Evaluating Sustainability of Biodiesel production Chain

Rafael Batista Zortea[a], Vinícius Gonçalves Maciel[b*1], Jaylton Bonacina de Araujo[c], Rodrigo Trevisani Juchen[c], and Cássia Maria Lie Ugaya[d]

[a]*Sul Rio Grandense Federal Institute, IFSUL, Av. Piratini, 100, Zip Code: 93216-120, Sapucaia do Sul, Brazil*

[b]*Polytechnic School, Post-Graduation Program in Materials Engineering and Technology, Pontifical Catholic University of Rio Grande do Sul, Porto Alegre, Brazil*

[c]*Gyro Center of Life Cycle Sustainability Assessment, Federal University of Technology, UFTPR, Curitiba, Brazil*

[d]*Federal University of Technology- Paraná, UTFPR, Brazil, CNPq fellow*

Corresponding Author*

Gonçalves Maciel V
Polytechnic School, Post-Graduation Program in Materials Engineering and Technology, Pontifical Catholic University of Rio Grande do Sul, Porto Alegre, Brazil
E-mail: *vinicius.maciel@ufrgs.br

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Abstract

This work provides an evaluating of the life cycle sustainability of biodiesel from soybean in Southern Brazil, one of Brazil's most important production regions of biodiesel and soybean. Life cycle approach and Dashboard of Sustainability (DoS) were applied to identify the hotspots gathering social, environmental and economic dimensions with the intention to obtain a sustainability factor index (SFI). Primary and secondary data were collected (specific and generic) covering all biodiesel soybean factories in Southern Brazil. Three environmental impact categories, three types of costs and four stakeholders were assessed. The results suggest that biodiesel production presented the most positive contribution to the economic dimension among all stages and that transportation had the worst value in all sustainability dimensions. In terms of the biodiesel production chain, the most critical impacts were acidification for environmental, supply costs for economic and the stakeholders' local community/society (together) for social. Also, issues associated with energy sources, feedstock improvements and shortening distances are key factors that could contribute to the overall sustainability of soybean biodiesel chain. There are opportunities for improving the environmental and economic dimensions together in industrial stage from methanol and electricity. Also, the social dimension can be upgraded in all life cycle if their actors compromise with social policy. The SFI presented was in the direction of sustainability, and it is possible to perceive the social dimension with a higher possibility of improvement. SFI remains similar results throughout of biodiesel chain production. Besides that, the results can support future strategies associates with energy security policy and social, economic, and environmental development of biodiesel production chain.

Keywords: biofuel, life cycle sustainability assessment, social life cycle, dashboard of sustainability.

Introduction

The energy security policy is a strategic objective to the social and economic development of the countries and may be achieved with alternative sources to fossil fuels. Due to the fact that oil is becoming increasingly scarce and it is considered a non-eco-friendly source of energy, the increasing production of fuels from renewable sources is the most viable alternative in the short and medium-term, and this requires the fulfillment of sustainability requirements in a broad sense: environmental, economic, and social (Rodrigues and Accarini, 2007).

In Brazil, the proportion of biodiesel blend with fossil diesel was growing rapidly until 2010, to reach the targets set by the National Program for Biodiesel Production and Use (PNPB) (Esteves et al., 2016). Recently, in March of 2018, the proportion of blend biodiesel increased from 8% to 10% and the soybean oil industry had the commitment to supply demand of almost 5.5 billion of liters (an increase of 28% in relation to 2017) (César et al., 2019). In Brazil, soybean oil represents around 85% of the feedstock used for biodiesel production and about 72% in the Southern region (Oliveira and Coelho, 2017). Besides that, Rio Grande do Sul (RS) state is one of the most important producers of biodiesel in Brazil (IBGE, 2018).

Very recently, it was evaluated the potential social, economic and environmental impacts of soybean production using the Dashboard of Sustainability (DoS) which showed while environmental data was presented per process, data from economic and social dimensions were aggregated posing a new obstacle to overcome. Moreover, social dimension evaluation is still challenging when must be integrated with quantitative data from environmental and economic dimensions (Zortea et al., 2018). Very recently, Bodunrin et al. (2018) reported that there are no LCA studies encompassing simultaneously environmental, economic and social assessment of soybean's biodiesel in Brazil.

Regarding the biodiesel production, the State of Rio Grande do Sul had nine plants (see Table S1 in Appendix A. Supplementary material (SM)) until September of 2014 (Figure 1). Indeed, MDA (2014) states that these plants work with a supply chain linked with Rural Producers Cooperative (RPC), mainly formed by family farmers and micro producers. This RPC is able to receive a Social Biofuel Label (Table S1) that returns some benefits for these companies (Brasil, 2005). Hence, the biodiesel chain could have an important contribution to local development and social cohesion. Despite the potential to the development of biodiesel, there are no specific studies of its sustainability associated with its life cycle.

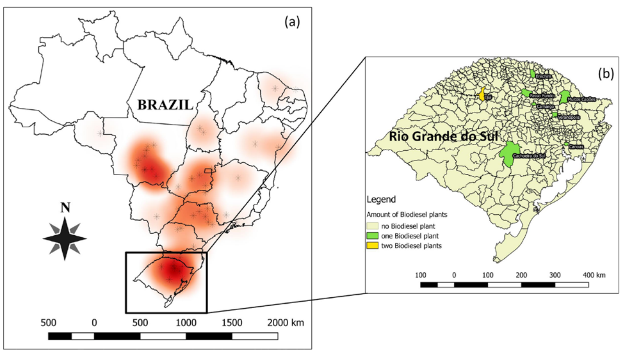

Figure 1. The production capacity of Biodiesel in Brazil (a) and localization of Biodiesel plants in RS state (b) (adapted from IBGE (2018)).

