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The Application of Circular Footprint Formula in Bioenergy/Bioeconomy: Challenges, Case Study, and Comparison with Life Cycle Assessment Allocation Methods

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Abstract: Allocation methodological choices in Life Cycle Assessment (LCA) is a relevant issue for the Circular Bioeconomy context. The recent Product Environmental Footprint Guide from the European Commission includes the Circular Footprint Formula (CFF) as a new way to deal with energy recovery/recycling processes. This paper investigated CFF vs. other different LCA allocation methods in Brazilian briquette production. A cradle-to-gate LCA study was conducted considering 1 MJ of energy from recovered and dedicated Eucalyptus briquette production. Global Warming Potential (GWP) and Cumulative Energy Demand (CED) were selected as the impact categories to evaluate the allocation methods choice that influences the potential impacts. LCA results were compared regarding four allocation methods. Eucalyptus wood as a biomass supply scenario achieved impact results up to 4.3 kg CO_2-eq. for GWP and 0.0272 MJ-eq. for CED. The recovery wood scenario presented LCA burdens reduction by up to 206% for GWP, however a 492% increase in the CED results. CFF provided the lowest results for both impact categories. However, the CFF method still doesn't address particular aspects of circular bioenergy systems. Biomass and bioenergy LCA require further adjustments focusing on biochemical flows in the CFF calculation procedure to lead the development of innovative circular business models.

Keywords: circular economy; energy recovery; recycling; life cycle engineering; circular business models

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1. Introduction

The Bioeconomy and bioenergy are two of the most pertinent issues for global sustainable development and the Bioeconomy context, as they are associated with benefits such as the minimization of environmental quality degradation and resources depletion [1,2]. Bioenergy is a promising way to valorize forest and agro-industrial biowaste widely produced around the world [3,4] In this context, biofuels can be used as substitutes for petrol or diesel in the automobile and the energy sectors; densified biomass can be used to power thermal power plants; and biodegradable wastes can play a role in energy recovery via biogas mechanisms [5]. Also, biofuel popularization could drive the development of policies that would make it easier to carry out Sustainable Development Goals (SDGs) [6]. Therefore, there is a close relationship between the use and promotion of bioenergy and the aims of Circular Bioeconomy implementation, once they are complementary in terms of maintainability and resource efficiency goals [7]. Within the Circular Bioeconomy perspective, the use of solid biowaste as an environmentally friendly solution for the energy supply has become highly relevant at a global level [8–10]. One of the most promising solid biofuels to produce sustainable bioenergy are biomass briquettes [11–13].

Briquettes are high-quality fuels and have been successfully made from a variety of biomass [14]. Sawdust and other wood by-products, a binder, and other minor additions are commonly used to produce briquettes [15]. Problems associated with biowaste final disposal can be solved by using agricultural, forest, and industrial biomass wastes as bioenergy sources in the form of briquettes [14]. Briquettes are frequently utilized as a fuel for home and industrial purposes because they offer several advantages for the production and transmission of energy [16].

Biomass briquettes are regarded as renewable in terms of the environment because of the benefits in terms of the carbon cycle [16]. However, their energy use does not guarantee environmental sustainability for the phases of production, conversion, distribution, and circularity. Life Cycle Assessment (LCA) is a tool developed to analyze the environmental impacts of different systems [17,18]. Its scope includes every stage of a product's life cycle, including the extraction of raw materials, manufacture, consumption, and end of life [19]. An LCA technique could be used to evaluate what environmental impacts are inherent to briquettes and which are "imported" by bioenergy systems, i.e., due to systems involved indirectly as service suppliers, such as the use of fossil fuels, transportation, and infrastructure [18].

Additionally, approaches for calculating and creating indicators are needed to assess the circularity of products and processes [20,21] and the energy consumption of biofuels, including biomass briquettes. Also, the key issue for the Circular Bioeconomy context is about the complexity of allocation methodological choices in LCA [22,23]. While some recycling allocation techniques are effective for technical cycles, for example, the Circular Footprint Formula (CFF), they can fall short when evaluating bioenergy systems because certain parameters cannot be easily integrated into the analysis. This is especially true for the biological cycles in the biomass and bioenergy supply. Still, few studies have analyzed this issue for a quantitative pathway [24] discussing the challenges and proposing future directions for research on better integrating the Circular Bioeconomy with the practice of LCA. Also, there are no papers published so far on the application of the CFF to investigate solid biofuels. This paper aims to contribute to filling this gap. What should be done to properly apply an energy recovery LCA method in the context of solid bioenergy (briquettes)?

The goal of this paper was to evaluate and compare the CFF and LCA recycling/energy recovery methods in a Circular Bioeconomy case study, indicating the benefits, limitations, and challenges of the environmental performance of recovered biomass briquettes in Brazil.

Hence, in Section 2 the LCA methodology and the case to be studied are described. In Section 2.2 the use of the different LCA allocation methods are presented, namely: the 50/50 method, the quality-adjusted 50/50 method, and the CFF method, as they are currently the most studied [25]. Section 3 describes the case study results and discussions.

2. Materials and Methods

2.1. Life Cycle Assessment

2.1.1. Definitions of Goal and Scope

According to ISO 14,044 [26], the first LCA stage is the moment in which the temporal, technological, and geographical boundaries are determined. The LCA results depend on the data quality criteria, the cut-off rules, and the impact categories to be addressed. This study consists of a deep analysis of CFF as applied to bioenergy systems through the comparison with two other allocation procedures: the 50/50 and the Quality-adjusted 50/50 methods.

These allocation methods were used to calculate the LCA results for three different manufacturing scenarios, considering the LCA study from [27] for biomass briquettes made from urban pruning activities in Brazil. The scenarios are

- Scenario 1: briquettes made of wood from a dedicated forest energy supply. Brazil is a world reference for tree plantation productivity, with high annual production volumes of wood per area and short plantation cycles [28]. Brazilian planted forests occupy an area of 9.55 million hectares, with 78% being Eucalyptus species [29], used in the production of pulp and paper, wood-based panels, and for energy purposes.
- Scenario 2: briquettes made of wood waste with 50% of the heating value compared to Scenario 1. This scenario was chosen because urban pruning residues have a high moisture and ash content, which reduces the quality of the biomass. [30] also analyzed the useful calorific value of biomass from urban pruning waste in Recife, Brazil, where it obtained an average value of 6.18 MJ/kg, while eucalyptus biomass has an approximate useful calorific value of 12.14 MJ/kg [31].
- Scenario 3: briquette production made of wood waste with the same heating value as the wood from a dedicated forest energy supply (Scenario 1). Therefore, this scenario was performed disregarding any possible difference in the efficiency of the heating value between wood and residual wood.

