboo and fibers derived from cereal residues such as straws, sugarcane bagasse, and wood to improve the paper's tear resistance. In 2013, bamboo accounted for 77% of the Brazilian cellulose pulp produced from non-wood plant fibers, highlighting its importance as an alternative raw material (Souza et al., 2015). However, the amount of harvested bamboo was insufficient to meet the minimum demand of 1 million tons/year as required by the pulp mills in the last decade (Santi, 2015), making the traditional wood production as the most important player in the market. In 2020, Brazil had approximately 9.6 million hectares of forestry for cellulose pulp purposes, with 7.3 million hectares dedicated to eucalyptus, 1.8 million hectares to pine, and 0.3 million hectares to other wood species (Cunico et al., 2021).

The technological aspect of bioenergy generation using bamboo is well documented in the literature (Scurlock et al., 2000; Anselmo Filho and Badr, 2004). While most researches focus in quantifying both the CO_2 absorbed by natural bamboo forests and the biomass converted into carbon (Nakai et al., 2003; Sakai et al., 2006; Sakai and Akiyama, 2005), other studies have also evaluated bamboo's potential as an agricultural soil fertilizer (Embaye et al., 2005; Christanty et al., 1996; Shanmughavel and Francis, 1996), which highlights several advantages of cultivating and using bamboo for different purposes. The largest bamboo plantation (*Bambusa vulgaris*) in Brazil is located in the Maranhão state, which ultimate goal of producing kraft paper for cement bags and milk Tetrapak® boxes. Both kraft and sulfite pulping processes can be applied to produce similar types of paper, but each one has its own specific advantages. The kraft process is applicable to a wider variety of tree species with high fiber strength, and it tolerates wood contaminants while achieving high lignin removal rates (up to 90%) and efficient chemical recovery. In contrast, the sulfite process produces a pulp with shorter fiber length and its chemical recovery process is less efficient, making the sulfite process most used for special product applications such as very smooth papers (Kramer et al., 2009). The kraft process uses sodium hydroxide (NaOH) and sodium sulfide (Na_2S) as pulping chemicals, while the sulfite process uses a mixture of sulfurous acid (H_2SO_3) and bisulfate ion (HSO_3^-). Both processes allow the reuse of pulping chemicals for energy recovery and solvent regeneration. The bamboo-based paper whitening through kraft process can reach 89% of effectiveness, providing comparable quality to the sulfite process (Tripathi et al., 2018). Bamboo kraft pulp can be delignified with oxygen to reach excellent levels of whitening, making it suitable for the production of white papers and even for sale as bleached market pulp (Cunico et al., 2021).

With the increasing pressure on natural capital by human-made processes as highlighted in different studies (United Nations, 2023; Rockström et al., 2023; Odum and Odum, 2000); Wackernagel and Rees, 1996), it is crucial to develop more efficient production systems that demand lower amount of fossil resources to ensure a sustainable future, including bamboo and paper production. From a literature review, it was identified that few studies are available regarding the environmental issues of bamboo-derived products chain. Bonilla et al. (2010) performed an emergy (with 'm') synthesis to evaluate the role of labor in giant bamboo plantations in Brazil compared to bamboo production in China and Australia. Bamboo production in China achieved higher emergy sustainability index (ESI), but when the partial renewability approach is included in the human-labor input, Brazil becomes the most sustainable giant bamboo producer. Lu et al. (2018) applied an integrated emergy and economic method in order to evaluate the ecological performance of three varieties of bamboo planted in sloping farmland. All bamboo plantations obtained positive effects on water conservation and soil erosion control, besides showing higher emergy-based sustainability performance than other common agricultural crops planted in the same area. Yang et al. (2011) used the emergy synthesis to evaluate three kinds of Chinese industries (tourism, tea and bamboo), concluding that bamboo industry has high potential for growth in despite of being dependent on non-renewable resources. Putra and Anita (2004) applied emergy and life cycle assessment (LCA) to evaluate the oil palm empty fruit bunch as alternative feedstock to pulp production, identifying that emergy evaluation of palm waste utilization still require additional efforts for more solid conclusions. Chen et al. (2023) used LCA to compare environmental impacts of tableware production using bamboo with standard polypropylene tableware. The authors investigated the impact of production, transportation, waste and disposal methods on resources, the environment, and human health. The lack of studies evaluating the environmental performance – independently of scientific method applied – of office paper production using bamboo instead of wood shows a scientific gap that needs to be covered to support effective decisions towards more sustainable paper production.

This study aims to assess the environmental performance of producing office paper from bamboo compared to eucalyptus. Brazilian production chain is considered as case study. The two well-known scientific methods of emergy synthesis (Odum, 1996) and LCA (ISO, 2006a; 2006b)are used to cover different perspectives of bamboo-based paper production. The increasing interest of the scientific literature in using these two methods is because they complement each other, providing different perspectives of the system's environmental performance from different spatial and temporal scales (Agostinho et al., 2023). While emergy synthesis focuses on the upstream system performance from a large-scale perspective, the LCA focuses on downstream system impacts at regional and global scales, besides including one of the current most important indicators ($kgCO_{2\text{-eq.}}$) related to climate change.

This work presents quantitative comparisons between office paper produced from eucalyptus and bamboo, highlighting their advantages and disadvantages based on emergy and LCA. This study provides valuable insights based on quantitative environmental indicators to support public policies for more sustainable paper production.

