

Assessment of Two Environmental Indicators in *Agave sisalana* Seedling Production

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Sisal (*Agave sisalana*) is a renewable and versatile natural fiber widely used in ropes, rugs, bags, and composite materials for the automotive and construction industries. Beyond its industrial applications, sisal plays an important socioeconomic role, particularly in semi-arid regions such as northeastern Brazil, where it represents a major source of income for local communities. Maintaining this production chain, however, relies on continuous crop renewal, which depends directly on the availability of healthy and sustainable seedlings. In this context, nursery practices become essential for ensuring productivity and controlling phytosanitary problems, such as red rot, which has significantly affected sisal fields since the 1970s. This study evaluates key environmental indicators associated with the production of *Agave sisalana* seedlings, focusing on Global Warming Potential (GWP) and Cumulative Energy Demand (CED) of fossil origins. A gate-to-gate life cycle assessment was conducted to quantify the contributions of inputs such as fertilizers, polyethylene, electricity, and transportation. Fertilizer use was identified as the largest contributor to GWP (61.8%), while electricity (56.5%) and polyethylene (27.20%) were the largest contributors to cumulative energy demand. These results highlight significant opportunities for sustainability improvements through renewable energy adoption, input optimization, and enhanced operational efficiency. The integrated assessment provides a basis for advancing sustainable nursery practices and reducing the environmental footprint of *Agave sisalana* seedling production. Nevertheless, a more comprehensive assessment including additional environmental indicators is required to capture the full range of impacts and to guide more robust sustainability strategies.

Keywords: Nursery. Energy Demand. Greenhouse Gas Emission. Global Warming Potential. Life Cycle Assessment.

Sisal fiber has a bunch of uses, from making twine, rope, rugs, and bags to being used in the auto and construction industries through composites. It is also a big source of income for a lot of communities. Sisal is becoming increasingly important in the world looking for affordable alternatives because it is versatile and sustainable [1,2].

Extracted from the leaves of the *Agave sisalana* plant, sisal fibers are renewable and relatively inexpensive natural resources. Grown mainly in northeastern Brazil and other semi-arid regions, these robust and drought-tolerant plants have been cultivated for centuries due to their high resistance and durability [1-3].

Addition to their economic and social relevance, sisal crops have an environmental dimension, as they can contribute to carbon sequestration in

semi-arid ecosystems and represent a low-impact alternative to synthetic fibers [2,4,5].

However, maintaining this production chain depends directly on crop renewal, which reinforces the importance of efficient and sustainable practices for seedling production.

The production of *Agave sisalana* seedlings from bulbils in nurseries is an important strategy for the renewal of productive areas, especially in the face of phytosanitary problems such as red rot, which since the 1970s has severely affected sisal in the Northeast, particularly in Bahia, reducing productivity and leading to the premature death of plants [6]. Factors such as nutritional deficiencies, water stress, and low physiological resistance increase susceptibility to pathogens [7,8].

To contain the spread of the disease, it is essential to use healthy seedlings obtained through techniques such as tissue culture or propagation via selected bulbils [9].

These bulbils, originating from the inflorescence of adult plants (8–10 years old), should be chosen based on the vigor, size, and health of the mother

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plant, in addition to being larger than 10 cm and undergoing preventive treatments [10,11].

Proper cultivation in a nursery ensures the adequate development of seedlings, which, after growing, can be transplanted to the field, contributing to the sustainability and productivity of the crop [12].

Despite its importance, there are still few studies that quantify the environmental impacts of sisal seedling production. As this stage represents the foundation of the entire value chain, it is essential to understand its contributions to key environmental parameters.

Considering the relevance of this initial stage for the entire sisal production chain, this study aims to evaluate two critical environmental indicators: carbon footprint fossil and cumulative energy demand, to support more sustainable and efficient practices in seedling production. The selection of these parameters is justified, since greenhouse gas emissions and energy use are among the main drivers of climate change and resource depletion, making them fundamental for the environmental performance of agricultural systems.

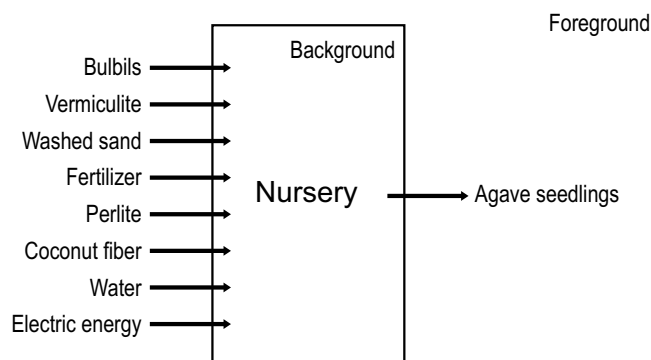
Materials and Methods

This study was conducted in accordance with the Life Cycle Assessment (LCA) methodology, as outlined in ABNT NBR ISO 14040 and ABNT NBR ISO 14044 (2009; 2014) [13,14], with the objective of assessing the global warming potential associated with the production of *Agave sisalana* seedlings.