Beyond the allocation methods, a baseline LCA was performed for each scenario, using the avoided product approach, as implemented by [27]. The avoided product approach is a system expansion by substitution method adopted in LCA for multifunctional products and processes. System expansion in LCA refers to expanding the system boundaries by including additional functions related to the co-products [32]. Using the avoided product approach, only the impacts from the main product system's output (e.g., briquettes) are accounted for. The impacts from the remaining outputs are considered from other product systems, once these remaining outputs substitute the inputs from these product systems [33]. In this study, the LCA results of Scenarios 2 and 3 counted with a system expansion related to the impacts avoided by processing residual wood into briquettes instead of directly landfilling it—similarly to [27].

Scenario 1 did not count with this approach because of its linearity. By considering briquettes production with biomass taken from dedicated forests, the resulting biofuel does not substitute any other product or alternative end-of-life strategy, in a way that there are no avoided impacts to be associated with it.

A cradle-to-gate perspective was considered for all the scenarios—using an attributional LCA approach—and the system boundaries were modeled to cover the material and energy flow from the biomass supply and the production stages, including drying and densification processes for the briquetting (see Figure 1). The product packaging process, transport activities, and the combustion phase of the briquettes were not considered within the system boundaries under analysis. The Functional Unit (FU) was defined as 1 MJ of energy produced from the biomass briquettes.

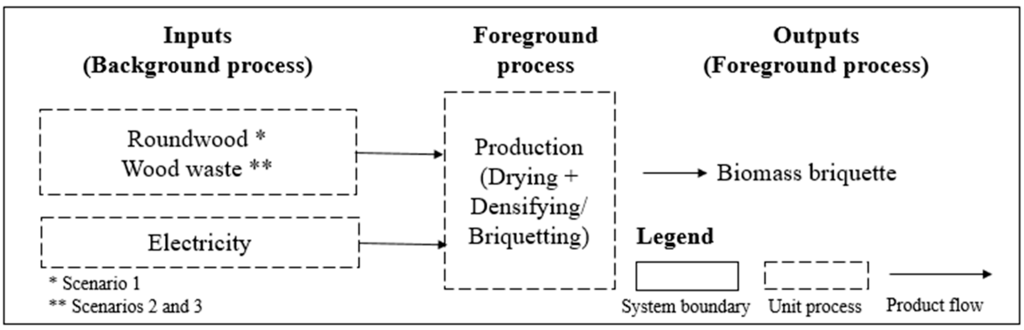

Figure 1. A general product system for biomass briquettes.

In the foreground process, drying the biomass means reducing wood moisture to 12% which is considered the ideal moisture content for the briquetting process [34–36] through a rotary drum dryer with a production capacity of 5000 kg/h. Once the wood leaves the drying process, it serves as the main input for biomass briquetting, which is performed by a mechanical piston press machine [37].

2.1.2. Life Cycle Inventory, Data Quality, and Main Assumptions

This step involves the definition of the procedures to be used for data collection and management up to the quantification of all the inputs and outputs of the product system [38,39]. The open LCA software tool version 1.10 was used to model the product systems under investigation. In Scenario 1, the biomass data supply was considered as roundwood supply from a eucalyptus-managed forest. For Scenarios 2 and 3, the biomass source was the wood waste flow (Table 1) as represented by the mix of bark chips, cleft timber, wood chips, residual hardwood, and softwood inputs considered in the LCA study performed by [27].

Table 1. Life cycle inventory.

Flow	Unit	Quantity
Inputs		
electricity, high voltage from hydroelectric power station	kWh	6.30×10^{-2}
Roundwood for scenario 1 wood waste for scenarios 2 and 3	kg	1.05×10
Outputs		
Biomass Briquette	kg	1.00×10

The difference of 0.05 kg in the mass balance from Table 1 relates to the water losses in the biomass drying stage. The ecoinvent 3.7 cutoff unit process database was adopted for the background datasets of electricity and wood waste supplies. When regional background data was not found on the ecoinvent database, datasets were taken from the Rest of the World (RoW) region. Roundwood background data was extracted from the SICV database, a Brazilian free and open-access national LCA database covering economic sectors such as agribusiness and forestry activities in the country [40].

The inventory data was converted to the UF (1 MJ-eq.) based on the briquette calorific value for each scenario. The amount of energy and wood demanded by each scenario varied according to the calorific value established for the final product. For the eucalyptus (Scenario 1) and residual wood briquettes (Scenario 3) a Lower Heating Value (LHV) of 12.14 MJ/kg was considered, while for the residual wood briquettes with less efficiency (Scenario 2) the briquette's LHV was 6.18 MJ/kg.

2.1.3. Life Cycle Impact Assessment and LCA Interpretation of Results

For the present study, all the scenarios were evaluated concerning two impact methods: the IPCC 2013 GWP 100y and the CED (v. 1.0.1, January 2015) available at the openLCA software tool. The IPCC GWP 100y is a methodology developed by the Intergovernmental Panel on Climate Change (IPCC) to quantify the Global Warming Potential (GWP) impacts from products and processes, based on the time-integrated global mean radiative forcing of a pulse emission of 1 kg of some compound relative to that of 1 kg of the reference gas, being CO_2 [41]. A product's Cumulative Energy Demand (CED) represents the direct and indirect energy used throughout the life cycle, including the energy consumed during the extraction, manufacturing, and disposal of the raw and auxiliary materials [42]. Both the impact categories, i.e., GWP and CED are commonly studied by LCA practitioners with special reference to the Energy sector [28,43]. A complementary analysis of results was performed considering the uncertainty analysis of the LCA for these categories, as the life-cycle uncertainties may have a relevant influence on the LCA interpretation process [18,44].

For the LCA interpretation of results, three allocation methods were used as described in Section 2.2. The comparative LCA results were internally normalized [44] to facilitate the LCA contribution analysis and the hotspots analysis in Section 3. A mathematical description of the CFF method and the remaining ones under investigation is given in the next paragraphs.