Moreover, César et al. (2019) emphasize the high participation supplied by family farmers in the South of Brazil, because this region presents good infrastructure and tradition of organization in cooperatives collaborating as decisive instruments in the insertion of sustainable way. The authors reported that the South of Brazil accounts for 13 of 48 production units of biodiesel; this installed capacity is responsible for 38% of all biodiesel production in the country. In this case family farmers contributing to a high scale, promoting development for the country in relation to biofuels and generating wealth also for small farmers.

Understanding the social, economic and environmental impacts of biodiesel chain is the key to enable sustainability based on decision-making. Then, it is important to analyze these dimensions together, mainly because the Brazilian Government justifies this change (Diesel to biodiesel) based on social and economic arguments (MDA, 2017).

Therefore, the aim of this work was to evaluate the life cycle sustainability of the soybean biodiesel chain considering the soybean production, transportation and industrial manufacturing of Biodiesel. The results of this study provide a better understanding of the sustainability of Biodiesel's chain, showing the hotspots processes for each dimension assessed and the trade-offs among them. These results should be used to prioritize research and policy measures in order to improve the overall sustainability of biodiesel production chain under a life cycle perspective.

Method

In this study, a Life Cycle Sustainability Assessment (LCSA) was performed focusing to provide an evaluation of the biodiesel sustainability based on three separate analysis that follows identical system boundaries: environmental, economic and social dimensions. Thus, the sustainability issue is assessing based on singular life cycle results of each sustainability dimension. The methodology is complemented with DoS, also known as Life Cycle Sustainability Dashboard (LCSD) when it is performed in line with ISO 14040:2006 and 14044:2006 (Finkbeiner et al., 2010; Traverso et al., 2012; ABNT, 2009a, 2009b). This approach has been applied in a previous study published for this research group (Zortea et al. 2018) and showed to be a better method to understand the sustainability issue. Thus, this approach attempts to align the three assessments of these results in an LCSA (Kloepffer, 2008; UNEP/ SETAC, 2011). Following Zortea et al. (2018), the life cycle inventory and impact/effects assessment were organized in each of the three dimensions. Each dimension was measured using three impact categories, summing 9 (nine) impact categories that were converted into a sustainability index with no weights among classes.

Goal and scope

The goal of this study is assessing the sustainability of soybean's biodiesel production chain in Southern Brazil context. The scope was defined as a cradle-to-grave approach and the system boundaries are shown in Figure 2. The industrial stage, transport, and use phase were evaluated complementing the life cycle sustainability assessment of the agricultural stage of biodiesel soybean in Southern Brazil (RS state) published in Zortea et al. (2018). The functional unit was 1 (one) GJ of soybean biodiesel, except for S-LCA, which differences in production do not affect the general social effects by the selected method.

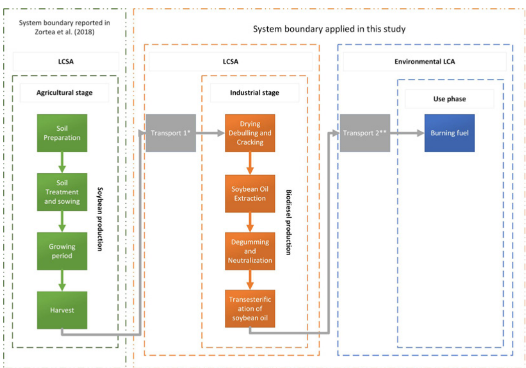

Figure 2. System boundaries applied in this work.

Life cycle inventory analysis

In this section, the method details for the construction of LCI are showed as well as the allocation criteria applied. Life cycle inventories for each dimension were collected separately from primary and secondary data.

Environmental inventory

The life cycle inventory (LCI) of the agricultural stage was obtained in a previous study published by this research group (Zortea et al., 2018). Data related to the industrial stage were collected on environmental licensing available from the environmental agency of RS state. Note that, the data were collected from four of nine plants because just four environmental licenses processes had been available for public consulting.

LCIs of soybean meal and crude oil production for industrial stage were collected from datasets available in Brazilian Life Cycle Inventories database (SICV: acronym in Portuguese for Banco Nacional de Inventários do Ciclo de Vida) (SICV, 2018), which was based mostly on Environmental reports of industries and literature source in some soybean mill plants in RS state which means that this dataset is representative (more than 60% of 2014 total productivity) within this region. Moreover, this inventory has international recognition and based on integrated information infrastructure (IBICT, 2018).

It is important to highlight that the Brazilian Law number 10.650/2003 (BRASIL, 2003) created public access to data and information available in environmental agencies in Brazil, in this case, using this legal requirement, the method and results for this inventory were followed as described in Zortea and Cybis (2014). Then, an analysis was performed to define the data that could be used to fulfill the inventory. Lastly, for missing data, other sources were used, such as Almeida et al. (2017), Lima et al. (2017), Crown (2009) and Jungbluth et al. (2007) to aim to complete the inventory.

Despite the fact that, in Brazil, ethanol is less expensive than methanol, according to Holanda (2004) and Knothe et al. (2005), 100% of biodiesel produced in RS state (around 144.000 ton per month) was produced using methyl esters, i.e., using methanol (FEPAM, 2007, 2009, 2010, 2011). Therefore, the choice must have been for an inventory producing methyl ester biodiesel in place of ethyl ester biodiesel.

