Sustainable Engineering Management based on Absolute Environmental Sustainability Theory for Addressing Climate Change and Particulate Matter Formation Impacts in Solid Biofuels Production

Gabriela Giusti[1][0000-0002-8513-8353], Antonio Carlos Farrapo Junior[1][0000-0002-9150-2959], Eduardo Vieira de Campos[1][0009-0001-1480-8153], Yara de Souza Tadano[2][0000-0002-3975-3419], Diogo Aparecido Lopes Silva[1][0000-0002-7514-7467]

[1] Research Group on Sustainability Engineering, Federal University of São Carlos, João Leme dos Santos Highway, SP-264, km 110, Itinga, Sorocaba, SP, 18052-780, Brazil
[2] Federal University of Technology - Paraná, Doutor Washington Subtil Street, number 330, Jardim Carvalho, Ponta Grossa, PR, 84017-220, Brazil
gabriela.giusti@hotmail.com.br

Abstract. There has been a recent growth in global demand for low-carbon energy resources, such as solid biofuels, replacing their petroleum-based equivalents in industry. However, there is a gap about the absolute sustainability theory applied to the operations management of these energy systems. This research aimed to assess the Absolute Sustainability Rate (ASR) of five Brazilian solid biofuel systems: eucalyptus charcoal briquettes (S1), urban pruning briquettes (S2), eucalyptus residual wood pellets (S3), peanut residues pellets (S4), and pinus residual wood pellets (S5). The methodology approach combined Life Cycle Assessment with Planetary Boundaries, allocating the global safe operating space for production systems, and calculating the ASR focusing on climate change and health effects due to particulate matter. System S5 was the only absolutely sustainable for both assessed impacts, especially due to CO_2 absorption of land use change and energy co-generation. Conversely, S1 was not sustainable for none of the environmental categories, particularly due to the impacts of charcoal production. The study concluded that renewable energy sources are not necessarily absolutely sustainable, but can provide various environmental benefits when compared to equivalent fossil sources. The ASR results, focusing on climate change, highlighted the economic potential of these systems in the global carbon market. However, mitigating actions are relevant to avoid impacts in other categories, such as effects on population health. The ASR indicator and its methodology adopted by this paper can be expanded to promote more sustainable engineering management in the energy and other relevant industrial sectors in Brazil.

Keywords: Planetary boundaries, Biomass, Sustainable Engineering.

1 Introduction

It is estimated that the world population will reach around nine billion inhabitants by 2030 [1], increasing the pressure on the environment due to a higher demand for food, water, mineral, and energy resources. Simultaneously, in recent years, there has been an exponential growth in global demand for low-carbon energy resources, such as biomass, replacing their petroleum-based equivalents due to their lower pollutant emissions [2]. Brazil, privileged with various favorable environmental characteristics, holds significant potential for the production of plant biomass, that can be used for the production of densified biofuels in the form of pellets and briquettes [3], [4], [5].

Pellets and briquettes, typically produced through drying, grinding, and densification industrial processes of agroforestry residues (such as sawdust, bark, sugarcane bagasse, etc.)[4], [5], constitute an effective strategy to mitigate undesirable characteristics of agro-industrial by-products, such as low density, reduced calorific value, and irregular shape [6]. According to data from the Brazilian Pellet Industry, in 2022, 66 pellet industries were in operation, with a significant concentration in the Southern region of the country and a total production of 1,550,000 tons for the year (3.33% of the global market), representing an increase of nearly 50% compared to the 1,080,000 tons produced in 2021[7].

However, the combustion of solid biofuels results in the emission of Greenhouse Gases (GHGs) and other atmospheric pollutants, such as Particulate Matter (PM) and its precursors (SO_2, NH_3, NO_x)[8]. These emissions are relevant in the context of environmental preservation and human health, as GHGs can contribute to climate change, and particles can be inhaled by the population, with the potential to cause various health effects, especially cardiorespiratory diseases [9]. In addition to the combustion stage, other phases of the life cycle of densified biofuels have the potential for GHG and PM emissions, such as agricultural, densification, and transportation processes [10].