2.2. System Allocation Methods

System allocation is a strategy used to represent the sharing of input and/or output flows of a process/product system between a product system under study and other product systems [26]. Beyond the reference results obtained through LCA, three different allocation methods were calculated for all the scenarios: the 50/50 method, the Quality-adjusted 50/50 method, and the CFF.

2.2.1. 50/50 Method

According to [25], the 50/50 method equally splits the environmental burden of virgin material production and its final disposal between the product using this virgin material and the product where this material is lost from the technosphere. In each recycling process, the environmental burden is split equally between the product system supplying recyclable material and the product to which the recycled material is applied. The calculation of the environmental burden using this method is provided by Equation (1):

$$E = 0.5 \times [(1 - R_1) + (1 - R_2)] \times (E_V + E_D) + 0.5 \times (R_1 \times E_{Rin} + R_2 \times E_{Rout}) \quad (1)$$

where,

- E is the environmental burden (e.g., GWP, CED);
- R_1 is the ratio of material in the input to the production that has been recycled in a previous system [0, 1];
- R_2 is the ratio of the material in the product that will be recycled in a subsequent system [0, 1];
- E_V is the environmental burdens from virgin/primary material production;
- E_D is the environmental burdens from waste disposal;
- E_{Rin} is the environmental burdens from the recycling process supplying recycled/secondary material to the product;
- E_{Rout} is the environmental burdens from the recycling process accepting materials from the product.

The first summand of the equation consists of the share of the environmental burdens from both production and disposal of used virgin material, while the second summand consists of the share of the environmental burden from the usage of recycled material.

2.2.2. Quality-Adjusted 50/50 Method

This method was proposed by [45,46], based on the best practices approach from French Association for Normalization [47]. While this method distributes the impacts due to recycling in a 50/50 way (similarly to the 50/50 method presented by Equation (1), it also includes the virgin and disposal impacts over the different products in the overall product cascade system and allows the accounting for changes in inherent material properties (i.e., the quality of the material). The formula of this method is presented by Equation (2):

$$\begin{gathered} E = (1 - R_1) \times E_V + 0.5 \times R_1 \times (E_{Rin} + E_V - E_D^*) \\ +0.5 \times R_2 \times \left(E_{Rout} - Q_S/Q_P \times E_V^* + E_D\right) + (1 - R_2) \times E_D \end{gathered} \quad (2)$$

where,

- E^*_D indicates the avoided E_D through recycling;
- Q_S is the quality of the recycled material used for the investigated product [0–1];
- Q_P is the quality of primary/virgin material used for the investigated product [0–1];
- E^*_V indicates the avoided E_V through recycling.

The first summand of the equation consists of the environmental burden from the use of virgin/primary material only. The second summand consists of the share of the environmental burden from the usage of secondary/recycled material. The third summand consists of the share of the environmental burden from the disposal and/or new recycling of recycled/secondary material. Finally, the fourth summand consists of the share of the environmental burden from the disposal of the remaining waste.

Figure 2 presents the application of the 50/50 and the Quality-adjusted 50/50 methods to a system where a material is used in two products through recycling, being completely used for energy recovery after the manufacturing of the second product.

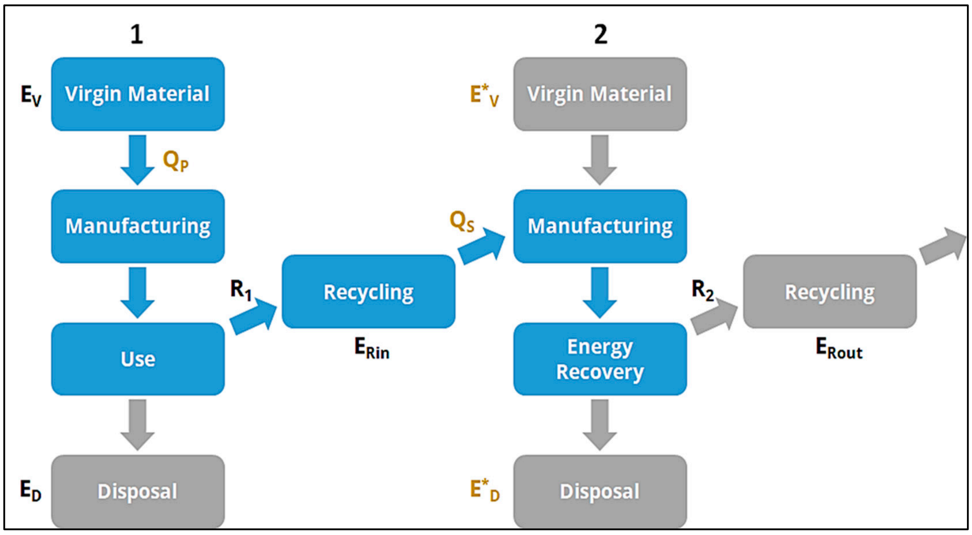

Figure 2. General illustration of how the 50/50 and the Quality-adjusted 50/50 methods are applied to a hypothetical case. The gray color indicates processes and flows that are avoided through recycling. Symbols in bold black represent variables from both 50/50 and the Quality-adjusted 50/50 methods, while symbols in bold dark yellow represent the specific variables present for the Quality-adjusted 50/50 method only (Reprinted/adapted with permission from Ref. [25]) 2020, Ekvall et al.)

2.2.3. Circular Footprint Formula

The CFF was proposed by the Product Environmental Footprint Category Rules Guidance (Version 6.3), developed by the European Commission [32]. This method accounts not only for the share of recycled material (R_1) and the ratio of the material in the product that will be recycled in a subsequent system (R_2), but also for the quality of recycled material entering (Q_{Sin}) and leaving (Q_{Sout}) the life cycle, and the balance between supply and demand for individual recycled materials—addressed by Factor A, a material-dependent factor which aims to reflect market realities [25]. In addition, CFF also accounts for the credits and/or burdens from energy recovery processes (i.e., for heat and electricity recovery) applied during the product life cycle. Equation (3) introduces the formula for this method:

$$\begin{aligned} E = {} & (1-R_1) \times E_V + R_1 \times \left[A \times E_{Rin} + (1-A) \times E_V \times \left(\frac{Q_{Sin}}{Q_P}\right)\right] \\ & + (1-A) \times R_2 \times \left[E_{Rout} - E_V^* \times \left(\frac{Q_{Sout}}{Q_P}\right)\right] + (1-B) \times R_3 \\ & \times (E_{ER} - LHV \times X_{ER,heat} \times E_{SE,heat} - LHV \times X_{ER,elec} \times E_{SE,elec}) + (1-R_2-R_3) \times E_D \end{aligned} \quad (3)$$

where,

- A is a factor that represents the balance between supply and demand for recycled material [0.2–0.8];
- Q_{Sin} is the quality of recycled material entering the life cycle [0–1];
- Q_{Sout} is the quality of recycled material leaving the life cycle [0–1];
- B is an allocation factor of energy recovery processes that applies both to burdens and credits;