2. Materials and methods

2.1. Case study description, data source, scope and functional unit

The bamboo plantation has three periods during its 25-year lifespan (Fig. 1), including implementation, adaptation, and operation. The time window for this study encompasses 25 years of bamboo production. Although bamboo has the potential to be an alternative source for office paper production, the amount produced is still not sufficient to feed market needs, lacking large-scale maturity. Consequently, there is a scarcity of data in the literature regarding the production of office paper from bamboo, making it difficult to develop a complete and accurate inventory for the transport and industrial stages after agricultural harvesting. To overcome this challenge, information from Corcelli et al. (2018) and (Tripathi et al., 2018) - as well other non-published industrial reports - were used to identify the main processes related to industrial stage of paper production. Since producing paper from wood and from bamboo requires similar industrial processes, materials and energy, the industrial stage is disregarded from calculations to allow comparison between obtained numbers in this study with the ones obtained by Corcelli et al. (2018) that have considered eucalyptus

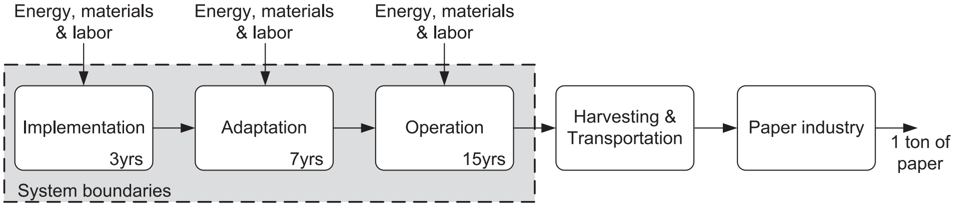

Fig. 1. Spatial scale and time considered in this study. Focus is on the implementation, adaptation, and operation phases of bamboo agricultural production.

produced in Brazil for paper production. Besides, the transportation of culms/wood logs to the industrial stage (industrial processes, material and energy requirements, etc.) for bamboo and eucalyptus are similar as those considered by Corcelli's et al. (2018) study, and thus these processes were also disregarded as shown in Fig. 1. Differences would exist mainly in the agricultural production of raw material, particularly in the planting and harvesting processes. To enable a comparison among results, the functional unit has being standardized as one ton of office paper, produced from bamboo and from eucalyptus. Additionally, due to a lack of accurate and updated data on the yield of paper from bamboo in Brazil (the yield of 55% comes from fifty years ago; Ciaramello, 1970), we have assumed a 50% yield in this study for converting bamboo into paper.

Data source for bamboo production mainly comes from Grupo João Santos (2000), a report published by the most important Brazilian bamboo company. Although data refers to a 20-yr report, it is still considered updated because very few technological advances in the bamboo production chain occurred over this period, since papermaking based on wood received larger attention. Additionally, experts in bamboo production validated all data through personal interview. The report used as reference provides information on the number of culms per hectare, culm productivity, and biomass productivity, among other factors for the *Bambusa vulgaris* specie. When needed, secondary data were obtained from other works, including, Shanmughavel and Francis (1996), Azzini et al. (1987), and Ghelmandi Netto (2009). Important to emphasize that Azzini and coworkers are pioneers of bamboo studies in Brazil since 1970's, recognized as experts in the field. Additionally, Shanmughavel and Francis' (1996) work is widely recognized in cited in the literature, while Ghelmandi Netto (2009) – one of co-author of this study – is a dissertation that took three years of intense studies and field work experiences. All these characteristics guarantee the quality of primary and secondary data used.

This study applies the emergy synthesis and LCA as complementary tools to provide quantitative indicators for the environmental performance of office paper production from bamboo. While the former quantifies nature's effort to provide resources to the system from a donor perspective (upstream impact), the latter focuses on net GHG emissions (downstream impact) resulting from the production system and its capacity to cause the greenhouse effect (Agostinho et al., 2023). Both methods are crucial for achieving the objectives of this work, which are separately and detailed discussed in the following sections.

2.2. Emergy synthesis

Emergy accounting is a holistic approach that considers the donor side in quantifying value, making it capable of recognizing different qualities of energy. It is considered a robust method for indicating sustainability in production systems from a biophysical perspective (Giannetti et al., 2013). Emergy is defined as all energy of one type available, used directly or indirectly, to obtain a given resource or service. The measure unit of emergy is the solar emjoule (sej; Odum, 1996). The quality of energy is quantitatively expressed by the unit emergy values (UEVs), which is the relation between all the emergy demanded by a system with the service or good output (Oliveira et al., 2016) in sej/unit. Emergy concepts and definitions can be found mainly in Odum (1996) and Brown and Ulgiati (2002, 2004).

Emergy synthesis is carried out in three main steps. The first step involves drawing up an energy flow diagram of the system to be evaluated, using the language of symbols proposed by Odum (1996). These diagrams indicate the input flows of energy, material, labor, and information that are necessary to provide a good or service (Brown and Ulgiati, 2002). They are conceptual representative models of the studied systems and help to better understand, from a holistic perspective and with reduced complexity, the internal relations and external demands of natural and economic resources that sustain the production system. Fig. 2 shows a generic diagram used in the emergy synthesis, with its acronyms, flow classifications, and main derived indicators.

After obtaining the energy diagram and comprehending how the system works, the quantification of energy, mass, monetary, and information flows that cross the system boundaries is initiated. This step is known as inventory, which is similar to the one used in other metrics such as LCA. The flows are classified (Fig. 2) as renewable from nature (R) when they are acquired from nature free of charge and have a natural renewal rate greater than the speed at which these resources are extracted, non-renewable from nature (N) when they are obtained free of charge from nature but its natural renewal rate is slower than the speed at which these resources are extracted, and those coming from the economy (F) when the resource is paid. For consistency reasons between this present study with Corcelli's et al. (2018) one that considered data for 2015, the monetary values available by (Grupo João Santos, 2000) report – the main source of raw data in this study – were adjusted for the year 2015 based on the Brazilian general price index market. The monetary values were converted from Brazilian Reais (BRL) to Euros (EUR) using the average conversion ratio for 2015 (1 EURO = 4.301 BRL).