In this context, the Life Cycle Assessment (LCA) tool can assist in the quantification and management of ecosystem and human health impacts associated with the solid biofuel production chains [4], [11]. The primary advantage of this environmental impact assessment tool is its comprehensiveness, allowing access to the environmental impacts and aspects of all phases of a product's life cycle, from raw material acquisition to recycling or final disposal, depending on the desired scope of application [12], [13]. These characteristics of LCA are crucial for a comprehensive understanding of the diverse impacts of densified biomass, especially considering that, in 2018, the Brazilian agro-industrial sector, the supplier of inputs for pellet and briquette manufacturing, for example, has accounted for over 40% of the national CO_2 eq. emissions and more than 30% of the national kilo-DALY (Disability Adjusted Life Years) that is the impact indicator for human health effects due to PM emissions [14].

Despite the relevance of LCA, few studies worldwide focus on sustainable engineering applied to pellets and briquettes as case studies [4], [15]. Recently, [2] conducted a comparative analysis of the transportation choices for solid biofuels exported from Latin American Countries to Europe. Their study unveiled a notable impact linked to the consumption of petroleum-derived fuels in maritime and road transport. However, the authors refrained from evaluating whether these systems operate within the bounds of Absolute environmental Sustainability (AeS), prompting the question: " Are renewable systems necessarily absolute sustainable?"

The concept of AeS, which aligns with the idea of the Safe Operating Space allocated to systems (allocated SoSOS) is based on the Planetary Boundaries (PB) concept and refers to a state in which human activities are conducted in a manner that does not cause irreversible harm to the environment [16], [17]. This means that the management and production practices and processes should be capable of sustaining natural resources, ecological systems and human health over the long term, without compromising the ability of future generations to meet their own needs [18].

There remains a noticeable gap in the number of studies addressing AeS topics yet, particularly within emerging economies such as in Brazil. Therefore, this study aims to address the gap in knowledge by investigating the AeS of Brazilian solid biofuels (pellets and briquettes) production, with a particular focus on mitigating climate change and health effects due to PM formation, which are relevant impact categories for biofuel systems as a whole.

2 Materials and methods

In this research, Absolute Environmental Sustainability Rates (ASRs) indicators were evaluated with a focus on climate change and health effects due to PM from five Brazilian solid biofuel production systems. The annual impact of the five systems was calculated through LCA methodology, while the allocated SoSOS was determined by allocating the planetary boundaries to the system level, as detailed in sections 2.1 and 2.2, respectively.

2.1 Life Cycle Assessment of biomass pellets and briquettes

The LCA methodology can be divided into four stages [12], [13]: Goal and scope definition; Life cycle inventory analysis (LCI); Life Cycle Impact Assessment (LCIA); and interpretation, as detailed in the next subsections.

Goal and scope definition

Five Brazilian solid biofuel systems were analyzed, including eucalyptus charcoal briquettes (S1), urban pruning briquettes (S2), eucalyptus residual wood pellets (S3), peanut residues pellets (S4), and pinus residual wood pellets (S5). Each of the case studies of solid biofuel producers is situated in five distinct Brazilian states: Minas Gerais, Paraíba, Santa Catarina, São Paulo, and Paraná. These cities correspond to Sete Lagoas, João Pessoa, Lages, Itaju, and Telemaco Borba, respectively.

The choice of these five distinct cases was made because they are representative at the country level (five different Brazilian states), and also because the biomass comes from distinct sources, and is produced under different conditions. The systems were analyzed from cradle-to-gate based on the data collected by [2]. The Functional Unit (FU) was restricted to producing 1 MJ of energy from pellets/briquettes. According to the energy efficiency conversion on the Lower Heating Value (LHV) of each kind of biomass, Table 1 summarizes the cases, geographical scope, biomass supply, LHV sources, and annual plant production estimations.