- R_3 is the ratio of the material in the product that is used for energy recovery at End-of-Life [0–1];
- E_{ER} is the specific emissions and resources consumed (per functional unit) arising from the energy recovery process (e.g., incineration with energy recovery, landfill with energy recovery, etc.);
- LHV is the Lower Heating Value of the material [MJ/kg];
- $X_{ER,heat}$ is the efficiency of the energy recovery process for heat [0–1];
- $E_{SE,heat}$ is the specific emissions and resources consumed (per functional unit) that would have arisen from the specific substituted heat source [0–1];
- $X_{ER,elec}$ is the efficiency of the energy recovery process for electricity [0–1];
- $E_{SE,elec}$ is the specific emissions and resources consumed (per functional unit) that would have arisen from the specific substituted electricity source [0–1];

The first summand of the equation consists of the environmental burden from the use of virgin/primary material. The second summand consists of the burdens and benefits related to secondary materials input, while the third summand consists of the burdens and benefits related to secondary materials output. The fourth summand represents the energy recovery processes, for both heat and electricity purposes. Finally, the fifth summand consists of the share of the environmental burden from the disposal of the remaining waste.

Figure 3 presents the application of the CFF to a general system where a material is used for energy recovery after its final use.

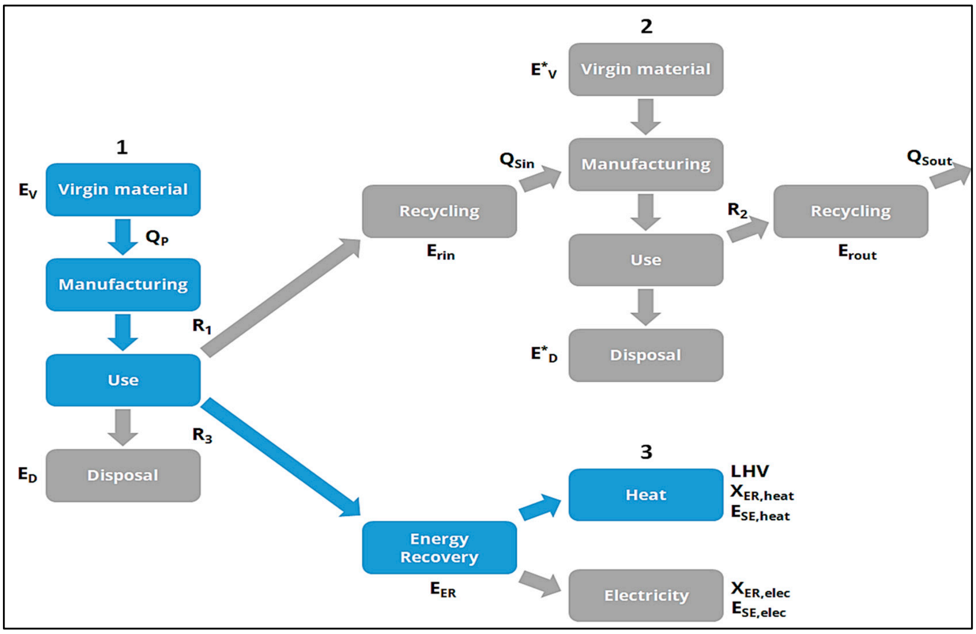

Figure 3. Illustration of how the CFF applies to a hypothetical case of a material that is used for energy recovery after being used in a product. The gray color indicates processes and flows that are avoided through recycling and therefore never take place (Reprinted/adapted with permission from Ref. [25] 2020, Ekvall et al.).

2.2.4. Designed Tests for the LCA Allocation Methods

A summary of the designed tests for evaluation of the LCA methods are introduced by Table 2, which illustrates the behavior of the methods' equations for each briquetting scenario. The null value was represented by red color in the formulas of the associated method and scenario, while the blue parameters highlight the operations that returned a non-null value, which attributed a positive or negative influence on the GWP and CED results for each scenario. The system expansion behavior, according to each scenario, can be noted on the equations used to obtain the LCA results, which were calculated as the sum of the environmental impacts related to each system input discounted by the avoided impacts due to the expanded system.

Table 2. The behavior of the equations used by each LCA allocation method in the three biomass briquetting scenarios.