Moreover, besides the use of methyl esters, other inputs as the type of catalysts and the many sources of oilseeds can be used as raw material providing alternatives for supporting the decision making as such: the lowest production value, percentage of oil in the seed (best performance), region agricultural potential and maintenance of food production (Zonin, 2008). For instance, César et al. (2017), affirm that Brazil produces important oilseeds as: cotton, peanut, canola and sunflower. Based on these pieces of information, come up the question: which reasons the soybean is the oilseed used in the majority? Zonin (2008), sustains difficulties related to technical knowledge with other crops and the necessity of more research results; César et al. (2017) cite soybean oil has already had infrastructure, organizations, financial resources and technology established, a fact not evidenced to another oilseed crops. Lastly, Zonin (2008) asserts that soybean crop is inserted in a productive context of Brazil-based on a technological level and appreciated prices that soybean has presented; which makes Brazil one of top's soybean producer in the world (OECD-FAO, 2018). Last, but not less important, Knothe et al. (2005) emphasize that biodiesel is obtained by a transesterification reaction where around 10% of production volume is composed by glycerin. In this case, these same authors draw attention to be used, the glycerin need to present a degree of purity very high (>99.5%) which demands complexity and a costly process, because the glycerin generate in the Brazilian biodiesel factories has a degree of purity around 40-90% (Quintella and Castro, 2009).

On the other hand, the transport stage inventory was built in a different approach. First, the distances were estimated, the results and general information are presented in Table 2. Besides that, this study encompasses the transport of the main supplies and logistics of biodiesel soybean production. Therefore, based on the information analysis and information called Aliceweb (Alice Web, 2014) and in the Chemical Industry Brazilian Yearbook (ABIQUIM, 2012), it was searched.

About this searching, it was verified that 4 (four) supplies are imported in a major way: hexane, phosphoric acid, sodium hydroxide, and methanol. Thus,to determine the origin countries, shipping distances, ports that receive this supplying, it was established one assumption as cut-off criteria as follows. It was selected as the main countries and Brazilian Ports that are responsible for more than 50% of total supplying importing. Based on this cut off criteria, Table 3 presents the results for each supply linking with main countries and Brazilian Ports and their distances. It was considered a standard distance of 300 km for the remaining materials, which is the average distance from the main industrial site in Brazil (São Paulo) and the location medium point of biodiesel plants in RS state.

Table 1. transport inventory.

Transport	Itinerary	Average distance (km)	Considerations
Transport 1	Harvest area until storage silo	20	The average radius of soybean crop – Cunha (2008)
	Storage silos until soybean milling	134	Distance between location medium point of 23 municipalities producers and location medium point of biodiesel plant (weight for soybean production in each municipality and in each biodiesel plant)
Transport 2	Soybean milling until Biodiesel plant	0	It was considered that all soybean milling is located next to biodiesel plants
	Biodiesel plants until the refinery	203	The average distance among biodiesel plants and the RS Refinery (weight for production in each biodiesel plant)

Table 2. Consumption of raw material importation during biodiesel industrial stage in RS.

Raw material	Origin Country	Receiving Port	Shipping distance (km)	Functional Unit (t.km)	Terrestrial distance (km)	Functional Unit (t.km)
Hexane	US	Rio Grande (RS)	10200	1,80092	500	0,08828
phosphoric acid	US	Santos (SP)	9300	0,77734	1100	0,09194
sodium hydroxide	US	Barcarena (PA) and São Luís (MA)	5600	5,19149 and 2,00652	3700	3,43009 and 1,32574
Methanol	New Zealand, Trinidad and Tobago, Venezuela	Paranaguá (PR)	8200	21,26369	750	1,94485

Source: Aliceweb (Information Analysis System of Foreign Trade). Available in Alice Web (2014).
SEA-DISTANCES.ORG. Available in Sea Distances (2014).
Google Maps (2014).

Moreover, concerning the transportation fleet, it was considered trucks with load capacity between 35000 to 52000 liters to liquid bulks and trucks with a capacity between 26 and 50 ton to grains (LETSARA, 2014; SULCARGO, 2014). Based on the information above, this work chooses trucks with capacity above 20 ton. Therefore, the truck profile closer to these characteristics was EURO3 trucks.

Lastly, the use phase is related to when the fuel is burned. Therefore, it was calculated 1 (one) GJ profile emission based on the references researched (Kozerski, 2006), when biodiesel is used as an energy source. This emission profile is presented in Table S6 in the SM.

It is important to highlight in relation to this inventory that both transport and use stage were evaluated together as presented in Figures 4 and 5. These impacts results were integrated for environmental dimension, because the use phase does not present relevant impacts for economical dimension and it was not viable to measure this stage for social dimension, Therefore, these authors choose this approach to facilitate the integration of results in the intepretation (section 3,4). In this case the soybean's biodiesel life cycle assessment becomes easier to be understood.

Economic inventory

Due to the singularity of this kind of data (difficulty to obtain with companies and to evidence them), this inventory was made based on secondary data. The economic quantifications were made following an annual estimation and using several sources to fulfill all economic flows. Therefore, significant and major vastly recognized in Brazil served as a basis to data collection such as: Brazilian Association of Chemical Industry (ABIQUIM, 2012), Santos (Santos, 2012), RS Electric Energy Company (CEEE, 2013), RS Sanitation Company (CORSAN, 2014), RS Economy and Statistical Foundation (Feix, 2012), Supply Companies (Crown, 2009; CEPEA, 2014), Logistics and Economies Research Centers (ESALQ-LOG, 2014) and scientific publications in this subject (Zortea, 2001; Cunha et al., 2008; Santos, 2008; Barros et al., 2009). Moreover, the RS state has an Agroenergy Structure Project. This project was developed in collaboration with Research Foundations and Companies and Producers Cooperatives. In this way, it was used as a comparative indicator helping not only in the economic inventory but also contributing to the social inventory and presenting more than a few sources of information related to soybean biodiesel (Fontoura, 2010).