Table 1. Scope definition for each case study analyzed

	Cases	**City/State**	**Final Product**	**Biomass source**	**LHV* kg/MJ**	**LHV* source**	**Annual production (ton/year)**
S1	Charcoal Briquettes	Sete Lagoas/MG	Briquettes	Eucalyptus charcoal	0.0633	[2]	6.000**
S2	Residual Briquettes	João Pessoa/PB	Briquettes	Urban pruning waste	0.0531	[19]	6.000**
S3	Eucalyptus wood Pellets	Lages/SC	Pellets	Eucalyptus residual wood	0.0633	[2]	9.000
S4	Peanut shell Pellets	Itaju/SP	Pellets	Peanut shell and barks	0.0584	[20]	6.000
S5	Pinus wood Pellets	Telemaco Borba/PR	Pellets	Pinus residual wood	0.0531	[2]	60.000

*LHV = Lower Heating Value

** Annual production estimative based on a medium-sized plant according to data from [7]

The main goal of the LCA was to obtain the potential impact of each system on climate change and health effects due to PM formation, to measure the actual impact of these systems, and then to calculate the ASR.

Life cycle inventory

The inventory data for the pelletizing and briquetting processes was taken from the Brazilian cases of previous research [2], considering cradle-to-gate system boundaries, which means that the transport activities were not included. Pelletization and briquetting are processes used to convert biomass into more convenient and uniform forms for transportation, handling, and storage [4]. In pelletization, biomass materials are ground into a fine powder and then compressed into small, cylindrical pellets under high pressure. This process typically involves the use of a pellet mill, where the biomass powder is forced through small holes in a die to form the pellets. The heat generated during compression can help bind the biomass particles together, creating durable pellets [21]. Briquetting, on the other hand, involves compacting biomass materials into larger, denser briquettes. This is typically achieved using a briquetting machine, where the biomass is compressed under high pressure without the need for a binder [22]. The resulting briquettes are larger and more robust than pellets, making them suitable for applications where durability is important [23].

The comparative cradle-to-gate systems included background LCA datasets such as electricity, water, thermal energy supplies, transport activities, and biomass supplies. It is also important to highlight that for the biomass supply, all cases considered the use of residual biomass as a co-product instead of biomass from energetic crops. The LCI data can be accessed in the previous research by [2].

Life cycle Impact Assessment

The LCI data obtained by [2] were modeled using OpenLCA software version 1.11, utilizing the ecoinvent database version 3.7. After the modeling, the software assisted in the LCIA stage. According to [12], [13], LCIA involves three mandatory steps: selection of the impact category, classification, and characterization. Classification is based on identifying elementary flows that cause an impact in the analyzed category, while characterization involves multiplying these elementary flows by their respective characterization factors. Characterization factors are obtained through characterization models, allowing them to be converted into a common impact indicator for the category of interest [24].

For the climate change impact category, the literature supports the use of characterization factors developed by the Intergovernmental Panel on Climate Change (IPCC), so the choice of the method is not likely to generate significant changes in impact results [25], [26]. Thus, the impacts of climate change were obtained in [4], which utilized the ReCiPe 2016 v. 1.03 hierarchic midpoint method in the LCIA stage.

On the other hand, for the health effects due to the PM formation category, [24] recommends the use of regionalized characterization factors that reflect the climate conditions of the location where emissions occur. Specifically for Brazil, [27] concluded that the characterization models provided by [28], [29], [30] are the most recommended for application in LCA case studies in the country. However, [31] recently noted that the use of one model or the other can lead to significant variations in impact results. Therefore, both models were applied in this research to assess the sensitivity of the LCA results to the choice of characterization model for this impact category. The models work with global average factors and regionalized factors for Brazil. Additionally, [28] provides factors at the state level, and [29], [30] at the municipal level in Brazil. Impact results were obtained considering the different levels of regionalization available in the selected characterization models. For comparison purposes, the global average factors from the [32] recommendation were also applied.

Since [28], [29] and [30] models are not available in LCA software or LCIA methods, the calculations were conducted in Excel spreadsheets, identifying emissions of ammonia (NH_3), nitrogen oxides (NO_x), sulfur dioxide (SO_2), and primary PM. [29], [30] and the [32] recommendations provide separate factors for emissions in areas of high and low population density. [29] and [30] only provide factors for primary PM, thus secondary PM emissions (NH_3, NO_x, and SO_2) had a null impact. The methodological procedure developed here was similar to that carried out by [31].