Approach.	Scenario	Equation
Avoided product	1	Wood Impacts + Energy Consumption Impacts for Briquetting wood—Treatment of Waste Wood on Landfill
	2	Residual Wood Impacts + Energy Consumption Impacts for Briquetting Residual Wood—Treatment of Waste Wood on Landfill
	3	Residual Wood Impacts + Energy Consumption Impacts for Briquetting Residual Wood—Treatment of Waste Wood on Landfill
50/50 method	1	$\{0.5 \times [(1 - R1) + (1 - R2)] \times (Ev + \underline{Ed})\} + [0.5 \times (R1 \times Erin + R2 \times Erout)]$
	2	$\{0.5 \times [(1 - R1) + (1 - R2)] \times (\underline{Ev} + \underline{Ed})\} + [0.5 \times (R1 \times Erin + R2 \times Erout)]$
	3	$\{0.5 \times [(1 - R1) + (1 - R2)] \times (\underline{Ev} + \underline{Ed})\} + [0.5 \times (R1 \times Erin + R2 \times Erout)]$
Quality-adjusted 50/50 method	1	$[(1 - R1) \times EV] + [0.5 \times R1 \times (Erin + EV - Ed^{*})] + \{0.5 \times R2 \times [Erout - (Qs/Qp) \times Ev^{*} + Ed]\} + [(1 - R2) \times Ed]$
	2	$[(1 - R1) \times EV] + [0.5 \times R1 \times (Erin + EV - Ed^{*})] + \{0.5 \times R2 \times [Erout - (Qs/Qp) \times Ev^{*} + Ed]\} + [(1 - R2) \times Ed]$
	3	$[(1 - R1) \times EV] + [0.5 \times R1 \times (Erin + EV - Ed^{*})] + \{0.5 \times R2 \times [Erout - (Qs/Qp) \times Ev^{*} + Ed]\} + [(1 - R2) \times Ed]$
Circular Footprint Formula (CFF)	1	$[(1 - R1) \times Ev] + \{R1 \times [A \times Erin + (1 - A) \times Ev \times Qsin/Qp]\} + [(1 - A) \times R2 \times (Eout - Ev^{*} \times (QSout/QP)] + \{(1 - B) \times R3 \times [(Eer - LHV \times Xerheat \times Eseheat) - (LHV \times Xerelec \times Eseelec)]\} + [(1 - R2 - R3) \times Ed]$
	2	$[(1 - R1) \times Ev] + \{R1 \times [A \times Erin + (1 - A) \times Ev \times Qsin/Qp]\} + [(1 - A) \times R2 \times (Eout - Ev^{*} \times (QSout/QP)] + \{[(1 - B) \times R3 \times [(Eer - LHV \times Xerheat \times Eseheat) - (LHV \times Xerelec \times Eseelec)]\} + [(1 - R2 - R3) \times Ed]$
	3	$[(1 - R1) \times Ev] + \{R1 \times [A \times Erin + (1 - A) \times Ev \times Qsin/Qp]\} + [(1 - A) \times R2 \times (Eout - Ev^{*} \times (QSout/QP)] + \{[(1 - B) \times R3 \times [(Eer - LHV \times Xerheat \times Eseheat) - (LHV \times Xerelec \times Eseelec)]\} + [(1 - R2 - R3) \times Ed]$
		Parameter description
Factor A		A balance between supply and demand for recycled material [0.2–0.8]
Ed		is the environmental burdens of the waste disposal
Ed*		indicates Ed is avoided through recycling
Erin		is the environmental burdens of the recycling process supplying recycled material to the product
Erout		is the environmental burdens of the recycling process accepting materials from the product
Ev		is the environmental burdens of virgin material production
Ev*		indicates Ev is avoided through recycling
R1		Share of recycled material [0–1]
R2		the rate of recycling of material after use in the product [0–1]
Qp		is the quality of the material delivered by the primary production [0–1]
Qs		quality of material recycled from the investigated product [0–1]
Qsin		the quality of recycled material entering the life cycle [0–1]
Qsout		the quality of recycled material leaving the life cycle [0–1]
S		the quality of the recycled material divided by the quality of virgin material [0–1]
B		allocation factor of energy recovery processes: it applies both to burdens and credits—Equals to 0 as default
R3		is the proportion of the material in the product that is used for energy recovery at EoL
Eer		specific emissions and resources consumed (per functional unit) arising from the energy recovery process (e.g., incineration with energy recovery, landfill with energy recovery, ...)
LHV		lower heating value of the material [MJ/kg]
Xerheat		the efficiency of the energy recovery process for heat
Eseheat		specific emissions and resources consumed (per functional unit) that would have arisen from the specific substituted energy source. For this case, heat
Xerelec		the efficiency of the energy recovery process for electricity
Eseelec		specific emissions and resources consumed (per functional unit) that would have arisen from the specific substituted energy source. For this case, electricity

Along with the results and discussion in Section 3, a detailed analysis of the LCA results is given regarding Table 2. Based on the selected LCA recycling methods, it is clear all of them are more concerned with the mass of materials flowing through the life cycle of a product. However, for biological processes in the context of the Circular Bioeconomy [24], the discussed equations do not include biochemical flows, and this may lead to some relevant research implications that will be discussed in Section 3.3.

3. Results and Discussion

The LCA results were set as the reference values for all scenarios, as a consequence of their higher robustness and complexity (ISO, 2009, 2006) when compared to the other methods. In this sense, Section 3.1 presents the LCA results overview for GWP and CED in all scenarios. Section 3.2 shows the results for the other allocation methods, also comparing them with the results of CFF. Section 3.3 discusses the results in terms of research implications and provides recommendations toward the Circular Economy in bioenergy systems.

3.1. Overall LCA Results

The baseline LCA results obtained for all scenarios presented different behavior between the two impact categories (GWP and CED), as is illustrated in Figure 4:

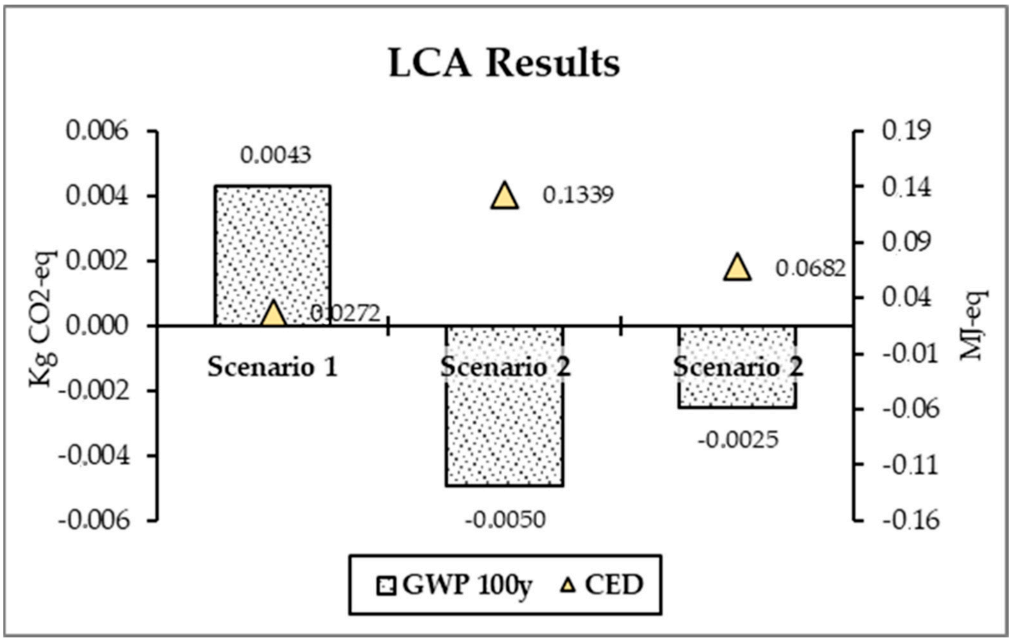

Figure 4. LCA results for the three studied scenarios.