The aim was to collect specific data, though when it was not possible, generic data was used. For example, whenever costs data related to soybean's fungicide were not available, data of fungicides used by generic grains in Brazil was used. Also, it should be emphasized that economic inventory was evaluated only in terms of costs, because the purpose is to verify the efficiency comparing all costs encompassed in the soybean biodiesel life cycle, in other words, analyzing by life cycle cost (LCC). These economic values were calculated following elementary flow to obtain the functional unit defined. Later, a revision of the costs was made with the objective standard all economic flow to June 2014 (reference value) using an economic index, described in the life cycle impact assessment, as follows (see section 2.3.2). As the results were calculated using several sources of Diesel and biodiesel, the same were compared with the bibliography released related to costs of Brazilian soybean biodiesel. In this sense, Barros et al. (2006, 2009) have published studies which collaborate with this proposal. Besides that, to harmonize the value and to render them comparable, it was defined some assumptions, as follows: zero profit; R$ (Brazilian Real) 2,204 for each U$ 1,00 (current exchange rate in June, 30th of 2014); all values updated to June of 2014 using an economic index, called General Prices Index-Internal Availability (IGP-DI in Portuguese) from the Getúlio Vargas Foundation (FGV/ IBRE, 2014); and no taxes or charges. Comparing the values reported in Barros et al. (2006) and Barros et al. (2009) with the result obtained in this work the variation found was around 6-7%, that can be considered acceptable whether take into account exchange factors such as prices variation, exchanges rate oscillation and several ways of monetary correction. In Table S7-S8 in the SM is detailed all costs for the oil extraction stage and soybean biodiesel production.

Social inventory

Regarding the social dimension, its life cycle inventory was based on evidence of companies collected using primary data (from the company as sources, such as website, reports, and policies) and secondary data (information from certification bodies and governmental organizations, such as Labour Ministry and Agricultural Development Ministry). The data collection was based on obtaining evidence that each company carries social actions out related to its workers, local community/society and value chain actors; stakeholders assessed in this work. In this case, the procedure followed a sequence order: search of evidences and data in all company external communications (websites, flyers, reports, memos, etc.), sending e-mails for the responsible sectors of each company, phone calls for the responsible and sectors of each company and, lastly, evidence and data collection using others sources such as: Labor Justice, Federal Government data, certification bodies, etc. In case no information was obtained following this procedure, the data was evaluated as "no evidence" related to the social dimension. The same procedure was made to logistic and transport companies. Besides that, to evaluate workers' perception, questionnaires were sent to the Unions representative, however, there was no answer until the conclusion of this study.

Allocation

Besides the biodiesel product, the soybean biodiesel's life cycle contains soybean meal and glycerin as a co-product. In this case, it is important to verify if an allocation procedure should be necessary. Based on the several difficulties to use a system expansion (Weidema,

2000) and following suggestion made by Aguirre-Villegas (2012), this study applied a combination of subdivision and allocation ratios partitions of common processes to both product and co-products with the intention to provide an accounting structure that can be applied without undue complexity. Zortea (2015) detailed all this allocation process including an environmental impact comparison using energetic, mass and economic allocation factors, who suggested the use of the energetic approach as a reference allocation factor using the boundaries demonstrated in Figure 3. It is important to highlight Figure 3 presents only a qualitative characterization of the allocation method used in this work.

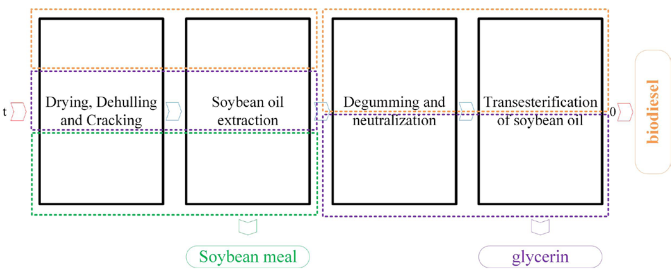

Figure 3. Summarized flowchart of life cycle biodiesel production with allocation suggestion used in this work.

Life cycle impact assessment (LCIA)

Except in the case of the social dimension, the LCIA results were related to the functional unit. Therefore, the other two dimensions had their input and output data linked with a functional unit defined in this work. It is important to highlight this consideration because this association will influence the results in the interpretation stage. In contrast, different approaches were adopted for each LCIA dimension, with the intention to emphasize specificities that each dimension presents in its respective inventory.

Environmental LCIA

The environmental LCIA was performed based on Standards ISO 14040 and ISO 14044. Data necessary to model the upstream processes was obtained from the ecoinvent database and Simapro Software v 8.0.3.14 were used for process modeling and impact characterization. The impact assessment model selected for this work was CML-IA (midpoint) (PRé, 2014). The midpoint impact categories evaluated were: acidification, eutrophication and global warming, following the same methodology performed in Zortea et al., (2018).

Economic LCIA

In this dimension, three economic indicators were selected, such as feedstock costs, infrastructure and maintenance costs, and financial expenses. These impacts rely on the costs acquired by the elementary processes through the life cycle and transformed into three economic impacts. Costs obtained were updated to June 2014 using an economic index named General Prices Index-Internal Availability (IGP-DI in Portuguese) from the Getúlio Vargas Foundation (FGV/ IBRE, 2014). For this case, the monetary unit: Brazilian Real (R$). The exchange rate on June 30th, 2014 between the US Dollar (U$) and the Brazilian Real (R$) was 1 U$ = R$ 2.204 (Banco Central do Brasil, 2014).

