Carbon footprint of *Agave sisalana* leaves processing

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Abstract: The aim of this work is to carry out a Life Cycle Assessment (LCA) to quantify the carbon footprint of 1 ton of sisal fiber production, including the stages of decortication, sun drying, brushing, grading, and baling. Diesel consumption significantly contributes to the carbon footprint during the decortication stage of sisal leaves processing for fiber extraction. It was observed that diesel consumption is a main contributor to the carbon footprint in the sisal leaves processing in the decortication stage for fiber extraction. The mixtures of diesel and biodiesel in 86:14 and 80:20 (on a volumetric basis) can reduce 5% and 10 % of the carbon footprint, respectively, highlighting the potential strategy to make sisal fiber production more sustainable.

Keywords: ***Agave sisalana,*** **vegetable fiber, environmental impact, greenhouse gas (GHG), life cycle assessment**

1. Introduction

The *Agave sisalana* plant is cultivated in the semi-arid region in Northeast Brazil. This agricultural activity is classified as low-tech, typically with no irrigation and low productivity. During leaves processing, a substantial amount of organic waste is generated and, mostly, these residues are distributed on the field by hand to restore nutrients to the soil (1).

Sisal fibers are extracted from the leaves of *Agave sisalana*. This process constitutes an economic activity that is relevant for job and income generation in this region (2).

Sisal fiber is an intermediate product used to produce twine, rope, carpets, and bags, and has also been used in composites in the automotive and civil construction industries (1).

In this context, it's important to evaluate the environmental impact of *Agave sisalana* leaves processing. To this end, the Life Cycle Assessment (LCA) is a widely used standardized methodology to quantify the environmental impacts of a product system throughout its life cycle (3). Material Flow Analysis (MFA) is used to evaluate the mass balance, supporting the LCA.

Previous LCA studies have been conducted to assess the environmental impacts associated with sisal fiber production (1,3). These studies reported that the energy consumption and waste generation associated with sisal leaves processing sisal are main drivers of the environmental impact of sisal fiber production.

The sisal leave processing involves the following stages: fiber extraction or decortication, drying, brushing, baling and grading. The decortication occurs in field with the use diesel machinery in most sisal farms in Brazil (1).

In this context, the aim of this work is to carry out an LCA to assess the carbon footprint of 1 ton sisal fiber production. Proposed scenarios for the replacement of diesel by biodiesel and these fuel mixtures were evaluated. In this regard, this study supports decision making for improved environmental practices in the sisal supply chain.

2. Methodology

Material Flow Analysis (MFA) and attributional Life Cycle Assessment (LCA) methods were used to assess the mass balance and global warming potential performance of the *Agave sisalana* leaves processing, respectively.

The MFA was carried out using STAN® software version 2.7.10. The mass balance data were obtained from Broeren et al. (1) based on the yield rates of the sisal leaves processing stages, consumption of diesel and electricity and moisture of the dried sisal fiber (13% w/w).

For the moisture content of the wet fiber, it was assumed to be 65% according to Widyasanti et al. (2). The mass of evaporated water during drying was estimated using mass balance calculations.

The reference flow was 1 ton sisal fiber produced. The sisal fiber production involves decortication, sun-drying, brushing, grading, and baling. The resulting outputs include processing residue, water vapor from drying, and baled sisal.

LCA methodology based on ABNT NBR ISO 14044 and 14067 (4, 5) was used to evaluate the carbon footprint. The product system was extended from gate to gate to cover only the leaves processing (Figure 1).