Finalizing the inventory, each previously identified flow is

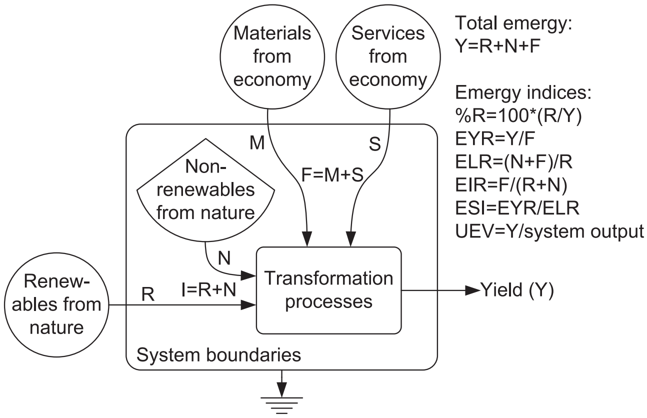

Fig. 2. Generic energy diagram used in emergy synthesis. The external energy sources are represented by circles, while the energy storage is indicated by a tank symbol. The arrows represent the energy flows. The natural environment resources are represented by the letter "I", while the resources from the economy are represented by "F". The indices used in emergy synthesis include EYR (emergy yield ratio), ELR (environmental loading ratio), EIR (emergy investment ratio), ESI (emergy sustainability index), and UEV (unit emergy value). This diagram was adapted from Agostinho et al# (2019).

multiplied by its respective unit emergy value (UEV) standardized by emergy baseline of 12.00E+24 Sej/year from Brown and Ulgiati (2016). The UEV's were obtained from the scientific literature, most of them are available on the work of Giannetti et al. (2019) that provides a large database of UEV's from different previous studies. After choosing UEVs from this database, they were double-checked in their original referenced studies for consistency purposes. Besides being a transformation coefficient, the UEV also represent the energy quality or resource hierarchy on an energy scale, similar to a memory that tracks back all previous energy demanded to make it available. For deeper information on the energy quality concept, please refer to Odum (1996). As a result, all inputs are expressed in the same unit of solar emjoules (sej). All inputs are then conveniently aggregated as shown in Fig. 2 to calculate the following emergy-based performance indicators (more details in Agostinho et al., 2019):

- The emergy yield ratio (EYR=Y/F) is the ratio of the total emergy driving a process to the imported emergy. It measures the system's ability to utilize local natural resources with external resource investments from the economic system and indicates the potential contribution of the process to the economy.
- The environmental loading ratio (ELR = (N+F)/R) is the ratio of non-renewable and imported emergy use to renewable emergy use. It represents the pressure exerted by the system on the environment and serves as a measure of ecosystem stress, indicating the distance from a system that is supported only by renewable sources. According to Brown and Ulgiati (2004), ELR values below 2 indicate low pressure on the local environment, values between 2 and 10 indicate moderate loads, and values above 10 indicate high pressure and impact.
- The emergy investment ratio (EIR = F/(R+N)) indicates the effectiveness of an investment in driving local development processes. Depending on the implemented process, the same invested resource may enable the exploitation of different amounts of resources. Brown and Ulgiati (2004) interpret that the EIR determines whether a process makes efficient use of the invested emergy compared to alternatives.
- The emergy sustainability index (ESI=EYR/ELR) is an aggregated indicator that links the characteristics of EYR with ELR. It aims to maximize the use of local resources in a process while minimizing the environmental loading rate (Brown and Ulgiati, 2004).
- The renewability (%R=100*(R/Y)) is the ratio of renewable emergy to total emergy use, ranging from 0% to 100%. Higher values indicate better ratings. Processes with high renewability are the ones that can be sustained in the long run (Brown and Ulgiati, 2004).

2.3. Global warming potential (GWP) indicator from LCA

To determine the GWP resulting from the production of one ton of office paper using bamboo, both direct and indirect GHG inputs and outputs are considered (Fig. 3). Indirect emissions, also known as hidden costs (Agostinho and Siche, 2014), include GHG emissions resulting from the production chain of resources used in bamboo agricultural plantations. These emissions often occur in regions or countries far from the bamboo plantation site but must be allocated to it. For example, emissions arising from the production of chemical fertilizers occur elsewhere, but they must be attributed to the bamboo production system. Differently, direct emissions occurs locally by burning fossil fuels in machines, soil management practices that can release the carbon stored in organic matter, or harvesting practices such as biomass burning, among others. Biogenic carbon emitted by plant respiration is not included as it is assumed that this carbon will be absorbed by the bamboo production in the following production year.

For the purposes of this study, direct emissions refer to the GWP for the combustion of diesel by tractors and trucks used during agricultural management. To calculate the direct emissions for the production of one ton of paper, the total amount of diesel burned in the field was multiplied by the CO_2 emission potential of diesel oil, which is 2.603 $kgCO_{2\ eq}/L_{diesel}$ (Sulis et al., 2021). It should be noted that carbon emissions from organic soil were not taken into account because the bamboo planting method used in this study does not require soil disturbance as usual in annual crops in the northern hemisphere. Instead, the practice of non-tillage is largely adopted in Brazil, thereby preserving organic matter in the soil.