In the end, these factors for each impact category are used in the total quantification of the impact potential, in general, through Equation 1:

$$\mathrm{I}_k = \sum_{\mathrm{i}} (\mathrm{CF}_{\mathrm{i,c,k}} \times \mathrm{E}_{\mathrm{i,c}}) \tag{1}$$

Where:

I_k – Impact potential of k category;

$\mathrm{CF}_{\mathrm{i,c,k}}$ – Characterization factor of substance i emitted to compartment c for impact category k;

$\mathrm{E}_{\mathrm{i,c}}$ – Flow registered in the LCI, that is, emission of substance i to compartment c.

Interpretation

In the interpretation stage, the production system results were compared to each other, and the main hotspots of each system were identified. Additionally, the sensitivity of impact results to the choice of characterization method for PM formation was analyzed. Finally, the results were used to calculate the ASR indicator, as described in section 2.2.

2.2 Absolute Sustainability Rate

The ASR indicates whether the actual system's impact achieves the allocated SoSOS for specific impact category k. Thus, if the ratio between the actual system impact and the allocated $\mathrm{SoSOS}_\mathrm{k}$ is less than or equal to 1, it is concluded that the system is absolutely sustainable. If it is greater than 1, the interpretation is that the system is not absolutely sustainable (Equation 2).

$$\mathrm{ASR_k} = \frac{\mathrm{I_k}}{\mathrm{allocated\ SoSOS_k}} \tag{2}$$

The impact results of the five systems were obtained through LCA for climate change and health effects due to PM formation (section 2.1). For the calculation of the allocated $\mathrm{SoSOS_k}$, the allocation of planetary boundaries to the system level was performed using the downscaling-upscaling approach of [38]. Downscaling involves calculating individual SoSOS for category k ($\mathrm{SoSOS_{k,ind}}$, in impact indicator/person/year), and in this study, the per capita equality principle was applied, where the planetary boundary is equally divided among the global population, considering that everyone has an equal right to the operational space. Upscaling, on the other hand, involves increasing the $\mathrm{SoSOS_{k,ind}}$ to the system-level $\mathrm{SoSOS_{k,s}}$ ($\mathrm{SoSOS_{k,s}}$, in impact indicator/system/year). To achieve this, the individual SoSOS was initially expanded to the level of Brazil considering the country's population size ($\mathrm{POP_{BR}}$, in number of people), then to the energy sector level considering the representation of the sector's GDP (Gross Domestic Product) ($\mathrm{GDP_s}$, in dollars) relative to the national GDP ($\mathrm{GDP_{BR}}$, in dollars), and finally to the system level considering the representation of the energy supply of the systems ($\mathrm{ES_s}$, in MJ) relative to the national supply ($\mathrm{ES_{BR}}$, in MJ). Equation 3 presents the formula used to calculate the allocated SoSOS.

$$\mathrm{allocated\ SoSOS_k} \ = \ \mathrm{SoSOS_{k,ind}} \times \ \mathrm{POP_{BR}} \times \frac{\mathrm{GDP_S}}{\mathrm{GDP_{BR}}} \times \frac{\mathrm{ES_S}}{\mathrm{ES_{BR}}} \tag{3}$$

The variables $\mathrm{POP_{BR}}$, $\mathrm{GDP_s}$, $\mathrm{GDP_{BR}}$, and $\mathrm{ES_{BR}}$ were constant for all systems and for the planetary boundaries of climate change and health effects due to PM. The data used are for the year 2019, which corresponds to the temporal scope of the system's LCA [2]. The variable $\mathrm{ES_s}$ varied according to the production system and is presented in Table 1. Finally, the variable $\mathrm{SoSOS_{k,ind}}$ varied according to the assessed planetary boundary. Table 2 presents the utilized data and the source of information.

