Life Cycle Assessment in Agave Cultivation and Processing: A Review

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Agaves thrive in arid and semi-arid environments and can be transformed into various products through processing and refinement. The Life Cycle Assessment (LCA) methodology is employed to assess the environmental impacts of these processes. This study analyzes LCA studies related to the cultivation and processing of agave, identifying the main topics explored, relevant environmental impacts, and existing gaps. Information such as the functional unit, life cycle impact assessment methods, databases, software, objectives, and conclusions of the primary studies was evaluated. Various applications of agave and their potential environmental impacts were observed, with cultivation and processing showing comparatively lower impacts than other plants, mainly due to reduced water consumption and lower greenhouse gas (GHG) emissions.
Keywords: Agave. Biomass. Carbon Footprint. Water Footprint. Life Cycle Assessment.

Agaves comprise a group of more than 200 species of succulent plants that flourish in arid and semi-arid environments, having adapted to adverse conditions and low water availability [1,2]. These plants are native to semi-desert regions of the Western Hemisphere, including the southwestern United States, Mexico, Central America, northern South America, and the Antilles [1].

Agave's applications vary depending on the species. These plants can produce tequila, carpets, tapestries, doormats, stretchers, bags, and biomass for biofuel and bioproduct generation [3].

Brazil is among the leading producers and exporters of natural fibers from Agave sisalana Pierre, particularly in Bahia, which spearheads production alongside other northeastern states such as Paraíba, Ceará, and Pernambuco. This region concentrates the production of agave fiber, a crucial subsistence resource in the semi-arid areas of Bahia due to its drought resistance and phytochemical composition [1,4,5]. In Mexico, the cultivation of Agave tequilana Weber var. 'Blue' holds significant economic and social relevance, generating employment in agriculture and industrial processing, and substantially contributing to tequila exports [1,6].

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Given the diverse products derived from agave, it is essential to assess the environmental performance of its production processes to evaluate their sustainability. One of the industry's principal tools for this purpose is Life Cycle Assessment (LCA) [7]. This approach entails compiling input and output data related to material and energy flows across the entire life cycle of a product system, estimating the environmental impacts generated at each stage. ISO 14040/2009 (Principles and Framework) and ISO 14044/2009 (Requirements and Guidelines) offer a structured framework for conducting high-quality assessments [7,8].

This study aims to analyze the trends and findings of research on the application of Life Cycle Assessment (LCA) to the cultivation and processing of agave. The goal is to identify and compare the environmental impacts associated with agave across different life cycle stages and highlight current research gaps.

Materials and Methods

The article selection process was conducted through the ScienceDirect and Scopus databases, which provide comprehensive access to global research and analytical tools. Predefined keyword sets were combined using the Boolean operators "AND" and "OR," as shown in Table 1. The selected terms were associated with Life Cycle

Table 1. Quantities of articles.

Repositories	Agave AND (Cultivation OR Farming OR Growth) AND "Life cycle assessment"	Agave AND Processing AND "Life cycle assessment"	Duplicates
Science Direct	48	65	56
Scopus	4	4	
Selected	6	1	

Assessment and the cultivation and processing of agave. Searches were conducted in English within the "ARTICLE TITLE, ABSTRACT, KEYWORDS" fields, and the "Research articles" filter was applied. The review was performed in May 2024. Review articles were excluded, as this study aimed to analyze trends in primary research, particularly those involving experimental or observational data.

Articles were then filtered to remove duplicates and to exclude those whose titles or abstracts did not align with the research topic or were not fully available. This selection involved reading each article to confirm whether the search terms were the focus of the research rather than mentioned in passing. Specifically, the selected studies had to involve agave biomass (although other biomasses could also be included) and must have conducted LCA analyses focusing on cultivation or processing to identify the primary environmental impacts related to agave.

Table 1 presents the number of publications retrieved from the repositories using the selected search terms. A total of 65 articles were initially identified, of which only 7 met the inclusion criteria.

Results and Discussion

Table 2 presents the selected studies in descending chronological order based on their year of publication. It outlines each study's central objective, functional unit, database used, LCA software, life cycle impact assessment (LCIA) method, impact categories considered, and main conclusions.