The product system boundaries were defined as gate-to-gate, as illustrated in Figure 1, which depicts the processes evaluated in this study for the nursery.

The system was modeled using OpenLCA version 2.5, coupled with the Ecoinvent v3.10 database. The environmental impacts assessed included both the Global Warming Potential (GWP) over a 100-year time horizon, which quantifies the contribution of greenhouse gas emissions in terms of carbon dioxide equivalents (CO₂ eq), and the Cumulative Energy Demand (CED), representing

Figure 1. Product system of *Agave sisalana* seedling.



the total amount of energy required throughout the life cycle of seedling production. Biogenic carbon absorbed by sisal seed was not evaluated in this preliminary study.

Table 1 presents the inputs and output flows required to produce 2000 *Agave sisalana* seedlings.

The data used in the modeling were obtained from primary data collected directly in the field,

Table 1. Input and output flows to produce 2000 *Agave sisalana* seedlings.

Materials	Unity	Value
<i>Inputs</i>		
Agave bulbils	Item(s)	2000
Expanded vermiculite substrate	Kg	12
Expanded perlite substrate	Kg	6,666
Coconut husk	Kg	4.8
Water	mL ³	13,608
Fertilizer	Kg	75
Electricity (water pumps)	Kwh	87.48
Transport, lorry	t.km	16.49
Plastic (trays)	Kg	5,617
Polyethylene (screens)	Kg	3,301
<i>Output</i>		
<i>Agave sisalana</i> seedlings	Item(s)	2000

as they were difficult to find in the literature and to ensure greater accuracy and representativeness. The metal infrastructure of the nursery was already installed and is highly durable; for this reason, its contribution as input to the study was not considered. For cultivation, *Agave bulbils* were selected as propagative material, although propagation by other techniques is also feasible for this species.

Regarding the inputs used in the preparation of the substrate, washed sand, vermiculite, perlite, and coconut fibers were used to improve the soil structure and promote the healthy development of the seedlings. Irrigation was carried out with water from the local public network, using electric pumps, whose energy consumption was estimated based on the nominal power of the pumps and the operating time.

The inputs used in the nursery in Conceição do Coité, Bahia (Brazil) were mainly transported by truck. For those coming from Salvador, Bahia (Brazil), an average distance of 220 km was considered, while inputs such as sand were obtained from local suppliers, thus reducing the logistical impact. The calculation of the environmental impact of this stage was based on the total weight of each input transported and the respective distances, allowing for an accurate estimate of vehicle fuel

consumption (diesel) and associated atmospheric emissions, according to standard emission factors.

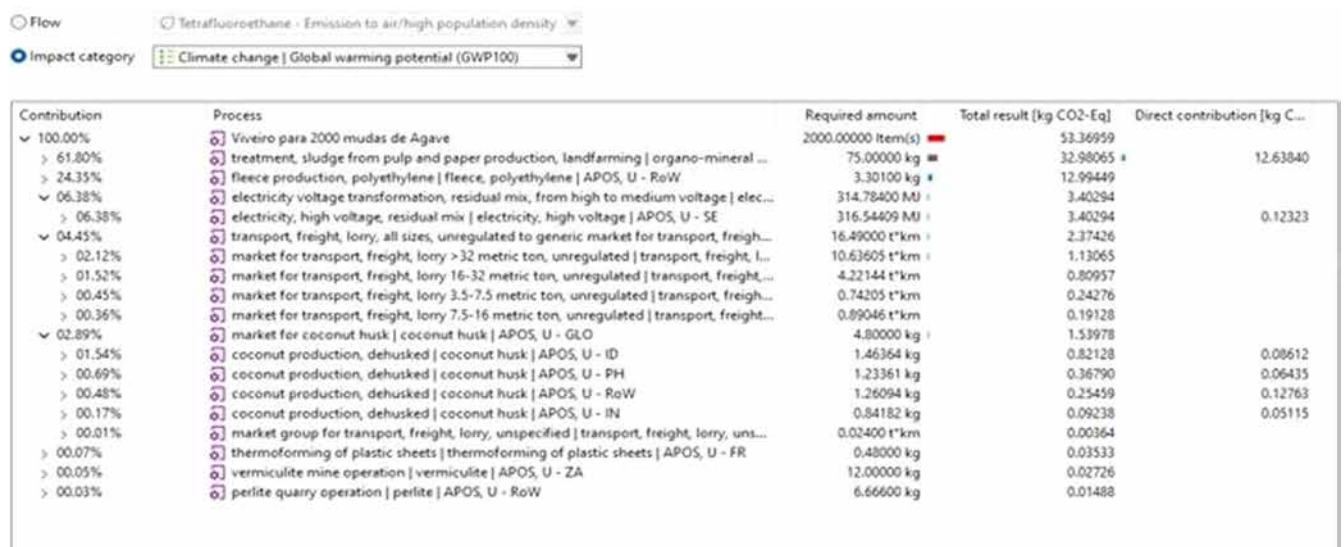
In addition to the supplies used to grow *Agave* seedlings, we also considered the rigid plastic trays where the bulbs are cultivated and nourished until they reach the desired size. These trays have an average useful life of five years. The nursery cultivation process lasts approximately six months, which means that the trays are used twice a year over the course of those five years. Therefore, the total weight of the plastic tray was distributed proportionally to its useful life.