The GWP had negative values for Scenarios 2 and 3 due to the avoided impacts related to the final disposal of residual wood in landfills (system expansion), which surpasses the CO_2 emissions from briquetting the residual wood. In this sense, results for GWP had a relative variation of 206%, ranging from −0.005 to 0.0043 kg CO_2-eq. per FU. As expected, the highest impact for GWP was noted in Scenario 1, which was modeled considering the restricted use of virgin biomass as raw material. Scenario 2 by itself had the lowest results for GWP, since it is based on a final product with approximately half of the calorific value of the other two scenarios, promoting more carbon credits through the end-of-life strategy of using residual wood as an energy source instead of landfilling it. It means that for 1 MJ of energy obtained from residual wood briquettes, Scenario 2 allows the saving of almost twice the landfilling emissions. Therefore, Scenarios 2 and 3 can be considered as good opportunities to achieve a 'net-zero' [48] in terms of carbon emissions toward a Circular

Bioeconomy, and could contribute to reaching SDGs 7 (clean energy targets) and 13 (action against climate change) [49].

Given the energy demanded by wood treatment in landfills, the CED results were superior to zero, with results ranging from 0.0272 to 0.1339 MJ-eq. (492% relative variation). Scenario 1 had the lowest results of the three scenarios followed by Scenarios 3 and 2. The behavior of CED results is a consequence of the background data taken from the ecoinvent database, which attributes higher energy demanded by wood waste obtention, instead of that associated with the same amount of wood supply. This non-expected phenomenon can be explained by more transport activities required for wood waste supply than in the virgin wood supply contributing to an increase in CED.

Also, it is important to investigate how the uncertainties contained in the data collected in the LCA may affect the reliability of the results obtained [50]. In this sense, the Monte Carlo is a stochastic simulation technique often used in probabilistic modeling [51]. Table 3 shows the LCA uncertainty analysis for the studied reference case using 1000 iterations for the Monte Carlo simulation (GWP and CED categories).

Table 3. LCA uncertainty analysis (avoided product approach).

	Global Warming Potential Kg CO_2-eq.	**Cumulative Energy Demand (MJ-eq.)**
Mean	1.06×10	1.53×10^{-1}
Standard deviation	7.86×10^{-2}	8.59×10^{-2}
Minimum	8.57×10^{-1}	3.17×10^{-2}
Maximum	1.36×10	6.12×10^{-1}
Median	1.06×10	1.31×10^{-1}

The results show that the standard deviation value is low for both impact categories, 7.86×10^{-2} for GWP and 8.59×10^{-2} for CED, it can be concluded that the uncertainty is low, since the results showed that most values are concentrated around the mean, with a low probability of occurrence of extreme values. The uncertainty LCA results for the baseline case (avoided product approach) are within the defined 95% confidence interval in the briquette production system in both impact categories (GWP and CED). Furthermore, this result could be applied to the other three allocation methods studied (50/50, 50/50 quality-adjusted and CFF), given the LCA results are the same differing only by the allocation method each scenario adopted.

3.2. Allocation Method's Effects on the LCA Results

From the LCA results obtained for each scenario the GWP and CED results were recalculated using the allocation methods described in Section 2.2 and are introduced in Figures 5 and 6, respectively.

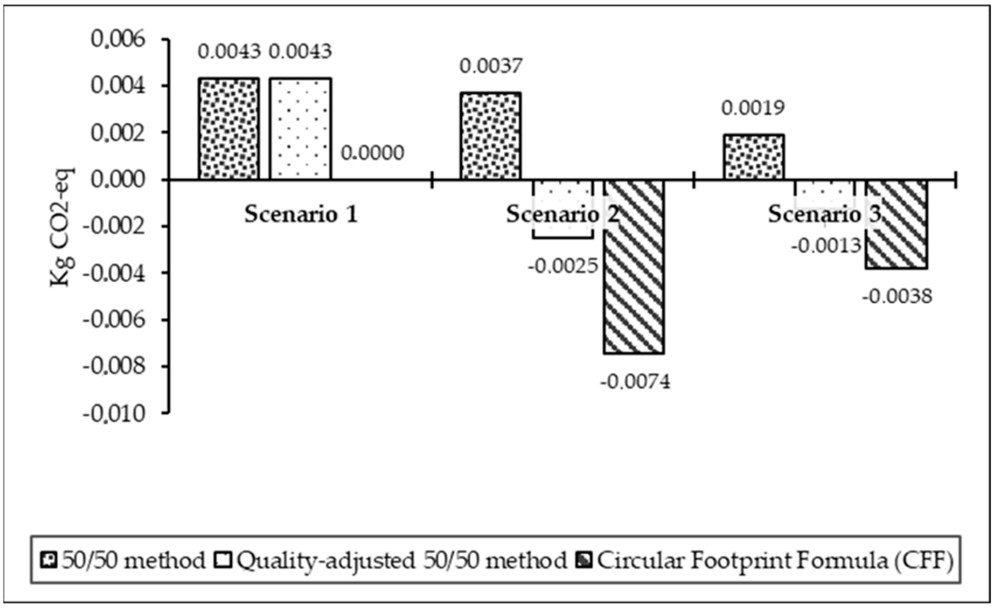

Figure 5. Comparison of GWP results per FU using different allocation methods for each scenario.