The impact categories identified across the analyzed studies include:

- Global Warming Potential (GWP)
- Stratospheric Ozone Depletion (SOD)
- Terrestrial Acidification (TA)
- Freshwater Eutrophication (FE)
- Freshwater Ecotoxicity (FET)
- Terrestrial Ecotoxicity (TET)
- Human Carcinogenic Toxicity (HCT)
- Fossil Resource Scarcity (FRS)
- Ionizing Radiation (IR)
- Ozone Depletion Potential (ODP)
- Photochemical Oxidation Formation Potential – Human health (HOFP)
- Photochemical Oxidation Formation Potential – Ecosystems (EOFP)
- Terrestrial Acidification Potential (TAP)
- Freshwater Eutrophication Potential (FEP)
- Human Toxicity Potential – Cancer (HTPc)
- Human Toxicity Potential – Non-cancer (HTPnc)
- Fossil Fuel Potential (FFP)
- Water Consumption Potential (WCP)
- Acidification Potential (AP)
- Photochemical Oxidation Potential (PCOP)
- Eutrophication Potential (EP)
- Renewable Energy Use (REU)
- Non-renewable Energy Use (NREU)
- Greenhouse Gas Emissions (GHG)
- Fine Particulate Matter Formation (PMFP)
- Cumulative Energy Demand (CED)
- Water Consumption (WC)

- Global Warming (GW)
- Ozone Formation – Human Health (OFHH)
- Fine Particulate Matter Formation (FPMF)
- Ozone Formation – Terrestrial Ecosystems (OFTE)
- Human Non-carcinogenic Toxicity (HnCT)
- Land Use (LU)
- Mineral Resource Scarcity (MRS)

These diverse impact categories highlight the comprehensive nature of environmental performance assessments within LCA agave cultivation and processing studies. Despite methodological variations across studies, global warming potential, water consumption, and cumulative energy demand were among the most consistently analyzed and reported categories. Such consistency reflects these indicators' critical importance in evaluating the sustainability of agave-based production systems.

The literature reveals a wide range of proposals using the LCA methodology for agave, resulting in variations in the software, impact categories, and functional units selected. Among the studies, midpoint impact categories were more frequently evaluated than endpoint categories, with Ecoinvent being the most commonly used database. The Global Warming Potential (GWP) was the most frequently used impact category in the reviewed analyses. This category assesses the contribution of various greenhouse gases (GHGs) to global warming, expressed in carbon dioxide equivalents (CO_2 eq). Evaluating this impact helps identify which stages of the agave life cycle emit the most GHGs and how those emissions can be reduced. For instance, Yan and colleagues (2020) reported that the global warming impact of agave was 62% lower than corn's and 30% lower than sugarcane's, highlighting its significantly lower carbon footprint [13].

Table 2. Selected studies with the agave plant that conducted Life Cycle Assessment (LCA)

Ref.	Objective	Functional Unit/ Database	Software/ Method of LCIA	Impact Categories	Main Conclusions
[9]	Evaluate the environmental impacts of current agave bagasse management practices and compare them with alternative valorization processes, where the bagasse is anaerobically digested or processed and used as reinforcement in a polylactic acid (PLA) bioplastic composite.	1.1 tons of agave bagasse / N.F	SimaPro 9.5.0 / ReCiPe 2016 v1.1	GWP, SOD, TA, FE, FET, TET, HCT, FRS	PLA production chains need further development and standardization to reduce their environmental footprint. The low methane yield in anaerobic digestion does not offset its impacts.
[10]	Evaluate the environmental impacts of mezcal production from Agave cupreata in Michoacán, Mexico. The central issue is the influence of management options for vinasse, bagasse, and biomass energy. The study was conducted using life cycle assessment (LCA).	A 0.75-liter bottled mezcal produced/ Ecoinvent	N.F / ReCiPe midpoint	GWP, PMFP, FEP, CED	Regulations should focus on forest management to make sustainable use of wood (FSC systems), improving road conditions to reduce fuel consumption, and encouraging practices such as avoiding the use of agrochemicals during the growth of the agave, promoting the application of agroforestry systems, and organic pest control that can benefit the maintenance of agave cultivation in the long term. The results of this research can assist producers in prioritizing the reduction of material intensity and environmentally damaging emissions and monitoring progress.