Table 2. Data used to calculate allocated SoSOS

Parameter	**Value**	**Unit**	**Source**
$\mathrm{POP_{BR}}$	210,147,125	capita	[33]
$\mathrm{GDP_s}$	137,302,000,000	US$/year	[33]
$\mathrm{GDP_{BR}}$	2,995,500,000,000	US$/year	[33]
$\mathrm{ES_{BR}}$	12,371,994,000,000	MJ/Brazil/year	[33]
$\mathrm{SoSOS_{CC,ind}}$	522	kg CO2/person/year	[34]
$\mathrm{SoSOS_{PM,ind}}$	1.6×10^{-3}	DALY/person/year	[35]

Legend: CC – climate change; PM – particulate matter

Finally, ASR indicator (Equation 2) is used as a final decision-making measure on the more sustainable compared systems.

3 Results and discussion

3.1 Life Cycle Assessment

The LCA results (Table 4) indicated that the S4 system (peanut residues) exhibited the lowest potential impact for climate change and the second lowest impact for health effects due to PM emissions, surpassed only by the S5 system (pinus wood residues). On the other extreme, the S1 system (eucalyptus charcoal) demonstrated the highest potential impact for both analyzed categories.

Table 3. System's potential impacts for climate change (CC) and human health due to particulate matter (PM) calculated with the recommended models for Brazil

Impact Category	LCIA Model	Unit/MJ	S1	S2	S3	S4	S5
CC	ReCiPe 2016	kg CO_2 eq.	1.10×10^{-1}	-3.59×10^{-2}	-3.01×10^{-2}	-2.30×10^{-1}	-3.05×10^{-4}
PM	Ober. Global	DALY	1.80×10^{-6}	1.41×10^{-7}	3.64×10^{-7}	4.95×10^{-9}	8.25×10^{-11}
PM	Ober. Brazil	DALY	3.94×10^{-6}	3.29×10^{-7}	7.81×10^{-7}	1.41E-08	1.80×10^{-10}
PM	Ober. State	DALY	9.51×10^{-6}	4.06×10^{-7}	2.07×10^{-6}	1.11×10^{-7}	5.15×10^{-10}
PM	Fan. Global	DALY	1.93×10^{-5}	2.67×10^{-6}	7.99×10^{-6}	8.37×10^{-9}	1.71×10^{-9}
PM	Fan. Brazil	DALY	1.23×10^{-5}	2.08×10^{-6}	6.23×10^{-6}	1.49×10^{-9}	1.32×10^{-9}
PM	Fan. City	DALY	4.58×10^{-6}	2.24×10^{-7}	2.68×10^{-6}	1.69×10^{-9}	5.68×10^{-10}
PM	Fri. Global	DALY	1.60×10^{-5}	2.28×10^{-6}	6.51×10^{-6}	4.97×10^{-9}	1.28×10^{-9}

Legend – Impact category: CC = climate change; PM = particulate matter

Legend – LCIA Model: Ober = Oberschelp et al. [28]; Fan = Fantke et al. [29], [30]; Fri = Frischknecht and Jolliet [32]

Legend - Color scale: 🟥 Most impactful 🟧 🟨 🟩 🟩 Least impactful

Specifically for climate change impacts, Table 3 indicated that systems S2 (urban pruning briquettes), S3 (wood pellets), S4 (peanut residue pellets), and S5 (pinus wood residue pellets) had negative impacts, which mean positive effects in the environment, suggesting that during their life cycles (cradle-to-gate), these products have the potential to sequester more GHGs than they emit. According to [2], the carbon stock resulting from LUC (Land Use Change) processes during biomass production is the main reason for the negative impacts in the mentioned systems. This is observed in places where LUC shifts from a cultivation that stores less carbon in the soil to one that stores more carbon, resulting in carbon capture from the atmosphere. On the other hand, the authors discuss that the higher impact of S1 is a result of the high consumption of fossil fuels in the production chain.

Regarding health effects due to PM emissions, despite significant differences between total impacts obtained with different characterization models and their various regional levels (reaching up to a 65 times difference in S4), the system ranking remained consistent. System S1 had the highest potential impact for the category, followed by systems S3, S2, S4, and S5, respectively. Scenario S1 showed an impact on average 14,758 times higher than scenario S5. For this impact category, no environmental benefits were identified by the LCA, with all impacts being positive.