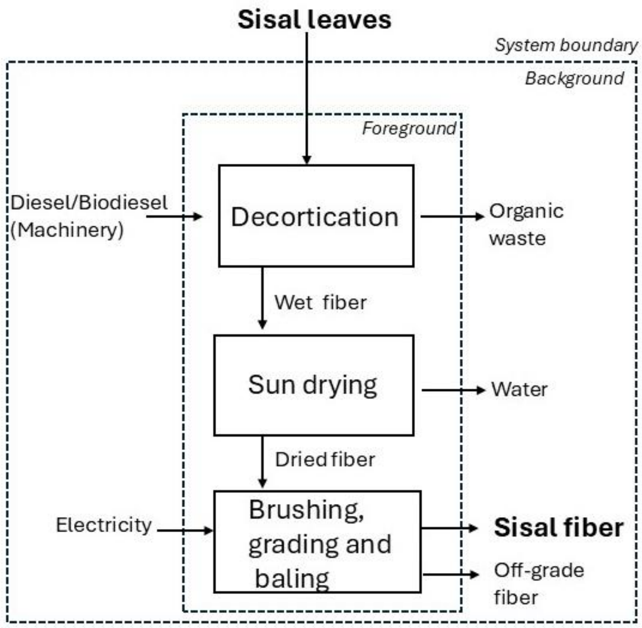

Figure 1: Product system of the sisal leaves processing.

Table 1 shows the input and output flows of sisal leaf processing to produce 1 ton of sisal fiber in the evaluated scenarios (SC1-SC4).

Table 1. Foreground inventory for 1 ton sisal fiber production in the evaluated scenarios

Parameter	Uni	SC1	SC2	SC3	SC4
Decortication					
Input					
Sisal leaves	kg	31000			
Diesel (machinery)	kg	34.5	-	-	-
Diesel/ Biodiesel (machinery)	kg	-	34.58	34.81	-
Biodiesel (machinery)		-	-	-	38.22
Output					
Wet fiber	kg	2600			
Waste	kg	28400			
Sun drying					
Input					
Wet fiber	kg	2600			
Output					
Water	kg	1350			

Parameter	Uni	SC1	SC2	SC3	SC4
Dried fiber	kg	1250			
Brushing, grading and baling					
Input					
Dried fiber	kg	1250			
Electricity	MJ	28			
Output					
Fiber baled	kg	1000			
Waste (off-grade fiber)	kg	250			

The evaluated scenarios differ regarding the fuel used in the machinery for decortication. The first scenario (SC1) considered the use of diesel in 100% fuel, while the second scenario (SC2) considered diesel mixture with 14% biodiesel, the third scenario (SC3) considered the mixture with 20% biodiesel, and the fourth scenario (SC4) considered 100% biodiesel. The remaining mass and energy flows are described in Table 1.

The product system was modeled using OpenLCA® software version 2.5 with the Ecoinvent database version 3.10. The impact method was the Global Warming Potential (GWP) for 100 years, which quantifies the greenhouse gas (GHG) emissions in carbon dioxide equivalent (CO_2 eq).

3. Results and Discussions

MFA for sisal processing is shown in Figure 2. According Broeren et al. (1), 31 tons of sisal leaves are used for 1 ton of sisal fiber production and 0.25 tons of waste generation (off-grade fiber). However, those authors did not report the quantities of residues during decortication. Then, this value was calculated in this study considering the 65% moisture of the wet fiber (2), 13% moisture of the dried fiber and the production data provided by Broeren et al. (1) in the mass balance calculation. Then, it was estimated that the decortication process produces 2.6 tons of wet fiber and generates 28.4 ton de organic waste (Figure 2), the latter represents the major output quantity which is disposed of in the field as residue. The organic waste can be a resource for further processing to add value to this material, for example, through the production of biochar, biogas, composite panels, or enzyme extraction (6,7). But in the sisal region of Brazil, this is not a typical practice.

It's noteworthy that the sisal processing generates 0.25 tons of off-grade fiber, and the use of this residue as a feedstock for bioenergy or biomaterials represents an important way for environmental impact reduction.

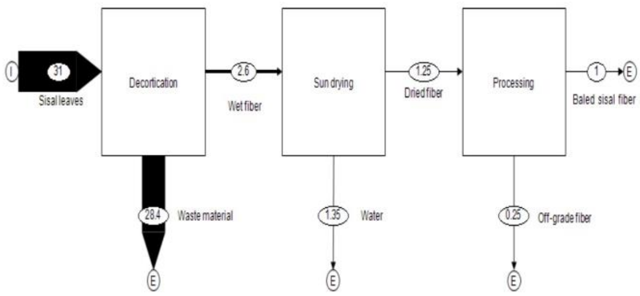

Figure 2: Mass Balance of the Sisal Fiber Production System

Figure 3 presents the results of the carbon footprint for 1 ton of sisal fiber production in the evaluated scenarios.