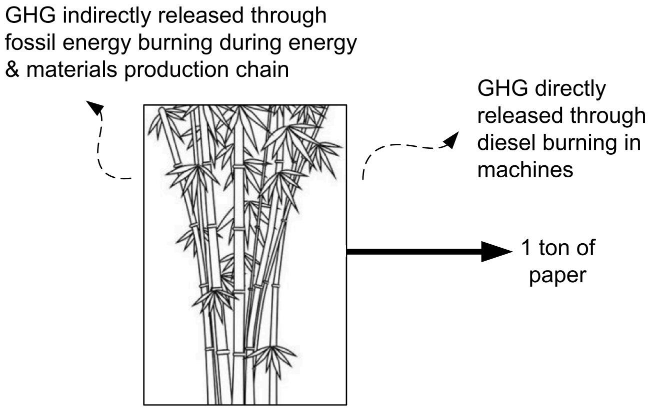

Fig. 3. GHG emissions from bamboo agricultural production.

Regarding the indirect GHG emissions, to determine the impact of each input material and/or energy demanded by bamboo production, the GWP equivalent factors from Table 1 are multiplied by the amount of each system input per hectare year (in kg/ha yr). These GHG equivalent factors were obtained from the Ecoinvent database (version 3.8, 2021) using the ReCiPe Midpoint (H) method for climate change impact category under the life cycle impact assessment (LCIA).

2.4. Results comparison and functional unit

Discussions are provided through a direct comparison among the obtained emergy and GWP indicators from this study with others in the literature. Specifically, three approaches are considered: (i) emergy indicators of bamboo agricultural production, (ii) GWP indicator of bamboo agricultural production, and (iii) emergy and GWP indicators within a scenario of replacing wood-based office paper by bamboo-based office paper in Brazil. The functional unit is standardized as 1 ton of bamboo-based office paper.

Table 1
GWP equivalent factors used to determine the indirect GHG emissions in bamboo agricultural phase.

Item	$kgCO_{2\ eq}/kg$
Herbicide	11.19
Lubricants	1.33
Diesel	0.41
Petroleum and Gas Production	0.14
Hyperphosphate	0.50
Steel	2.13
Plastic/Rubber	81.41
Formicide	10.24
Lime	0.02
Fertilizer NPK	1.36

Source: Ecoinvent database, Method ReCiPe Midpoint (H), climate change.

3. Results and discussions

3.1. Emergy synthesis of bamboo agricultural production

The energy diagram of Fig. 4 provides a visual representation of the resources required for office paper production from bamboo. It shows that agricultural phase utilizes both renewable natural resources such as sun, rain, and wind, as well as local non-renewable resources such as soil. Economic resources such as machinery, fuel, fertilizers, and labor are also required. The flow of money is represented only where services are involved, including direct and indirect human-labor, and does not circulate in the energy flows that come from nature. The bamboo produced is harvested and transported to the industry to be transformed into paper. The paper industry generates organic material as leaves and twigs that are feedback to the agricultural phase, and generates effluent that is treated in accordance with current legislation before being released to the natural environment. This is a classic case of end-of-pipe approach, which aims to minimize the negative environmental impacts of industrial processes by treating effluent before releasing it into the environment. Important to remind that although the functional unit established in this study is 1 ton of paper, the transportation and industrial phases are not accounted for according to the purposes of this study; exclusively the gray symbol is considered in the calculation procedures.

After modeling the functioning of the studied system, a complete inventory of energy, mass, information, and labor flows is elaborated, with each flow represented in its respective original unit. Next, appropriate unit emergy values (UEVs) for each flow previously quantified in the inventory are obtained from the literature to convert the original units (J, kg, $, etc.) into the same unit (sej), as shown in Table 2. It is important to note that this is not a simple conversion of units, since it reflects the efforts made by nature to make those resources available as expressed by the UEVs that capture the memory of all the available energy previously used. Table 2 is organized based on the classification of resources according to Fig. 2, including renewable (R) and non-renewable from nature (N), materials from the economy (F), and services (S). Direct labor (57%), fertilizers (14%), diesel (10%), indirect labor as represented by services (9%), and rainfall (8%) are the major contributors to the emergy of bamboo production.

Direct labor (6.56E+14 sej) is responsible for 57% of the total emergy in bamboo production, a value 39 times higher than the emergy found in Corcelli et al. (2018) with 1.68E+13 sej. This result was expected since bamboo production is labor intensive, quite different from the mechanized processes of eucalyptus production. Although representing higher emergy, the high demand for labor in bamboo production can be seen as a positive aspect under social lens, because more jobs are available for bamboo than for eucalyptus production. The obtained value for services (3.08E+01 €/ton$_{paper}$) and its emergy value (9.60E+13 sej/ton$_{paper}$) are lower than values found in Corcelli et al. (2018), that achieved 2.87E+02 €/ton$_{paper}$ and 1.55E+15 sej/ton$_{paper}$, respectively. The lower value for services, together with the value of direct labor shows that bamboo production demands higher amount of direct labor and smaller amount of mechanized processes than eucalyptus. The amount emergy for diesel oil found in this work (1.09E+14 sej/ton$_{paper}$) is almost 3.3 times lower than the diesel oil used in Corcelli et al., (2018); 3.69E+14 sej/ton$_{paper}$) reinforcing that bamboo plantation is less mechanized than eucalyptus. The amount of emergy for N-P-K based fertilizers found in this work was 1.55E+14 sej/ton$_{paper}$, a value about 3.8 times higher than eucalyptus of 4.04E+13 sej/ton$_{paper}$ (Corcelli et al., 2018).