The emissions inventory analysis of PM and precursor gases revealed that S1 had the highest emission rate for all substances of interest (primary $PM_{2.5}$, NO_x, NH_3, and SO_2), averaging 26,670 times higher than emissions from S5, which had the lowest potential impact. These emissions from S1 are primarily associated with biomass production, involving a wood carbonization process for charcoal generation, along with electricity consumption (derived from natural gas), heat, and transportation activities in the production process. For all evaluated systems, biomass production was the primary hotspot for PM impacts, especially due to energy consumption (electricity, heat, fossil fuels) and the demand for agricultural and transportation processes. The lower impact observed for systems S4 and S5 was mainly associated with the energy co-generation employed in these systems, utilizing part of the biomass supplied as raw material, thereby offsetting the electricity demand from the grid electricity in the system.

3.2 Absolute Sustainability Rate

The SoSOS allocated to systems focusing on climate change was 4.06×10^{-4} kg CO_2 eq./system/year. The ASR results for this environmental impact (Figure 1) show that, except for S1, all systems are operating within the allocated SoSOS, rendering them absolutely sustainable. This result was expected since climate change impacts were negative for scenarios S2, S3, S4, and S5, indicating that although there are elementary processes emitting GHGs and consuming part of the allocated SoSOS for these systems, CO_2 absorption from LUC compensates the emissions and generates environmental benefits.

On the other hand, the climate change impact of S1 exceeded the allocated SoSOS for the system, resulting in an ASR of 270.64. This outcome suggests that despite the renewable source of biomass in S1, the system is not absolutely sustainable. To operate within the allocated SoSOS, S1 must significantly mitigate its climate change impacts to reduce the current impact by 270 times. Mitigating actions should primarily focus on reducing the fossil fuel consumption of this system, identified as the main hotspot.

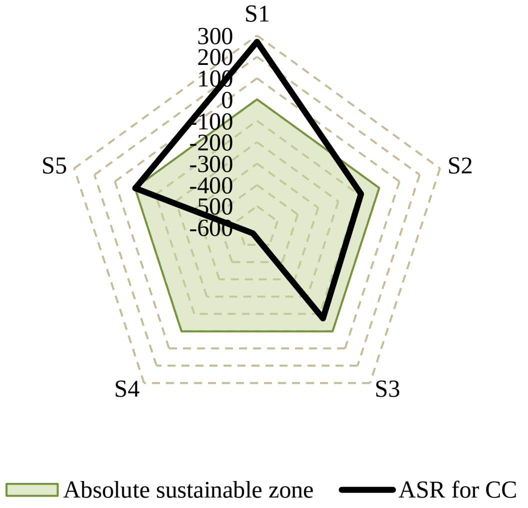

Fig. 1. Absolute Sustainable Rate (ASR) focused on Climate Change (CC) impacts

Despite the good environmental performance of four out of the five evaluated systems regarding climate change impacts, the ASR results focusing on health effects due to PM show that only S5 was operating within the allocated SoSOS (Figure 2). S4, on the other hand, surpasses the allocated SoSOS regardless of the characterization model used for impact calculation. However, changing the model results, the ASR ranging from 1.2 (municipal factors from the [29], [30] models) to 89.1 (state factors from the [28] model). The other three systems (S1, S2, and S3) present considerably higher ASRs than 1, regardless of the characterization model used in impact calculation, suggesting that despite the use of renewable sources, these systems cannot be considered absolutely sustainable concerning their potential to damage human health.

The allocated SoSOS for systems focusing on PM-associated impacts was 1.24×10^{-9} DALY/system/year. Thus, to become absolutely sustainable, solid biofuels must reduce their impacts on average by S1 - 7744 times; S2 - 933.7 times; S3 - 3056 times; and S4 - 16.8 times. This analysis indicates that systems S1, S2, and S3 are far from operating within a safe operating space, and mitigation measures need to be considered to make these systems more environmentally attractive. It is also noteworthy that, from a human health perspective, prioritizing systems S4 and S5 is advisable. Based on these results, the adoption of energy co-generation could be a viable practice for improving the impacts of systems S1, S2, and S3, as it was one of the main positive highlights of systems S4 and S5.