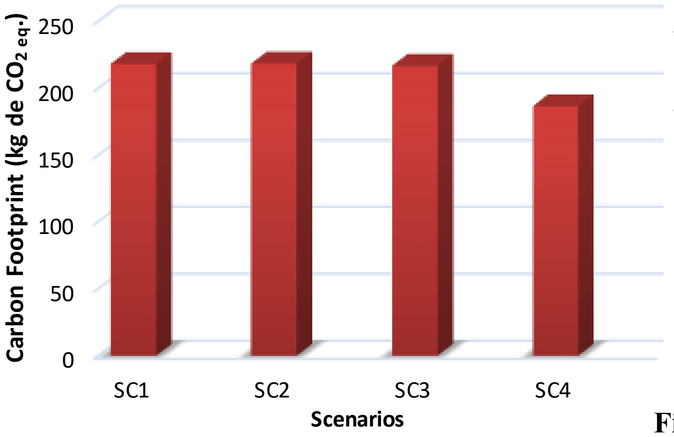

Figure 3. Carbon footprint for 1 ton of sisal fiber production in the evaluated scenarios.

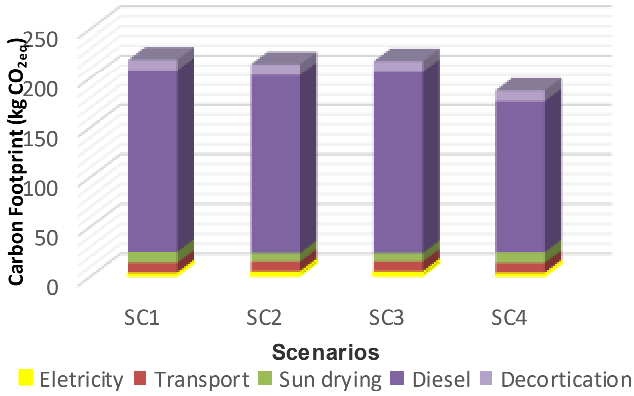

Figure 4. Carbon footprint the relative contribution of each process stage in the evaluated scenarios.

Figure 3 shows the impact of different fuel blend scenarios on the carbon footprint for the production of 1 ton of sisal fiber. Scenarios SC1, SC2, and SC3 display very similar values, around 220 kg CO_2-eq, reflecting the dominant role of diesel consumption in the decortication process. Only in scenario SC4 a more significant reduction is observed, with emissions reaching approximately 190 kg CO_2-eq, which highlights the direct effect of full substitution of fossil diesel by biodiesel. This difference indicates that marginal changes in the fuel mix (as in SC2 and SC3) result in limited gains, whereas complete substitution (SC4) is the only approach capable of significantly altering the emission profile of the process.

Figure 4 presents details the relative contribution of each process stage in the different scenarios. The comparison among scenarios shows that changes in fuel composition affect the intensity of emissions but do not substantially alter the hierarchy between the process stages.

The total carbon footprint reaches 218.17 kg CO_2-eq per ton of processed sisal, with diesel accounting for 89% of total emissions, highlighting decortication as the main critical stage. Transport (10%) and electricity (1%) appear as secondary contributors with marginal impact. This configuration reinforces the strong dependence of the agro-industrial stage on fossil fuel, limiting the potential for carbon footprint reduction without substantial changes in the process energy matrix (2,8).

The comparison among scenarios SC2, SC3, and SC4 reveals a gradual reduction in the carbon footprint as the proportion of biodiesel in the blend used in decortication machinery increases. In SC2, with 14% biodiesel, total emissions show a modest reduction of approximately 5.25% compared to SC1, reaching 206.6 kg CO_2-eq. Diesel remains the main source of impact (86%), followed by transport (10%) and electricity (4%). Although partial diesel substitution by biodiesel brings benefits, the reduction is relatively modest, suggesting the need for higher substitution rates or more efficient technologies (9).