Table 3 presents the emergy indicators for 1 ton of office paper production from bamboo and eucalyptus, with and without partial renewability. The specific emergy demanded to produce office paper from bamboo (568 sej/ton$_{paper}$) is about 28% higher than producing office paper from eucalyptus (442 sej/ton$_{paper}$), indicating that eucalyptus results in higher global efficiency. Bamboo has lower ability to provide free-natural emergy for societal development compared to eucalyptus (EYR of 1.09 vs. 1.49), mainly due to its higher dependence on resources from the economy represented by Labor (EIR of 14.37 vs. 2.05), higher environmental load (ELR of 14.37 vs. 2.49), lower environmental sustainability (ESI of 0.07 vs. 0.60), and lower renewability (%R of 7% vs. 28%). From a general perspective, office paper produced from eucalyptus shows better emergy performance than using bamboo as raw material, but it is noteworthy that both options show to be unsustainable over long periods as expressed by the ESI index lower than 1.

Given that labor and services (L&S) have a significant influence on

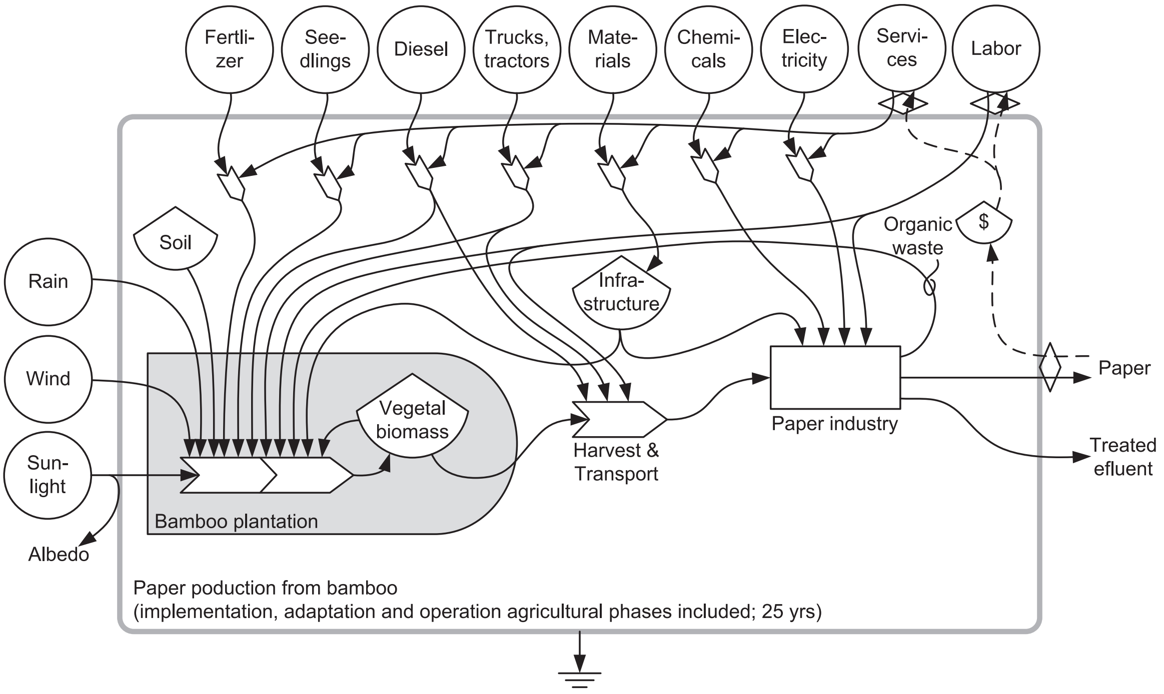

Fig. 4. Energy diagram of paper production from bamboo.

Table 2
Emergy synthesis table for bamboo agricultural production. Data are based on the functional unit of 1 ton of paper produced.

Item[a]	Description	Unit	Amount (Unit/ton_{paper})	UEV (sej/Unit)	Emergy (sej/ton_{paper})	%	Ref. for UEV[c]
Renewables (R)[b]					9.63E+13	8	
1	Solar radiation	J	1.25E+13	1.00E+00	1.25E+13	-	a
2	Wind (kinetic)	J	4.87E+08	8.00E+02	3.90E+11	-	b
3	Rain (geopotential)	J	2.21E+07	2.31E+00	5.12E+07	-	a
4	Rain (chemical)	J	1.38E+10	7.00E+03	9.63E+13	8	b
5	Geothermal heat	J	1.99E+09	4.90E+03	9.75E+12	-	b
Non-Renewables (N)					5.05E+10	0	
6	Soil	J	9.00E+05	5.61E+04	5.05E+10	0	c
Materials (M)					2.89E+14	25	
7	Diesel	J	7.65E+08	1.43E+05	1.09E+14	10	d
8	Lubricants	J	2.26E+06	1.40E+06	3.16E+12	0	d
9	Tractor (4×2)						
	Steel	g	1.20E+02	2.80E+09	3.35E+11	0	e
	Plastic/Rubber	g	2.99E+01	4.47E+09	1.34E+11	0	f
10	Agricultural machinery						
	Steel	g	1.38E+02	2.80E+09	3.87E+11	0	e
	Plastic/Rubber	g	1.54E+01	4.47E+09	6.87E+10	0	f
11	Water truck						
	Steel	g	5.86E+01	2.80E+09	1.64E+11	0	e
	Plastic/Rubber	g	1.46E+01	4.47E+09	6.55E+10	0	f
12	Transport						
	Steel	g	3.73E+02	2.80E+09	1.04E+12	0	e
	Plastic/Rubber	g	9.32E+01	4.47E+09	4.17E+11	0	f
13	Ant killer	g	7.96E+00	1.97E+10	1.57E+11	0	g
14	Natural hyperphosphate	g	3.16E+03	2.54E+09	8.02E+12	1	h
15	Lime	g	1.99E+04	5.26E+08	1.05E+13	1	i
16	Fertilizer 14–20–14						
	N	g	3.90E+03	5.75E+09	2.24E+13	2	g
	P_2O_5	g	5.57E+03	2.23E+10	1.24E+14	11	g
	K_2O	g	3.90E+03	2.18E+09	8.51E+12	1	g
Services (S)					7.14E+14	66	
17a	Labor (Non-Renewable)	J	1.35E+08	3.41E+06	4.59E+14	40	j
17b	Labor (Renewable)	J	5.76E+07	3.41E+06	1.97E+14	17	j
18a	Services (Non-Renewable)	€	2.16E+01	3.12E+12	6.72E+13	6	k
18b	Services (Renewable)	€	9.25E+00	3.12E+12	2.88E+13	3	k
Total emergy (with L&S)					1.14E+15		
Bamboo yield (Y)							
19	Bamboo (mass)	g_{bamboo}	2.00E+06				
19	Bamboo (energy)	J_{bamboo}	2.51E+10				
Specific emergy (with L&S)		g_{bamboo}		5.68E+08			
Transformity (with L&S)		J_{bamboo}		4.52E+04			