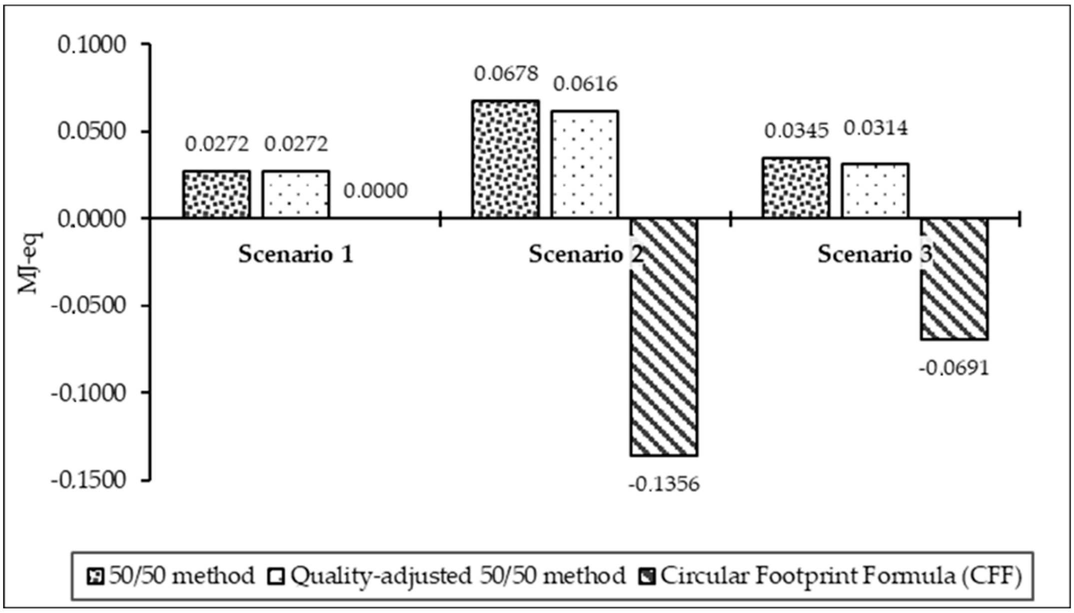

Figure 6. Comparison of CED results per FU using different allocation methods for each scenario.

Regarding the GWP results, Figure 5 shows Scenario 1 standing as the most impactful scenario for all the allocation methods. The results from the 50/50 method and 50/50 Quality-adjusted methods application were 0.0043 kg of CO_2-eq. per FU, similarly to the original results of the LCA study in Figure 4. This behavior was also noted in the CED results, as both the 50/50 method and the 50/50 Quality-adjusted method demanded the same amount of energy (i.e., 0.0272 MJ per FU). It implies the equivalence of these two allocation methods when applied to biological cycles from virgin materials, as the value of R2 (the rate of recycling of material after use in the product) is null for both cases (see Table 2 again).

The results variation from Scenario 2 to Scenario 3 had the same proportion for all the allocation methods in the two impact categories (GWP and CED). Scenario 2 had approximately twice the impact values of Scenario 3, even for the negative values. This can be explained due to the similarity between these scenarios related to wood waste briquettes production, which only differ by their LHV. For Scenario 2 the amount of wood waste used to manufacture the briquette is almost twice the wood needed for Scenario 3, varying the impacts in the same proportion.

The incidence of negative values on the CFF results for Scenarios 2 and 3 points to the avoided CO_2 emissions and energy demanded by the obtention of 1 MJ of energy from briquettes. This is a consequence of the avoidance of resource consumption per FU. These resources would have arisen from the specific substituted energy source considered (Eseheat), in this case, virgin wood from Eucalyptus. This phenomenon is also observed in Scenario 2 for the quality-adjusted 50/50 method (Figure 5), as the requirement of a higher amount of biomass implies the avoidance of more residual wood going to landfills. The use of CFF for other biological-based systems revealed that its application to renewable Low-Density Polyethylene (LDPE) could also create an incorrect climate incentive for incineration since the recovered energy substitutes energy sources for up to 300% more climate impact. However, it can be corrected by using an allocation factor for incineration [20].

The environmental burdens avoided through the recycling process (Ed*) increased and, since this parameter subtracts the impacts from the recycling process (Erin), it incurred a negative result only in Scenario 2. Once Scenario 3 considers a final briquette with a higher LHV compared to Scenario 2, it demands less biomass to generate the same 1 MJ of energy used per FU. This fact reduces the avoided burdens from the landfilling process, and consequently, generates results in smaller absolute values. A similar explanation can be addressed to CED results calculated by the quality-adjusted 50/50 method (see Figure 5), as the sum of values for Erin and Ev surpasses the Ed*.

It is also important to highlight the null results on both impact categories calculated with the CFF method in Scenario 1. The reason for these results is the fact that the burdens from the production of virgin material (Ev) are compensated by the benefits of energy recovery from this material at end-of-life.

These recycling methods are considered good for technical cycles, although they seem to have some gaps in the evaluation of bioenergy. To cut down on waste and using resources in agriculture, [52] recommend some closing resource loop circular indicators. Also [53] found the Cascade Factor (CF) as a potential circularity indicator for assessing biological cycles since it can either be used on full systems or in separate sectors, covering all the life cycle stages of a product and considering both closed and open-loop energy recovery of post-consumer residues. However, further studies need to be carried out to evaluate the feasibility of this application in solid biofuels.

3.3. Managerial/Policy Implications

What should be done to properly apply an energy recovery LCA method in the context of solid bioenergy (briquettes)? Some relevant research implications can be summarized:

General aspects of energy recovery methods for biological systems: this is a prominent issue in CE studies. However, the same cannot be said about energy recovery in biological cycles [52] because all the evaluated methods in this case study fail in some aspects. Other relevant issues should be addressed in the biological system instead of only the mass of allocated materials or energy. The CFF formula is the most complex of the evaluated methods, but even though some relevant issues in energy recovery are missing it has an essential role in bioenergy.

Opportunities for CFF and related literature: the CFF and other related indicators evaluate circularity under the same baseline—with physical and biochemical issues unseparated, and with much more focus on the physical flow. For biological processes, this can be seen as a limitation because some important issues are not addressed according to [24], such as the potential cascading effects, renewability (to regenerate environment), and biodegradability (nutrient cycles). The results discussed for the briquettes case study showed negative values regarding the CFF for Scenarios 2 and 3 and negative impacts for Scenario 2 in the quality-adjusted 50/50 method (Figure 5). This is related to the avoidance of resource consumption (wood) per FU, although the biochemical implications of briquettes adoption are not covered by the energy recovery methods under study. Therefore, the CFF and other methods directly depend on the mass of resource consumption made available in the inventory to produce briquettes (Table 1). A clear opportunity for the case of biofuels would be to expand the circularity analysis by including, in a separate analysis, the biochemical parameters for the product system such as cascading effects of biomass [53], and water balance (that affect biomass quality and LHV, for example). The current version of the CFF does not clearly evaluate these criteria. Therefore, circularity in biological processes would be valuable if the following set of criteria were developed (Equation (4)):

$$\text{Circularity} = \text{f (Physical flows; Biochemical flows)} \quad (4)$$

where,

- Physical flows could be determined by the total mass of recovered resources in the system based on cascading use of resources. This can be evaluated based on the use of indicators such as the (CF) [53] and other mass-related circular indexes.
- Biochemical flows should be based on the renewability and biodegradability of the resources in the investigated system, and for the biomass briquettes, some relevant issues to be covered are carbon cycle and water balance. Trees and other renewable resources can provide carbon sequestration and contribute to air quality regulation and water provisioning [54]. Therefore, we may consider such resources performing ecosystem restoration in the biological cycle of Circular Bioeconomy systems. Other examples of biochemical flows would be chemical balances for food and feed-based products, where nutrient cycles might have an essential role in the system's circularity performance.