Social LCIA

Social LCIA was performed based on UNEP Guidelines for Social Life Cycle Assessments (S-LCA) of Products (UNEP/SETAC, 2009) which recommends five stakeholders should be assessed: society, employees/workers, consumers, value chain actors and the local community, which are divided into 31 subcategories (Benoît-Norris et al., 2011). For that reason, this study adopted UNEP Guidelines considerations, taking into account particularities of the RS soybean biodiesel production, such as:

(1) The stakeholder "consumers" were not included because the product analyzed in this work will be mixed in a ratio of 8% biodiesel and 92% Diesel. Therefore, it was not conceivable to discover consumers' different views of soybean biodiesel distinguishing which impacts are related to biodiesel or fossil diesel.

(2) The analyzed stakeholders "society and local community" are collected together, in some way, related to each other, and determining some distinction between data for the society or local community was not possible due to the subjectivity of the evidence collected. As the methodology adopted the same requisites already described by Zortea (2015) and Zortea et al. (2018) who considered all soybean biodiesel factories in RS state. In some situations, collected evidence express information related to all municipalities or state (society) and, in other situations; the data express information about a specific municipality or county (local community). Therefore, in order to minimize this contrast and enhance inventory robustness, these stakeholders were evaluated together.

The social impacts are related to stakeholders' perception, being the results associated with qualitative and semi-quantitative data to facilitate the identification and accounting in reference to potential social impacts as fair as possible. This data combination sought to catch, in a better way, possible results that may provide future efforts to minimize the risk of negative impacts and maximize positive impacts. Social impacts were not related to the functional unit since these results should not modify in case of the reference flow amount to be changed. However, the social impacts are related to the number of workers affected in each life cycle stage. Specifically, for this study, was analyzed two stages: industrial and transport stage. Therefore, in the case of the social dimension, the final impact results should be weighed with the ratio of workers encompassed for each stage. Zortea (2015) presents the number of potential jobs for each stage related to the production of biodiesel, for instance, 22000 L of soybean biodiesel produced corresponds to around 1 job for transport stage, 4 jobs to the industrial stage and 288 jobs to the agricultural stage. Particularly in this study, the ratio to be considered might be 4 to 1 for social impacts in industrial and transport stage, respectively. In other words, the industrial stage will have a representation four times stronger than transport stage and in case of the inclusion agricultural stage, these workers present a representation 72 times stronger than the industrial stage and 288 times stronger than the transport stage.

Besides that, in this specific study, it was used Social LCIA Type 1. This approach is based on the use of social performance reference points as a way of interpreting inventory indicators and assessing the magnitude and significance of social impacts. These reference points are minimum levels of social performance defined in accordance with legislation, policies and regulations. Thus, reference scales are used to assess the social performance of inventory indicators and compare them with the reference point (UNEP/SETAC, 2009). For this study, an adapted DoS scale was used, where the social impacts obtained by qualitative data were converted in semi-quantitative data, as is presented in Table 3 in Zortea et al. (2018).

Different of Subcategory Assessment Method (SAM proposed by Ramirez et al. (2014), in this work the levels of evidence were reduced from four to three. This grouping of levels was defined by reason of all data were in the same region. Therefore, it is possible to say that all data is encompassed by the same culture, legislation and market requirements. Besides that, the levels of observation and/or evidence have the objective to differentiate the maturity among the organization regarding social responsibility.

Method of integration

Once environmental, economic and social impacts were calculated, the integration of results can be performed to obtaining the SFI. In this stage, impact data (Table S15 in the SM) was inserted at the DoS feeding and performed the evaluation about the sustainability level of biodiesel life cycle assessed in this work. After that, an interpolation was made defining o (zero) for the worst case (biggest impact) and 1000 (thousand) points for the best case (lowest impact), and intermediate cases are calculated using a linear interpolation between these two references. The results of each evaluation are associated with a scale of colors, corresponding to different sustainability levels. It is important to be emphasized that all indicators were weighed upon the same scale, which is represented in numeric and graphic ways.

With regards to the environmental dimension, the related impacts (acidification, eutrophication and global warming) were normalized based on the references determined by CML-IA methodology. In this way, the composition of the environmental indicator in each stage was interpolated using the normalized results by CML-IA (Table S15 in the SM). Therefore, the reference was made comparing the current results with the world average related to this impact analyzed. Based on this world average, the lowest ratio (impact/world average) received the value 0 (zero), while the biggest ratio received the value 1000 (thousand) and the intermediate values were interpolated considered this range.

Regarding the economic dimension, it was applied a different approach. It was sought all supplies that can be considered competitors of soybean to produce fuels in RS state, such as fossil Diesel and biodiesel from corn oil (Table S15 in the SM). These costs were sought in the bibliography and released economic indicators. Then, these costs were compared and a range considering 0 (zero) for the highest cost and 1000 (thousand) for the lowest cost was made intermediates values, later it was interpolated between these references. It is important to say, that the same methodology was made for each cost impact category, in other words, the same interpolation and reference definition was realized in an individual way for feedstock costs, infrastructure and maintenance costs and financial expenses and after that, all costs were summed up.

For the social dimension, the evidence and observations were classified considering the score presented in Table 4. This classification was based on a final value for a group of the evidence collected. In this case, the social responsibility maturity level was classified based on a group of observations and/or evidence obtained (Tables S8 to S13 in the SM). For instance, the satisfactory level was defined when the company presented some evidence proving that the company maintains minimal practices related to that specific stakeholder. The same way was made for critical and vibrant, but in that case of the first one, it was considered no evidence or not fulfill the basic requirements, and considered approaches proving social responsibility management in the case of the vibrant level. Once determined the level of maturity for each stakeholder, the sustainability index was calculated (Table S15 in the SM).

Results and discussion

The environmental, economic and social inventories are presented in Tables S2-S14 in the SM, respectively. The impact results of each dimension are presented and discussed in this section.