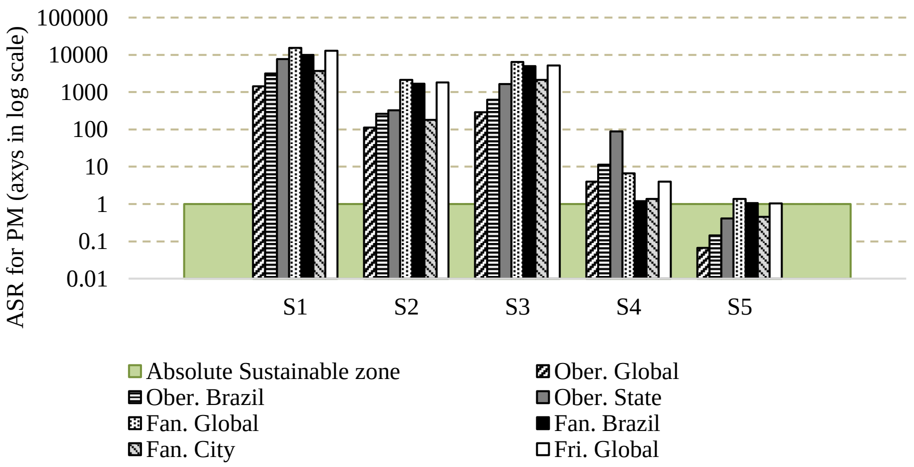

Fig. 2. Absolute sustainable rate focused on health effects due to PM impacts calculated using

the recommended models for Brazil (legend: Ober = Oberschelp et al. [28]; Fan = Fantke et al. [29], [30]; Fri = Frischknecht and Jolliet [32]

Regarding the impacts of PM, it is still pertinent to discuss the sensitivity of choosing the characterization model and the level of regionalization of characterization factors concerning the ASR results. Overall, despite significant differences in impact results, the use of different models created minimal confusion in interpreting the absolute sustainability of the systems. For systems S1, S2, S3, and S4, regardless of the model used, the system operated outside the allocated SoSOS. However, for system S5, four sets of characterization factors (developed by [28] for global, national, and state level; developed by [29], [30] for municipal level) indicated that the system was absolutely sustainable, while the other three sets indicated that the system was not absolutely sustainable, despite resulting in an ASR very close to 1. Variations between the models mainly arise from differences in geographical scopes, the list of elementary flows covered by the models, and differences in characterization factors [31]. It is noteworthy that at the most regionalized level of characterization factors (municipal or state), the ASR of system S5 was below 1, which can be considered the least uncertain result, given that the recommendation for this category is the use of regionalized factors.

3.3 Discussion and research implications

The results of this research highlight that pellet and briquette production systems, despite being renewable and presenting various environmental benefits compared to equivalent fossil sources, are not necessarily sustainable in absolute terms, especially when health impacts associated with PM are included in the analysis.

Reviewing previous LCA studies on pellets and briquettes available in the literature, [4] emphasize that studies conducted in Brazil primarily focus on the impacts of climate change. The authors mapped a range of global warming impacts from 1.75 to 26.3 g CO_2 eq/MJ globally and a range of -38.8 to 28.1 g CO_2 eq/MJ for Latin America, with negative impacts mainly attributed to LUC. According to the authors, biomass production stands out as the primary hotspot for the three Brazilian systems studied. The findings of [4] align with those of [2], which supports the present research.

Similar to this research, [4] did not analyze the impacts associated with the transportation and use of biofuels. This limitation can affect the ASR results obtained in Section 3.2 because emissions of GHGs and PM from these life cycle stages remained unknown. Depending on their intensity, the potential impacts for the two evaluated categories could increase and, consequently, make the systems occupy a larger share of the allocated SoSOS.

In this context, it is pertinent to highlight the findings of [2] for the transportation (export) stage of solid biofuels. Emissions from this stage made the impact of the S5 system positive in the previous research, whereas, without transportation, this system has a negative impact (see Table 2). However, for the other production systems, transportation showed few influences on global warming impacts, with systems S2, S3, and S4 remaining with negative impacts. While the authors did not assess the PM impact category, transport activities are one of the main sources of anthropogenic emissions of PM and precursor gases[36], potentially substantially increasing health impacts.