A clear procedure for the implementation of Equation (4) should be developed, although the total circularity is a function of the physical and biochemical flows. The CFF, for example, has more than 10 parameters (Table 2), but all of them are focused on the physical flows and not analyzing, in a specific pathway, the biochemical flows of the biological cycle. The remaining recycling methods studied are in line with technical cycles but also fail in terms of biochemical flows for biological cycles. A more concise integration of CE with LCA is necessary to advance this topic from a broader perspective. Ref. [55] revealed that circularity indicators assume at some level the need to use circular inputs, recovered materials, and extending life span as relevant parameters. But this is not enough for biological systems where the biochemical flows may be the most determinant factors towards a more circular system [24,52].

Ecosystems have potential to supply a range of services that are of fundamental importance to human well-being, health, livelihoods, and survival [56]. Ecosystem Services (ES) can be defined as contributions of ecosystem structure and function (in combination with other inputs) to human well-being [57]. The biochemical flows in a circularity analysis should follow an ES perspective as the biological cycle maintains the ecosystem's capability of providing goods/services for supporting human life [58–60]. We recommend an analysis of the demand and supply of ES for a possible new version of the CFF application. An interesting approach for this is based on the techno-ecological synergy theory proposed by [54] and combined with LCA to perform a case study for ethanol biofuel. We believe that Equation (5) could be used combined with CFF results.

$$\text{Net circularity performance} = (S - E)/E \quad (5)$$

in which, the net circularity performance is a function of two main parameters, 'S' representing the biochemical flows, and 'E' the physical flows. 'S' is the natural supply of relevant ES (e.g., carbon sequestration, water provisioning, and others) for a product system's boundaries. 'E' represents the environmental burdens due to human activities, as previously calculated by Equation (3). Also, it is important to understand that ES representing 'S' are subjected to the same product system limited by Figure 2 to calculate 'E'. Through a cascade model, 'S' and 'E' can be accounted for as suggested by [61], while [62] address the valuation of 'S' considering the CICES© taxonomy for the categories of provisioning of resources and regulation & maintenance of climate.

This metric indicates a possible application of the concept of Equation (4) correlating the CFF within an analysis of the ecosystem's carrying capacity to obtain a net circularity performance indicator. However, it should be noted that the integration of an ES approach in LCA is not easy to put into practice because of the lack of ES in conventional LCA databases [54,61]. Also, it is important to consider the inclusion of other complementary methodologies to LCA, such as the CFF. Furthermore, in the context of bioproducts, the different methodologies can lead to conflicting results, influencing decision-making in opposing directions [63]. However, we understand that by combining CFF with process LCA and ES in a framework, this could lead to results that can bring more circular business models.

It is essential to mention that our case study can be generalized to other companies/products where energy recovery in biofuels is a key issue, especially when calculating circularity considering not only the mass of materials and energy but also the biochemical implications in terms of carbon and water balances, for example. Finally, the novelty of Equation (5) is the use of the CFF result as 'E'. A strong net circularity indicator would result if ≥ 0.

In terms of policy implications for circular business models, the use of Equation (5) (combined with CFF results) could be seen as a relevant input for environmental product declarations or climate declarations/policy developments because the current general rules do not consider such metrics. For example, the natural supply of ES is today not part of the general programme instructions in the international EPD® system [64], one of the most well-known environmental declaration programmes/initiatives. Environmental declarations are important market instruments for seeking harmonization in the environmental footprint of product communication on the international market.

4. Conclusions and Recommendations

This study focused on the evaluation and comparison of the CFF, the 50/50 method, and the quality-adjusted 50/50 method in a Circular Bioeconomy case study, considering the environmental performance of biomass briquettes in Brazil. The results revealed a difference between the LCA results depending on the amount and source of biomass. GWP results showed the highest impacts when using dedicated wood as raw material. On the other hand, the highest results for CED were observed for the scenario of wood waste with a smaller LHV, and due to the energy demanded (avoided) from dedicated and secondary wood treatment in landfills. Regarding the allocation methods' effects on the LCA results, the application of both 50/50 methods acquired similar results, implying the equivalence between these methods. Otherwise, the null CFF results mean that in the case of solid biofuels from dedicated wood, the burdens from the virgin material supply (E_v) are nullified by the benefits of energy recovery from this material at end-of-life.

An important issue to be highlighted is the complexity of applying CFF when compared to the other allocation methods, since it involves multiple parameters regarding material quality, marketing behavior, etc. It is worth mentioning that, for energy-based FUs, the CFF's portion which represents energy recovery processes (fourth summand) must be converted from a massic-based expression to an energy-based expression, in order to avoid a double count of the material LHV, as well as a dimensional flaw.

Among the evaluated methods, the CFF was the most comprehensive LCA allocation method for evaluating the environmental performance of biomass briquettes. However, in the context of solid biofuels, there are still some important issues to be covered, specifically in biological cycles. The carbon and water balances and ES are not contemplated by the CFF and any of the remaining compared methods. Furthermore, as stated by [25], the CFF does not consider the waste disposal avoided by energy recovery. In this sense, a set of circular criteria for physical and biochemical flows (Equation (4)) which include an analysis of the demand and supply of ES (Equation (5)) could be used combined with the CFF results to obtain a net circularity performance indicator. The circular biochemical flow integration would be important to enhance more knowledge in the Circular Bioeconomy field.

It is worth highlighting that this paper is not free of assumptions and limitations, that could be overcome in future research, which should also: (i) verify the effects of the allocation methods applied to solid biofuels from different biomass sources (i.e., peanut bark, coconut shell, rice husk, sugarcane bagasse, etc.); (ii) test other energy recovery allocation methods, including Equation (5); and (iii) switch the solid biofuel to pellets and other concurrent biofuels (charcoal).

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