In SC3, with 20% biodiesel, emissions decrease to approximately 194.7 kg CO_2-eq, representing a 10.67% reduction compared to SC1. Diesel still accounts for 91% of the impact, while transport and electricity together contribute less than 10%. These results indicate that, despite the progressive decrease in emissions, increasing the biodiesel share leads to diminishing returns, pointing to the need for deeper decarbonization alternatives (10).

In SC4, where fossil diesel is fully replaced by biodiesel, emissions are reduced to around 190 kg CO_2-eq, representing the most significant reduction among the evaluated scenarios. Unlike previous cases, the impact of diesel disappears, and emissions are mainly associated with transport (10%) and electricity (1%). Despite this improvement, it is important to note that stages such as sun drying, transportation, and electricity supply maintain a lower share (<5%), suggesting that the decarbonization of sisal processing primarily depends on replacing diesel in the shredding process (11). However, literature indicates that the carbon footprint of biodiesel varies significantly depending on the biomass source and agricultural management, highlighting the need to evaluate trade-offs such as land use change (12). Thus, although the evaluated scenarios show a trajectory toward lower GHG emissions, full environmental viability requires considering low-carbon biodiesel suppliers and more efficient machinery (13). When comparing the four scenarios, it is evident that, although all show a trend toward reduced emissions relative to the baseline scenario, the differences mainly reflect variations in the biodiesel fraction used. Scenarios with higher biodiesel content exhibit the lowest carbon footprints, showing that increasing the renewable fuel fraction is an effective measure, yet not sufficient. Additional strategies, such as using renewable electricity, optimizing logistics and energy use, recovering residual heat, and integrating process by-products, could further reduce emissions and enhance environmental efficiency. Scenarios with lower biodiesel fractions show limited reductions, suggesting that partial measures may be insufficient to achieve full environmental sustainability. Therefore, a consistent transition toward more sustainable sisal processing requires an integrated approach, combining renewable fuels, operational efficiency, and resource utilization, while carefully considering environmental and economic trade-offs.

Additionally, it is highlighted that the appendix contains the simulation data sheet, where the carbon footprint results are presented in detail, with the contributions broken down by category for each evaluated scenario. This supplementary material enhances the understanding of impact sources, ensuring greater transparency of the results and enabling more in-depth comparative analyses.

The Sankey diagram illustrates the distribution of GHG contributions across the production stages, with diesel burning during decortication standing out as the dominant contributor to the carbon footprint of 1 ton of sisal fiber, while other processes have comparatively smaller impacts.

The Sankey diagram shows the different phases of the sisal production chain with their carbon footprint contributions, being important for identifying hotspots and opportunities for mitigation.

The arrows representing diesel consumption are noticeably thicker, showing their significant contribution to the total carbon footprint.

On the other hand, smaller flows, such as electricity use, appear as thinner arrows, representing a smaller fraction of the impact compared to diesel use. This allows us to visualize how resources are distributed throughout the product system and where the greatest environmental impacts are concentrated, which can guide efforts to optimize these stages (Figure 5).

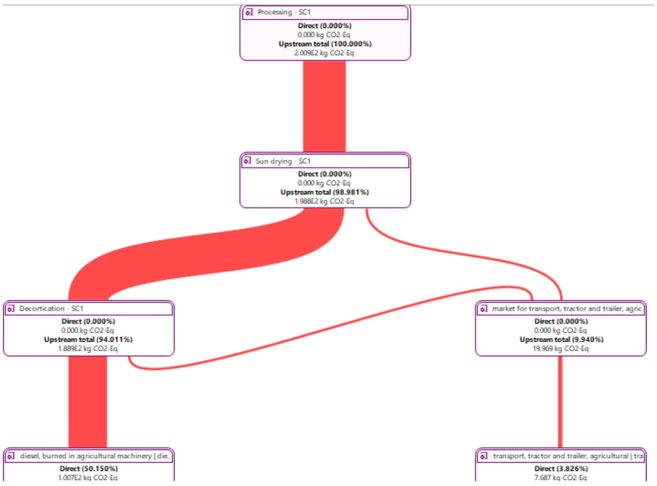

Figure 5. Sankey diagram of the carbon footprint for the production of 1 ton sisal fiber