[a] Calculations details are available as Supplementary Material.
[b] Only the highest emergy input is considered to avid double accounting.
[c] All UEVS are referenced on emergy baseline of 12.00E+24 sej/yr (Brown et al., 2016) and do not account for Labor and Services. a. Odum, (1996); b. Brown and Ulgiati, (2016b); c. Brown and Bardi, (2001); d. Brown et al., (2011); e. Bargigli and Ulgiati, (2003); f. Brown and Buranakarn, (2003); g. Romanelli et al., (2012); h. Brandt-Williams, (2002); i. De Vilbiss and Brown, (2016); j. Brandt-Williams, (2001); k. NEAD, (2022), EMR for BRAZIL in 2018 of 2.81E+12 sej/dollar, updated to 2015 year through by 1.11 Euro/US$ ratio.

Table 3
Emergy indicators of bamboo (data from Table 2 with L&S) and eucalyptus (Corcelli et al., 2018) agricultural production considering the functional unit of 1 ton of paper.

Indicators	Bamboo	Bamboo (with partial renewability included in L&S)	Eucalyptus
Specific emergy (sej/ton_{paper})	568	568	442
EYR	1.09	1.09	1.49
ELR	14.37	3.23	2.49
ESI	0.07	0.34	0.60
EIR	14.37	10.79	2.05
%R	7%	28%	28%

L&S, labor and services

total emergy of both bamboo and eucalyptus production systems, the partial renewability (Agostinho et al., 2008, 2010) of the emergy flows from economy (F resources) are included to better represent the environmental sustainability of both systems. Table 3 shows that when the partial renewability of 30% (year 2015 for Brazil; (NEAD, 2022) is included to calculate L&S items that together correspond to 65% of the total emergy of bamboo, there are an evident improvement in almost all emergy indicators. Special attention is for ELR (3.23) and %R (28%) indicators that achieved similar performance than eucalyptus. Although recognizing the importance of renewability fraction approach to express sustainability, deeper comparisons with eucalyptus are not provided to avoid inconsistencies with the results obtained by Corcelli et al. (2018).

3.2. GWP of bamboo agricultural production

To compare the GWP of 1 ton of office paper from bamboo with other studies that quantified GHG emissions from eucalyptus production, all numbers were standardized to the same functional unit of 1 ton of paper produced. Table 4 shows the four GWP values considered for comparison. Although Corcelli et al. (2018) do not calculated GWP emissions, the provide inventory in their study was considered to estimated (using data of Table 1) what would be the GWG emissions for eucalyptus.

Morales et al. (2015) assessed eucalyptus (*Eucaliptus globulus*) agricultural production in Chile, cultivated to generate biomass for bioethanol production. Authors applied a LCA including the preparation of the planting site to delivering 1 m^3 of eucalyptus chips to the bioethanol plant. The plantation had a lifespan of 12 years, and harvests were carried out every four years. Since the theoretical amount of eucalyptus needed to produce 1 ton of pulp considered in this present study is 3.46 m^3 (Foelkel, 2017), the GWP to obtain 1 m^3 of eucalyptus of 16.30 $kgCO_{2eq}/t$ cellulose (Morales et al., 2015) was normalized to express the equivalent GWP for 1 t of paper, resulting in 56.43 $kgCO_{2eq}/ton_{paper}$. Comparing this value with the GWP obtained for bamboo production (98.50 $kgCO_{2eq}/ton_{paper}$), it can be observed that eucalyptus releases ~43% lower GWP gases than bamboo to produce 1 ton of paper. However, when comparing bamboo with eucalyptus from Corcelli et al. (2015) data, numbers are highly different since bamboo releases ~63% lower GWP gases. The main item that have influence on the total GWP in Corcelli's et al. (2015) study is the diesel used in eucalyptus plantation. The amount of diesel and lubricants used in the eucalyptus production is 3.4 times higher than for bamboo production, and the amount of fertilizers is also high with 1.4 times higher.

In Xu et al. (2022), the authors quantify the CO_2 emissions and carbon storage of bamboo building materials. The amount of CO_2 emitted to produce 1 m^3 of bamboo building materials was 63 $kgCO_{2eq}/ton_{bamboo}$, that normalizing to the equivalent GWP for 1 t of office paper results in 217.98 $kgCO_{2eq}/ton_{paper}$. This value indicates a ~55% lower emissions for the bamboo-based office paper in Brazil compare to bamboo produced for building materials.