Environmental dimension results

The environmental impacts quantification and the main contributions are presented in Table 5, Figure 4 and Figure 5. It is possible to observe, in Figure 4, the use phase and transport have a bigger impact than the industrial stage for eutrophication and acidification impact categories, the burning fuel is the process with the greatest contribution. The same could be concluded for global warming impact category, but it is important to highlight that almost half of the impacts for use phase and transport have as source biogenic carbon that had the carbon capture accounted in the agricultural stage.

Therefore, comparing the results showed in Zortea et al. (2018), it was made Figure 5 that presents all soybean biodiesel life cycle including the agricultural stage. The scenario changes when the agricultural stage is included, showing that in the case of global warming and eutrophication impact categories the main impacts are from the agricultural stage that demonstrates a bigger impact than the industrial stage, usage phase and transport together. In Zortea et al. (2018), soil and land-use change emissions have represented the main contribution in global warming, also, for the eutrophication, the seed treatment and sowing process represent 96% of the impact in this category. In relation to acidification's impact category, the use phase and transport carry on dominating the environmental impacts.

Table 3. Environmental impacts contributions for stage and/or process (per functional unit).

Stage and/or process	Acidification		Eutrophication		Global Warming	
	kg of SO_2 eq.	%	kg of PO_4 eq.	%	kg of CO_2 eq.	%
Industrial phase (Total)[a]	0.0711	11.6	0.0138	8.9	7.0923	36.8
Process of soybean oil production (Total)[a]	0.0389	6.3	0.0074	4.8	4.0423	21.0
Process of transesterification (Total)[a]	0.0322	5.2	0.0063	4.1	3.0500	15.8
methanol[b]	0.0214	3.5	0.0014	0.9	1.5500	8.0
sodium hydroxide[c]	0.0065	1.1	0.0013	0.9	0.8651	4.5
Processes (Total)[d]	0.0295	4.8	0.0082	5.3	1.4339	7.4
Use phase and transport (Total)	0.5430	88.4	0.1410	91.1	12.2000	63.2
Burning fuel[d]	0.5420	88.1	0.1410	91.1	11.9200	61.8
Transport	0.0015	0.2	0.0000	0.0	0.2800	1.5
Total	0.6149	100.0	0.1548	100.0	19.2920	100.0

[a]Total of impacts considering life cycle impacts of supplies and impacts of the process evaluated. [b] impacts of methanol consumed in transesterification; [c] impacts of sodium hydroxide consumed for transesterification and soybean oil production; [d] total of impacts considering soybean oil production process and transesterification process); [e] 5.8031kg of CO_2 eq. are related to biogenic carbon accounted in Agricultural Stage; eq.: equivalent.

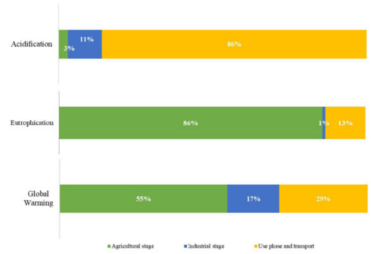

Figure 4. Environmental impacts contribution in industrial and use phase.

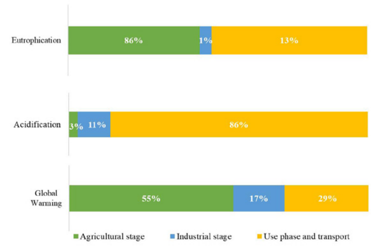

Figure 5. Environmental impacts contribution in each stage including agricultural stage.

Economic dimension results

Quantification of costs is presented in Table 6 and Figures 6 and 7. According to Table 6, the industrial stage and transport for soybean biodiesel in 2014 were R$ 34.79 per GJ of soybean biodiesel produced. Analyzing all the costs, the feedstock costs represent around 46% (almost R$ 16). Among the main costs' contributions are electric energy supplying, boiler operation, methanol, and sodium hydroxide. It is important to emphasize that the energy supplying contributes almost 60% of total feedstock costs, mainly due to the methanol which is the main responsible for 56 % of feedstock costs in transesterification process, though methanol was chosen in place of ethanol as alcohol for producing biodiesel in RS.

Table 4. Costs in Brazilian Reals (R$) per GJ of biodiesel produced.

	Industrial stage and transport	Soybean oil production	Transesterification
Feedstock costs	**15.93**	**10.67**	**5.26**
Electric energy	5.78	5.54	0.24
Boiler operation	3.42	2.36	1.06
Methanol	2.97	0.00	2.97
Sodium hydroxide	1.44	1.02	0.42
Others	2.33	1.76	0.57
Infrastructure and maintenance costs	**13.29**	**8.96**	**4.33**
Rental costs	5.85	4.35	1.50
Gum/soap costs	1.24	1.24	0.00
Transport	0.94	0.36	0.58
Social biofuel label	0.90	0.00	0.90
Storage expenses	0.72	0.69	0.03
Others	3.64	2.32	1.32
Financial expenses	**5.57**	**2.67**	**2.90**
Capital return	3.01	1.46	1.55
Equipment depreciation	1.30	0.34	0.96
Funding interests	1.25	0.86	0.39
Total	**34.79**	**22.3**	**12.49**

Source: Banco Central do Brasil (2014).
Data taken on June 30th, 2014 the exchange rate was: 1 U$ = R$ 2.204.
GJ: Gigajoule; R$: official currency of Brazil (Brazilian Real)

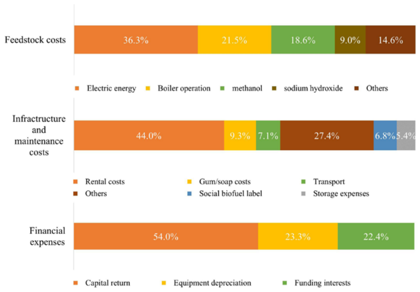

Figure 6. Composition of costs in Industrial stage and transport.