Additionally, sisal fiber acts as a biogenic carbon sink, retaining atmospheric CO_2 during plant growth and storing it within its structure over the product's lifetime. This storage capacity is particularly relevant in Life Cycle Assessment, since it can offset part of the emissions generated during cultivation, transport, and processing. As a result, even under relatively inefficient production conditions, sisal fiber may present a favorable net carbon balance, reinforcing its potential to be accounted as a source of carbon credits in sustainability frameworks (12,13)

4. Conclusions

The assessment of carbon footprint of sisal processing to obtain 1 ton of sisal fiber was carried out and showed that the energy use, mainly due to diesel consumption, is the major contributor to this environmental impact.

The results indicate that sisal decortication is the most intensive stage, both in terms of energy demand and carbon footprint, when compared to the remaining processing stages (fiber brushing, grading and baling) which use electricity. Diesel and mixtures with biodiesel consume for decortication process represent the major contribution to the carbon footprint.

This research shows a 33,29% impact reduction due to diesel replacement by biodiesel. However, this option needs to adapt the equipment called "Paraibana machinery" used in decortication, which still is not the common practice. Therefore, when using the fuel mixtures of 86:14 and 80:20 (on a volumetric basis) for diesel and biodiesel, the carbon footprint reduction is 5% and 10%, respectively. It´s noteworthy to highlight that with the Brazilian Federal Law nº 14.993/24, known as the future fuel law, the biodiesel addition in the diesel is planned 20% until 2030. This mandatory increase of biodiesel in fuel mixture is a strategy to support the carbon footprint reduction in sisal fiber production.

5. Acknowledgement

The authors acknowledgment Brazilian Industrial Research and Innovation Company (Embrapii) and Senai Cimatec for research grant.

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Appendix

Impact category: Climate change | Global warming potential (GWP100)

Contribution	Process	Required amount	Total result [kg C...	Direct contributi...
100.00%	Processing - SC1	1.00000 kg	218.17570	
98.96%	Sun drying - SC1	1250.00000 kg	215.90876	
93.97%	Decortication - SC1	2600.00000 kg	205.02772	
88.99%	diesel, burned in agricultural machinery | diesel, b...	1440.01679 MJ	194.14668	100.98875
16.18%	market for agricultural trailer | agricultural trailer | ...	5.21286 kg	35.30198	
12.50%	market group for diesel | diesel | Cutoff, U - GLO	32.00037 kg	27.27121	
08.49%	market for tractor, 4-wheel, agricultural | tractor, 4...	2.23203 kg	18.52618	
05.53%	market for shed | shed | Cutoff, U - GLO	0.04982 m2	12.05856	
04.99%	market for transport, tractor and trailer, agricultur...	28.00000 t*km	10.88104	
04.99%	transport, tractor and trailer, agricultural | transpor...	28.00000 t*km	10.88104	3.85268
04.99%	market for transport, tractor and trailer, agricultur...	28.00000 t*km	10.88104	
04.99%	transport, tractor and trailer, agricultural | transpor...	28.00000 t*km	10.88104	3.85268
01.04%	market for electricity, low voltage | electricity, low ...	28.00000 MJ	2.26694	0.00196
01.00%	electricity voltage transformation from medium t...	28.30893 MJ	2.18040	

Figure 1.S. Carbon footprint for 1 ton of sisal fiber production in SC1

Impact category: Climate change | Global warming potential (GWP100)