The same methodology was applied to the black monofilament screens, made of polyethylene, used to cover the nursery. These screens have an average useful life of ten years, a value considered for modeling based on their time of use. These materials are essential for the efficient operation of the nursery.

Results and Discussion

In Figure 2, the contributions to the carbon footprint of the *Agave sisalana* seedling nursery are presented, allowing the identification of the share of each input, process, and stage in the Global Warming Potential (GWP), expressed in kilograms of carbon dioxide equivalent (kg CO₂eq),

Figure 2. Impact of GHG emissions from the production of 2000 *Agave sisalana* seedlings.



throughout seedling production. These results are preliminary and serve to provide an initial insight into the relative importance of each component in the overall carbon footprint, pending further detailed analysis and data refinement.

Global warming refers to the gradual increase in the Earth's average temperature, caused by the accumulation of greenhouse gases (GHGs) in the atmosphere, such as chlorofluorocarbons (CFCs), carbon dioxide (CO₂), and other pollutants predominantly generated by human activities [15]. The increasing concentration of these gases intensifies the greenhouse effect, raising the temperature of the lower atmosphere and triggering large-scale climate change [16].

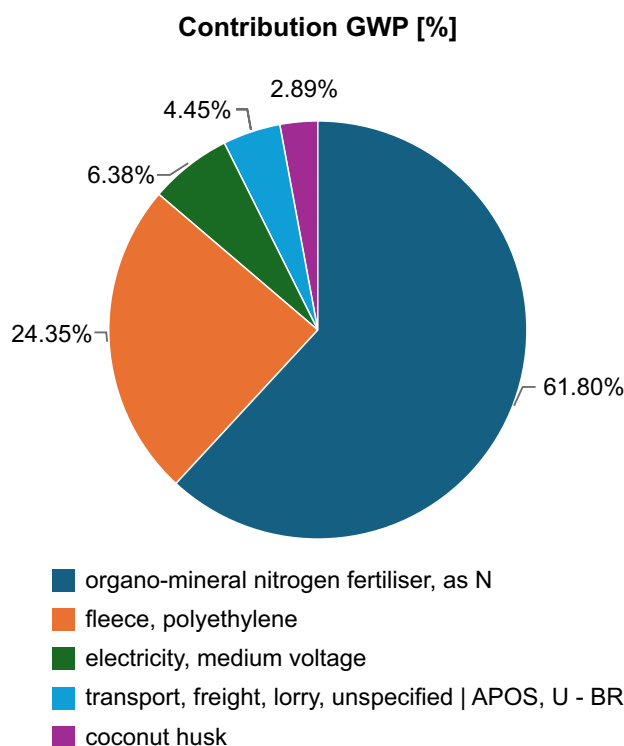
The analyzed production process resulted in a total GWP of 53.37 kg CO₂eq for 2,000 seedlings, equivalent to 0.026685 kg CO₂eq per individual seedling. This value is comparable to that reported in the literature for forest nursery seedlings (0.02945 kg CO₂eq) [16].

The analysis shows that the largest share of emissions is associated with fertilizer use, accounting for 32.98 kg CO₂eq (61.80% of the total), as illustrated in Figure 3. This impact includes both indirect N₂O emissions from soils and emissions associated with fertilizer manufacturing processes [17].

Polyethylene was the second most significant contributor, with 12.99 kg CO₂eq (24.35%), primarily linked to emissions generated along its production chain. Electricity used to operate water pumping systems for irrigation contributed 3.40 kg CO₂eq (6.38%), while road transportation by truck, even over relatively short distances within the same state, accounted for 2.37 kg CO₂eq, reflecting the impact of fossil fuel use.

It is important to note that this gate-to-gate analysis does not include the benefits of carbon sequestration by seedlings during growth, nor the impacts associated with the end-use phase. From a process sustainability perspective, the results indicate that targeted interventions to reduce fertilizer use, adopt lower-carbon alternatives (such as organic or renewable-based fertilizers),

Figure 3. Contributions GHG emission of produce 2000 *Agave sisalana* seedlings.



and replace plastic inputs with recycled or biodegradable materials could substantially decrease the total GWP. Furthermore, optimizing energy consumption—either by integrating renewable sources for water pumping or improving irrigation system efficiency—represents a concrete opportunity for emission mitigation. When combined with more efficient logistics planning, these measures can contribute to aligning seedling production processes with the principles of the circular economy and global carbon neutrality targets.