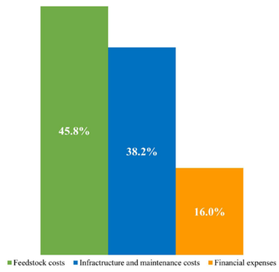

Figure 7. Contribution of each cost in the industrial stage and transport.

Infrastructure and maintenance costs represent around 38% of the total costs (R$ 13.3), mostly due to rental costs that contribute 46% of this category of cost. On the other hand, financial expenses demand 16% of total costs, distributed among capital return, funding interests and equipment depreciation as principal expenses. Taking into account an individual contribution in each process (soybean oil production and transesterification process), it is possible to verify that while to soybean oil production the main costs are in the energy supplying and rental costs, for transesterification process the biggest economic impacts are located in methanol and capital return. Another important result related to the differences in costs between these two processes, because both feedstocks costs and infrastructure and maintenance costs to soybean oil production is more than twice more expensive than the transesterification process, which demonstrates that economic hotspots are concentrated in the obtaining of soybean oil.

Other relevant aspects concernsthe contribution of importance inversion of equipment depreciation and funding interest cost impacts between soybean oil production and biodiesel transesterification (Table 6). This behavior may imply in the conclusion this occurs because soybean oil plants should be the oldest version. For that, the equipment depreciation costs end up being lessened, while the news transesterification biodiesel plants may have been built based on capital cost subsidies for biodiesel production infrastructure projects as is provided by Law (BRASIL, 2005).

Additionally, taking into account of biodiesel life cycle costs, this supplemented study demonstrated results which may go against pieces of information collected from the literature. For instance, Holanda (2004) and Knothe et al. (2005) affirmed that methanol is more expensive in Brazil than ethanol, however, this study presents opposite results. In this case, it is essential to understand that the results reported to them were based on different costs, years, monetary current, and life cycle boundaries.

Social dimension results

The social impacts are based on the inventory reported in Tables S08-S13 in the SM, which also presents the stakeholders evaluated in this work. Besides that, Table 4 explains the criteria used to convert the evidence collected (qualitative inventory) into semi-quantitative values. It is important to highlight that in the specific case of social dimension these semi-quantitative results were converted in impacts reproduced in a color scale as was demonstrated in Table 4. The social impacts results are presented in Table 7. Based on these results one of the aspects that draw attention is related to value chain actors' stakeholder that does not demonstrate any company with critical (red) level for the industrial stage. of the reason is all companies adhered to Social Biofuel Label, representing evidence that impact in a positive way for this specific stakeholder. Another important observation refers to a similarity of results for the local community and society stakeholders. This fact demonstrates a potential concern of industrial companies with these stakeholders that can be verified as a good impression. Lastly, in relation to transport phase, based on this sample summed up in only two companies demonstrates this sector has away longer than industrial sector to reach a good level of maturity to social responsibility.

Table 5. Social impacts related to biodiesel production and transport companies.

	stage	Workers	Local community and Society	Value chain actors
Company A	Industrial	Satisfactory	Satisfactory	Satisfactory
Company B	Industrial	Satisfactory	Critical	Satisfactory
Company C	Industrial	Vibrant	Satisfactory	Vibrant
Company D	Industrial	Vibrant	Vibrant	Vibrant
Company E	Industrial	Critical	Vibrant	Vibrant
Company F	Industrial	Critical	Satisfactory	Satisfactory
Company G	Industrial	Critical	Satisfactory	Satisfactory
Company H	Industrial	Vibrant	Satisfactory	Vibrant
Company I	Industrial	Satisfactory	Satisfactory	Satisfactory
Average of industrial stage		Satisfactory	Satisfactory +	Highly satisfactory
Company J	Transport	Satisfactory	Satisfactory	Critical
Company K	Transport	Satisfactory	Satisfactory	Satisfactory
Average of the transport phase		Satisfactory	Satisfactory	Highly unsatisfactory

Life cycle sustainability assessment (results integrated)

With the environmental, economic and social results, the next step was to convert these results into a sustainability indicator using methodology described in section 2.4. Figure 8 shows the results grouped into a slightly positive SFI, determined as a life cycle indicator.

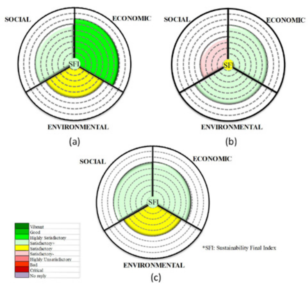

Figure 8. Impacts results of biodiesel production for industrial stage (a) transports and use phase (b) and sustainability indicator from grouping results related to impacts of E-LCA, LCC, and S-LCA (c).

Table 6. Impacts influences related to the biodiesel production and transport companies

	Dimension		
	Environmental	**Economic**	**Social**
Influence on SFI	Impact Categories	Cost Components	Stakeholders
Positive (↑)	Eutrophication and Global Warming (IND and T/U)	Financial expenses and Infrastructure and Maintenance Costs (IND and T/U)	Value chain actors (IND)
Neutral (=)	-	Feedstock costs (IND)	Workers and Local community/Society (IND and T/U)
Critical (↓)	Acidification (IND and T/U)	Feedstock costs (T/U)	Value chain actors (T/U)