In Marchi et al. (2023), authors studied the management of a hectare of bamboo plantation – *Phyllostachys edulis,* commonly known as Moso – in Italy to assess the carbon footprint offset compared with carbon storage capability. Bamboo plantation had a lifespan of 100 years. The average annual emissions of the bamboo plantation, from the first to the hundredth year, are equal to 2,593 kg $CO2_{eq}$/ha year. This value was multiplied by 25, the same lifespan of bamboo plantation evaluated in this study (64,825 kg $CO2_{eq}$/ha year). After this, the resulting amount of emitted CO_2 was multiplied by the same normalization factor – bamboo to paper – used in the bamboo plantation evaluated in this work (0.008). Full information about this normalization factor can be found in the Supplementary Material. The value found by Marchi et al. (2023) of 518.60 $kgCO_{2eq}/ton_{paper}$ is about 5.3 times higher than bamboo-based office paper production in Brazil. One of the reasons to this difference can be the distribution of inputs between the two plantation sites. In Marchi et al. (2023), 72% of the inputs are related to the management and maintenance of the plantation's road structures (for moving machines), 20% to diesel for field activities, 5% to fertilizers use and 3% to the remaining inputs. Differently, taking into account both direct and indirect CO_2 emissions in this present work, diesel is responsible by 65%, the fertilizers are responsible for 20%, machinery and transportation 14% and other inputs 1%. According to ECOINVENT database (Table 1) the fertilizers has higher CO_2 equivalent emission factor than diesel (1.36 vs. 0.41), indicating that those systems that demands higher amount of fertilizers would release, in principle, higher amount of GWP gases.

Table 4
GWP to produce 1 ton of paper from eucalyptus and bamboo as raw materials.

Scenarios	$kgCO_{2eq}/ton_{paper}$	Reference
Bamboo Planting and Harvesting	98.50	This work
Rotating Eucalyptus plantation for energy production in Chile	56.43	Morales et al., (2015)
Bamboo planting and harvesting to produce bamboo boards for construction	217.98	Xu et al., (2022)
Eucalyptus Planting and Harvesting in Brazil	267.80	Corcelli et al., (2018)
Bamboo Planting and Harvesting in Italy	518.60	Marchi et al., (2023)

From an overall comparison among numbers of Table 4, results are inconclusive since the GWP of bamboo-based office paper production in Brazil are within the range of GWP for eucalyptus production, at the same time showing by far lower emissions than two bamboo production systems. Efforts are still needed to obtain larger sample of GWP values (when they becomes available in the literature) for comparisons to sustain a solid conclusion on this subject.

3.3. *Insights on land area occupation and socio-political aspects in replacing eucalyptus by bamboo for paper production*

Although studying the environmental performance of bamboo-based office paper production focusing on a 1 ton of paper as functional unit is an important step for more effective decisions towards sustainability, it is equally important to have a larger perspective in obtaining clues about the general impacts resulting from replacing eucalyptus by bamboo. For this goal, the provided insights are focused on (a) land area demand, (b) availability of direct jobs, (c) policies perspectives supporting bamboo production, and (d) an example of local/regional economic impact from bamboo production.

Concerning the land area demand, the literature provides figures about land area impacts of using bamboo compared to eucalyptus in office paper production. According to the Brazilian Tree Industry IBÁ (2021), which represents the productive chain of planted trees in Brazil, 78% (7.45 million hectares) of the 9.55 million hectares of wood plantation in 2020 were eucalyptus. Using the numbers provided by Corcelli et al. (2018), 4.1 tons of eucalyptus logs with 50% moisture are required to produce one ton of office paper. In 2020, Brazil produced 2.1 million tons of office paper, which would require 8.6 million tons of eucalyptus logs with 50% moisture. The mass yield of the process in obtaining cellulose from bamboo considered in this work is 50%. Thus, to produce the same 2.1 million tons of office paper using bamboo, 4.2 million tons of bamboo would be required, a value 51% lower than the amount of eucalyptus in mass units. During the 25-year bamboo plantation, 251 tons of dry culms are produced per hectare (Ghelmandi Netto, 2009; 2017; Ghelmandi Netto et al., 2013), with an annual average of 10 tons of dry culms per hectare. Considering a 50% yield of culms for office paper production, 2 tons of culms are required for 1 ton of paper produced. Thus, 0.2 ha (or 2000 m^2) of area are required to produce each ton of paper from bamboo. The average annual increment rate (IMA) of eucalyptus is between 35 and 45 m^3 per hectare, and the recommended age for cutting eucalyptus is 7 years (Motta et al., 2011). Using an IMA of 40 m^3 per hectare, 280 m^3 of eucalyptus can be produced per hectare in seven years. The theoretical amount of eucalyptus needed to produce 1 ton of office paper is 3.46 m^3 (Foelkel, 2017), and Corcelli et al. (2018) reported that 4.1 tons of eucalyptus were required to produce one ton of office paper. Therefore, to produce 1 ton of paper, 14.2 m^3 (3.46 $\times$4.1) of eucalyptus is needed. If 280 m^3 of eucalyptus is produced per hectare, then 0.05 ha (506 m^2) of land is required to produce 1 ton of paper. As a result, eucalyptus needs only 25% of the planting area of bamboo to produce the same 1 ton of office paper, an important aspect in decision-making to avoid possible competition between agricultural areas for food production.