Complementary to GWP, Cumulative Energy Demand (CED) is another important life cycle indicator, defined as the total amount of energy required throughout the entire life cycle of a product, encompassing its production, use, and end-of-life stages [15]. This metric serves as a methodological approach to assess, analyze, and determine the sustainability of a product based on its overall energy consumption.

In the production process analyzed, the total CED was 12.734 MJ for 2,000 seedlings, including electricity, polyethylene, and fertilizers (Figure 4). Electricity accounted for the largest share, with 7,193 MJ (56.5% of the total), followed by polyethylene with 3.465 MJ (27.2%), while fertilizers contributed the remaining portion. These findings are preliminary and provide an initial overview of energy consumption distribution among the main inputs. These findings are consistent with previous studies highlighting the significant role of electricity and plastics—particularly seedling trays, greenhouse structures, and irrigation systems—in the total CED of nursery operations [19,20].

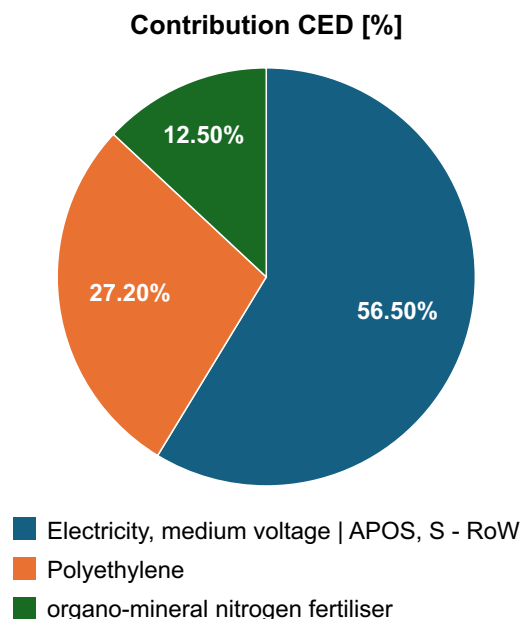
The CED assessment also indicates clear opportunities for impact reduction, including replacing fossil-based electricity with renewable sources (e.g., photovoltaic systems), optimizing plastic use, and selecting inputs with lower cumulative energy requirements. As emphasized in the literature, improving energy efficiency can provide not only environmental benefits but also economic advantages, given that energy is among the main operational costs in nursery production [21].

Together, the assessments of Global Warming Potential (GWP) and Cumulative Energy Demand (CED) provide a comprehensive understanding of the environmental impacts associated with the production of *Agave sisalana* seedlings. This dual approach is essential for advancing sustainable nursery practices that align with broader environmental and economic goals.

Conclusion

This study provided a preliminary assessment of the environmental impacts associated with *Agave sisalana* seedling production, employing a gate-to-gate system, and highlighting the main contributors to the Carbon Footprint (Global Warming Potential, GWP) and Cumulative Energy Demand (CED). Aligned with the initial objective of supporting more sustainable and efficient nursery practices, the results identified fertilizer use as the largest contributor to GWP, accounting for 61.8%

Figure 4. Contributions CED emission of produce 2000 *Agave sisalana* seedlings.



of greenhouse gas emissions, while electricity consumption and plastic inputs predominated in driving CED, together representing over 80% of the total energy demand. These findings reveal clear opportunities for interventions aimed at improving the sustainability of the production process, such as the adoption of renewable energy sources (e.g., photovoltaic systems to supply nursery electricity), the development of strategies to optimize and reduce fertilizer application, and the replacement or recycling of plastic materials with alternatives of lower environmental impact. Additionally, enhancements in irrigation system efficiency, combined with more sustainable logistical practices, may further amplify reductions in overall environmental impacts.

The scarcity of specific studies for comparison, together with the limitations of the available data, represents a significant constraint to this analysis. As next steps, sensitivity analyses focusing on critical parameters are recommended to further understand result variability and to refine mitigation strategies. Moreover, the incorporation of more detailed regional data could increase the robustness and accuracy of future environmental assessments.

Finally, expanding the analysis to cradle-to-grave approaches is essential to capture the environmental benefits associated with seedling growth and final use, as well as potential offsets resulting from carbon sequestration by the plants. A relevant gap in this study refers to the non-consideration of biogenic carbon fluxes, which could affect the carbon balance of the nursery system. Including this accounting in future evaluations is fundamental to provide a more comprehensive understanding of the net greenhouse gas emissions associated with *Agave sisalana* seedling production.

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