Based on climate change impacts, [2], [4] argue that solid biofuels represent a significant opportunity for Brazil in the growing carbon market. The results of this research support this reflection, demonstrating that depending on the biomass used, solid biofuels not only reduce impacts compared to equivalent fossil fuels but also have significant potential to operate within their allocated SoSOS.

However, focusing solely on climate change impacts might be critical [37]. Health impact assessments already show that mitigating actions need to be studied for biofuels, and beyond these impacts, other categories need evaluation within the context of planetary boundaries to estimate the absolute sustainability of the system comprehensively.

It's important to emphasize that the allocation of SoSOS is a controversial task, with various approaches available in the literature [37], [38]. In this research, the principle of equal per capita was considered, wherein all individuals receive an equal share of the global operating space. However, [38] discusses the disadvantages of this approach, highlighting its simplicity and the fact that a fair division is not necessarily an equal one.

The authors propose two other approaches for downscaling (grandfathering and ability to pay) and a second option for upscaling (green incentive), that involves the concept of eco-efficiency of systems. Applying all approaches to case studies, [38] showed that ASR results are sensitive to this choice.

Finally, it is noteworthy that sustainability studies for Brazilian solid biofuel systems were not identified in the literature. In this regard, the studies by [40] and [39] are highlighted. [40] propose an approach for assessing the sustainability of biofuels based on planetary boundaries and including all three dimensions of sustainability (economic, environmental, and social). The authors apply the framework to case studies, detailing the charcoal case, showing that the system operates within the safe zone for climate change but exceeds the safe space for PM. The research does not use the downscaling-upscaling method and does not focus on LCA, making it not directly comparable to this study. [39], on the other hand, use an LCA – Planetary Boundary approach and three allocation principles to assess the absolute sustainability of sugarcane ethanol in the context of Argentina. According to their findings, all evaluated fuels (gasoline and gasoline blends with 12, 16, and 20% ethanol) exceed the allocated SoSOS, despite carbon emissions slightly reducing in scenarios considering biofuels. Thus, the findings of [40] and [39] support the evidence of this research that renewable systems are not necessarily sustainable, and the analysis in terms of absolute sustainability should be prioritized in decision-making toward advances in sustainable engineering.

4 Conclusion

Solid renewable biofuel systems are not necessarily sustainable in absolute terms. However, depending on the biomass, these systems present significant environmental benefits and can operate within allocated SoSOS for climate change and human health damage due to PM. In the cradle-to-gate perspective, of the five evaluated systems, pinus residual wood pellets were the only one absolutely sustainable in the face of both accessed environmental impacts, considering a robust sensitivity analysis to characterization models for PM impacts. On the other hand, the eucalyptus charcoal pellet system was the least sustainable in absolute terms.

Mitigation actions should be directed to the hotspots of biofuel systems, taking the pinus residual wood pellet system as an example. Thus, the use of biomass sources with a high capacity to sequester carbon in the soil and the adoption of co-generation of energy in biofuel production emerge as alternatives with the potential to improve the environmental profile of non-sustainable systems. Given the significant power of the Brazilian agricultural sector and the potential for reducing impacts in the energy sector through the production and use of solid biofuels, these systems prove to be opportune in the country's context, especially considering the economic potential associated with them through the growing global carbon credit market.

This study has limitations in terms of the number of environmental impacts accessed in the analysis of absolute sustainability and the lack of sensitivity analysis of SoSOS allocation principles. Additionally, production chains were assessed in the cradle-to-gate approach, disregarding the impacts of the use and transport phases of biofuels life cycle. Therefore, it is suggested that future research builds upon the significant findings of this study, addressing the highlighted limitations.

Financial support

This research was financially supported by the National Council for Scientific and Technological Development (CNPq - grant number 401237/2022-2, 303343/2022-2 and 201121/2022-0), the Coordination for the Improvement of Higher Education Personnel (CAPES) (Finance Code 001), and the São Paulo Research Foundation (FAPESP - grant number 2021/06685–1).

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