For the availability of jobs, the same calculation approach can be performed. The bamboo plantation has a lifespan of 25 years (Grupo João Santos, 2000). To supply raw material for office paper production, the harvesting of first bamboo culm can be made after the third year of plantation. After this initial cut, bamboo culms are harvested every two years until reach its 25 year. On the other hand, eucalyptus requires more than twice the growth time (6.5 years) before it can be cut to produce office paper (Silva et al., 2015). Eucalyptus must be replanted after its fourth harvesting cycle, approximately 28 years. For comparison, pine needs to be replanted at each cut, between 15 and 20 years (Duarte et al., 2007). In comparison to eucalyptus, the planting and harvesting processes of bamboo is much less mechanized, which makes possible to employ a higher number of people in these processes and result in a positive aspect when labor laws are respected. Thus, it can be stated that bamboo has an advantage over eucalyptus under the social aspect, specifically in the availability of direct jobs. Another aspect that boost the total or partial usage of bamboo as a raw material for obtaining pulp and paper is its higher conversion yield for paper compared to eucalyptus. In addition, the similarity of technological characteristics (industrial processes) between bamboo and eucalyptus is also a contributing factor to the use of bamboo as a replacement for eucalyptus in the production of office paper (Cunico et al., 2021).

The worldwide concern about the scarcity of eucalyptus as raw material for paper (any kind) production justifies the use of bamboo as alternative. As one of the largest world hardwood pulp producer, Brazil depends heavily on eucalyptus. The potential for obtaining pulp and paper from non-wood fibers has not yet been fully explored due to some reasons, including the lack of large-scale production operating and mature industries, the lack of full knowledge about the properties of non-wood fiber materials for pulp and paper production, and the absence of scientific studies on the subject (Cunico et al., 2021). The Brazilian government's incentive to increase the use of bamboo as a raw material for pulp and paper production is essential. If 1% of the amount allocated to research related to eucalyptus in Brazil in 2007 were allocated to bamboo technology and research, a great leap of quality and knowledge could have been achieved regarding the use of bamboo as a raw material for the production of paper (Duarte et al., 2007). The Brazilian law 12,484/2011 established the National Policy for Incentive to Sustained Management and Cultivation of Bamboo (PNMCB), in which its main goal is to develop bamboo culture in Brazil from governmental and private actions. This law can be used as a reference to reduce costs of planting and harvesting bamboo, as well to support investments in scientific research towards technological improvement for the entire pulp and paper production processes based on bamboo.

In a study carried out in Nigeria, Ogunjimni et al. (2009) concluded that exploiting *Bambusa vulgaris* specie for various segments such as medicine, fishing, construction, among others, have a direct impact on local economies. Authors discussed that, depending on scale of production, bamboo production can reach national impacts regarding sustainability issues. In a scenario in which the advantages of bamboo production and usage were better exploited, the finding obtained in Nigeria could also happen in Brazil, especially in communities with less economic resources neighboring bamboo plantations because it demands lower access to economic investments for its implementation and operation stages when compared to eucalyptus. Although not deeply discussed in this study, there are several potential advantages in using bamboo for producing paper that deserves to be further assessed to clarify weaknesses and strengths for better decisions focused on sustainability.

3.4. Study limitations

One limitation of this study is the chosen spatial scope, which includes as boundaries the planting and harvesting stages of bamboo production for office paper conversion. It was not feasible to analyze the entire production process due to data inconsistencies for comparisons. Firstly, there is a difference in the way of transporting culms/wood chips from the planting site to the paper mills. While in the Brazilian case for bamboo production the distance between the factory and the bamboo plantation/harvesting site is about 100 km, Corcelli et al. (2018) considered eucalyptus production in Brazil and its oversea transportation by ships for processing in Scandinavian industries. Secondly, the lack of complete inventories from primary data for industrial office paper production from bamboo is another limitation that must be considered with care to avoid inaccuracies on results and discussions.

Updated values for bamboo conversion into office paper is another limitation. Previous research on this topic were published in 1970 s, thus currently data expressing the updated technological realities is needed. Many studies have explored the production of kraft paper from bamboo, but there is a lack of studies investigating bamboo-based office paper. When updated studies becomes available, numbers obtained in this study can be revisited to allow deeper discussions.

4. Conclusions

Although office paper production from bamboo has similar emergy performance than from eucalyptus for environmental load (both under moderate ELR of 3.23 vs. 2.49), renewability (%R of 28% for both) and environmental unsustainability (ESI 0.34 vs. 0.60), bamboo has lower emergy performance for global efficiency (5.68 vs. 4.42 E+08 sej/ton$_{\text{paper}}$), emergy yield (EYR of 1.09 vs. 1.49) and emergy investment (EIR of 10.79 vs. 2.05) than eucalyptus. These results indicate that eucalyptus should be used for office paper production rather than bamboo from an emergy accounting lens.

Regarding the global warming potential indicator, while office paper production from bamboo releases from 98 to 518 kgCO$_{2\ \text{eq.}}$/ton$_{\text{paper}}$, using eucalyptus releases from 56 to 267 kgCO$_{2\ \text{eq.}}$/ton$_{\text{paper}}$. Considering average values, eucalyptus releases lower amount of GWP gases, but additional studies including larger sample should be developed for more statistically solid conclusions on this regard.

Considering the methods, data and limitations of this study, eucalyptus should be used as raw material to produce office paper rather than bamboo to achieve higher environmental gains. It is suggested that additional indicators such as land area, labor availability, and socioeconomic local impacts be considered in future efforts under larger spatial and temporal perspectives when comparing eucalyptus with bamboo, to sustain effective related public policies.

CRediT authorship contribution statement

Agostinho Feni: Writing – review & editing, Writing – original draft, Funding acquisition. **Almeida Cecília M. V. B.:** Writing – review & editing, Writing – original draft, Formal analysis. **Ghelmandi Netto Luiz:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Liu Gengyuan:** Writing – review & editing. **Giannetti Biagio Fernando:** Supervision, Project administration, Methodology, Conceptualization.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.indcrop.2024.118234.

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