Contribution	Process	Required amount	Total result [kg C...	Direct contributi...
100.00%	Processing - SC2	1000.00000 kg	218.48987	
96.10%	Sun drying - SC2	1250.00000 kg	209.96719	
91.16%	Decortication - SC2	2600.00000 kg	199.17775	
86.19%	diesel-B14, burned in agricultural machinery | dies...	1439.91120 MJ	188.31684	87.00789
16.04%	market for agricultural trailer | agricultural trailer | ...	5.21248 kg	35.04022	
16.00%	agricultural trailer production | agricultural trailer |...	5.19840 kg	34.96632	3.11904E-5
00.03%	agricultural trailer production | agricultural trailer |...	0.01407 kg	0.07390	8.44422E-8
10.48%	market group for diesel | diesel | Cutoff, U - GLO	27.51830 kg	22.88828	
08.39%	market for tractor, 4-wheel, agricultural | tractor, 4...	2.23186 kg	18.32039	
06.19%	esterification of soybean oil | fatty acid methyl est...	4.47972 kg	13.51797	
05.28%	market for shed | shed | Cutoff, U - GLO	0.04982 m2	11.54209	
04.97%	market for transport, tractor and trailer, agricultur...	28.00000 t*km	10.86091	
04.94%	market for transport, tractor and trailer, agricultur...	28.00000 t*km	10.78944	
03.90%	market for electricity, low voltage | electricity, low ...	28.00000 MJ	8.52268	0.00203

Figure 2.S. Carbon footprint for 1 ton of sisal fiber production in SC2

Impact category: Climate change | Global warming potential (GWP100)

Contribution	Process	Required amount	Total result [kg C...	Direct contributi...
100.00%	Processing - SC3	1000.00000 kg	216.72355	
96.07%	Sun drying - SC3	1250.00000 kg	208.20086	
91.09%	Decortication - SC3	2600.00000 kg	197.41129	
86.08%	diesel-B20, burned in agricultural machinery | dies...	1440.08970 MJ	186.55026	81.02931
16.17%	market for agricultural trailer | agricultural trailer | ...	5.21312 kg	35.04529	
09.83%	market group for diesel | diesel | Cutoff, U - GLO	25.60159 kg	21.29405	
08.91%	esterification of soybean oil | fatty acid methyl est...	6.40040 kg	19.31485	
08.45%	market for tractor, 4-wheel, agricultural | tractor, 4...	2.23214 kg	18.32310	
05.33%	market for shed | shed | Cutoff, U - GLO	0.04983 m2	11.54366	
05.01%	market for transport, tractor and trailer, agricultur...	28.00000 t*km	10.86103	
04.98%	market for transport, tractor and trailer, agricultur...	28.00000 t*km	10.78957	
03.93%	market for electricity, low voltage | electricity, low ...	28.00000 MJ	8.52269	0.00203

Figure 3.S. Carbon footprint for 1 ton of sisal fiber production in SC3

Impact category: Climate change | Global warming potential (GWP100)

Contribution	Process	Required amount	Total result [kg C...	Direct contributi...
100.00%	Processing - SC4	1000.00000 kg	186.59374	
98.82%	Sun drying - SC4	1250.00000 kg	184.38503	
93.03%	Decortication - SC4	2600.00000 kg	173.59632	
87.21%	diesel-B100, burned in agricultural machinery | die...	1440.12960 MJ	162.73428	1.17116
51.78%	esterification of soybean oil | fatty acid methyl est...	32.00288 kg	96.62458	
18.79%	market for agricultural trailer | agricultural trailer | ...	5.21327 kg	35.05354	
09.82%	market for tractor, 4-wheel, agricultural | tractor, 4...	2.23220 kg	18.32686	
06.19%	market for shed | shed | Cutoff, U - GLO	0.04983 m2	11.55813	
05.82%	market for transport, tractor and trailer, agricultur...	28.00000 t*km	10.86204	
05.78%	market for transport, tractor and trailer, agricultur...	28.00000 t*km	10.78871	
01.18%	market for electricity, low voltage | electricity, low ...	28.00000 MJ	2.20871	0.00196

Figure 4.S. Carbon footprint for 1 ton of sisal fiber production in SC4