IND = Industrial Stage
T/U = Transport and Use phase

Table 7. Results of hotspots analysis for each dimension

Hotspots (activities or processes)	Dimension		
	Environmental	Economic	Social
Boiler operation	IND	-	-
Electric energy	IND	IND	-
Methanol	IND	IND	-
Fuel-burning	T/U	-	-
Rental Costs	-	IND	-
Freight/Shipping	-	T/U	-
Social responsibility policy	-	-	IND and T/U
Claiming for labor rights	-	-	IND
Process validation	-	-	IND
Involvement with suppliers	-	-	T/U

IND = Industrial stage
T/U = Transport and Use phase

As a way to exemplify the use of the evaluation results, Table 9 shows some of the activities and processes that are responsible for the critical values shown in Table 8. For instance, methanol causes a relevant impact in two dimensions (economic and environmental), because it is a hotspot for acidification and feedstock costs. This observation is confirmed by Interlenghi et al. (2017) that point methanol production as the most critical process among all processes of Brazilian biodiesel production chain in their conclusions, taking into account both economic and environmental dimensions. In this context, methanol becomes a critical variable (Figure 6, Table 5 and Table 6). A way of improving the environmental and economic dimensions would be evaluating other ways and processing methanol or still replacing for ethanol if this one could bring environmental and economic improvements for the life cycle soybean biodiesel. In this case, replacing methanol for ethanol may improve the Brazilian sugar cane industry and national commercial balance (Holanda, 2004; Alice Web, 2014). To perform this potential replacing, one possible suggestion could be supplier's involvement (Value Chain Actors – see Table 8 and Table 9) which would improve the social dimension results, as well as the SFI. It is important to highlight that care must be taken when replacing, for instance, changing methanol to ethanol can affect the sustainability index, confirming the high complexity of sustainability evaluation.

Considering that some activities or processes presented in Table 9 have a considerable influence on the biodiesel soybean life cycle impacts, by all means, some activity or process is changed or replaced, the results will be affected not only in that dimension but in all dimensions related to that specific process or activity. Also, this study demonstratedsocial responsibility policy is a hotspot for the biodiesel production chain (see Table 9). In this sense, César et al. (2019) have reported the importance of policy as a driver for competitiveness related to social soybean production in biodiesel's production chain.

In general, the impacts influents resulted in Tables 8 and 9 meets drivers and indicators reported as important variables for competitiveness in César et al. (2019). According to these authors, infrastructure and feedstock as important drivers of competitiveness encompassing indicators as value chain actors, feedstock costs, Social Fuel Seal, the participation of inputs in production costs, logistics and productive arrangements.

Final remarks

This study provides an improvement of knowledge on the life cycle sustainability of biodiesel's production chain. Overall, soybean biodiesel from Southern Brazil demonstrates characteristics of sustainability in its life cycle, but they also indicate that there are issues that should be improved in some hotspots detected with the intention to minimize potential impacts in the production of soybean biodiesel life cycle. Acidification, feedstock costs and value chain actors' stakeholder highlights as main hotspots, because their results presented higher impacts whether compared with other impacts and stakeholders when it is assessed industrial stage, transport and use phase of soybean biodiesel life cycle.

The soybean crop presents as current raw material to produce biodiesel, demonstrating this oil-seed prevails as the main alternative for biodiesel in South of Brazil. Another fact that should be highlighted is in respect of the usage of methanol in all biodiesel production plants in south of Brazil, in place of ethanol, although Brazil has one the largest world's production of sugar.

The results suggest that for improvements of biodiesel soybean specifically during industrial stage, transport, and use phase depends on actions related to energy sources (boiler operation, electric energy, methanol, and fuel-burning), feedstock improvements (methanol, electric energy and involvement with suppliers) and shortening distances (freight/shipping, rental costs and fuel-burning) (cf. table 8 and table 9).

Related to economic impacts, this work presents the consequences of improving the Brazilian matrix power with the input of biodiesel, demonstrating a good alternative for reducing Diesel importation demand and higher consumption of local soybean oil, providing value addition for soybean production and generating job vacancies and wealth to biodiesel chain.

However, one of the disadvantages comprehends the generation of new co-products as glycerin. In this case, the degree of purity does not permit this co-product to be used in, for instance, plastic, cosmetic and pharmaceutical industry.

Besides that, the nationalization of production and a better level of maturity in relation to social responsibility for all actors are also other indirect variables that can increase the SFI. These issues have an influence on the hotspots, such as social responsibility policy, claiming for Labor rights, process validations and involvement with suppliers. Also, any enhancement linked with methanol and electric energy process could have an advance in both environmental and economic dimensions for the industrial stage. Reducing these supplies is a way for minimizing these impacts and/or reducing impacts along their life cycle can provide better results. Social dimension can be upgraded in all life cycle if their actors compromise with social policy. Moreover, the implementation of the policy Social Biofuel Label confirmed to be an important action in a way to improve the SFI of soybean biodiesel production chain, because it demonstrated to be a valorized evidence that improves in a positive way the social impacts in all companies related to the stakeholder: value chain actors. (cf. table S10 in the SM). In this sense, cooperatives show itself as an important actor for biodiesel's production chain especially for providing infrastructure and a tradition of an organization to soybean production.

Also, the sustainability index results of industrial biodiesel production did not show a significant difference when compared to the agricultural stage reported by the latest study published by Zortea et al. (2018). Hence, these results suggest that the sustainability index remains similar results throughout of biodiesel chain production.

Using the DoS permits the evaluation of which activities or processes associated withthe biodiesel soybean's life cycle has the highest effects on LCSA impacts (environmental, economic and social), assuming the results are presented both in an integrated and separate way. This overview resulted in systematic analysis, demonstrating the importance to realize an integrated assessment.

The results of this study can support future strategies involving energy security policy and social, economic, and environmental development in Brazil. Besides that, this study gives the first complete assessment from cradle to grave of biodiesel produced from soybean in Southern Brazil.

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