Ref.	Objective	Functional Unit/ Database	Software/ Method of LCIA	Impact Categories	Main Conclusions
[11]	Compare the environmental performance associated with electricity generation from combustion and gasification processes of sugarcane and agave bagasse.	1 MJ of electricity produced/ Ecoinvent	SimaPro 8 / ReCiPe 2016	GWP, ODP, HOFP, EOFP, TAP, FEP, HTPc, HTPnc, FFP, WCP	In the cultivation stage, the main factors causing environmental damage are fertilizer use, diesel consumption, and emissions to air and water, with sugarcane cultivation having an impact 2 to 6 times greater than that of agave (except for FEP and HTPc). Combustion of sugarcane bagasse is the scenario with the highest environmental impact, followed by combustion of agave bagasse and gasification processes.
[12]	Agave juice and sugarcane molasses were compared as potential feedstocks for producing bioethanol in Mexico in terms of their environmental impact and economic factors.	1 MJ of energy / Ecoinvent	SimaPro 8 / ReCiPe 2016	GWP, ODP, HOFP, EOFP, TAP, FEP, HTPc, HTPnc, FFP, WCP	Production of bioethanol from agave juice had a lower environmental impact compared to sugarcane juice, attributed to lower pesticide, coal, and water consumption. Bioethanol production was the most impactful stage (>60%) due to low ethanol yields from fermentation. Economically, neither feedstock is viable with the current Mexican energy grid, but with 26.5% renewable energy, bioethanol production from agave juice becomes feasible.
[13]	The objective of this article was to conduct the first comprehensive LCA and economic analysis of 1st and 2nd generation (2G) ethanol produced from Australian grown agave, using data collected from a 5-year field experiment in Queensland.	1 GJ of fuel ethanol produced / Ecoinvent	SimaPro 8.4 (2018) / N.F	GW, SOD, IR, OFHH, FPMF, OFTE, TA, FE, TET, FET, ME, HCT, HnCT, LU, MRS, FRS, WC	Agave outperforms first-generation biofuel crops like corn and sugarcane in water-related environmental impacts and offers competitive ethanol yields. Despite its high land-use impact, agave can be cultivated on land unsuitable for food. It is a promising feedstock for biofuels in arid regions, with a yield of 7414 L/ha/year after 5 years, but it is economically unviable without government subsidies.
[14]	To investigate the economic and environmental feasibility of bioethanol production from Mexican lignocellulosic biomass, including wood species, grasses, bagasse, and crop residues. Comprehensive process modeling, economics, and life cycle assessment (LCA) were employed to understand the effects of these feedstock compositions on bioethanol yield, economic performance, and environmental impact within an integrated biorefinery environment that coproduces heat and power.	1 kg of biomass/ Ecoinvent 3	N.F / CML V3.03	GWP, AP, PCOP, EP	Overall, wood and agricultural wastes are competitive economically and environmentally, while lawns have had poor performance and the bagasse mixed results. The correlations based on biomass compositions suggest a proportional limit for a balanced process and GWP savings, facilitating rapid biomass screening and the identification of ideal raw material compositions.

Ref.	Objective	Functional Unit/ Database	Software/ Method of LCIA	Impact Categories	Main Conclusions
[15]	Conduct Life Cycle Assessment (LCA) of sisal fiber production in Tanzania and Brazil based on primary data, covering approximately 45% of global production. The specific objectives are to evaluate the effects of local differences in agricultural and fiber processing practices, and to assess the influence of methane emissions from waste disposal on the overall environmental performance of sisal fiber production, using modeling and scenario analysis.	One metric ton of sisal fiber/ Ecoinvent v2.2	N.F / ReCiPe Midpoint v1.12	REU, NREU, GHG	This study shows that sisal fiber produced in Tanzania or Brazil has low emissions of non-renewable energy (NREU) and greenhouse gases (GHGs) from cradle to port. Environmental performance of sisal fiber may vary significantly based on local practices, location and assumptions. Disposal of waste in open ponds can increase GHG emissions, but these can be mitigated by short disposal periods, bare ponds or use of waste to generate biogas. In all scenarios, NREU and GHG emissions from sisal fibres are 75% to 95% lower than those of glass fibres.

Other commonly assessed categories included terrestrial acidification potential and human toxicity (both carcinogenic and non-carcinogenic).Terrestrial acidification is primarily caused by pollutants like NH_3, NO_x, and SO_2, which form acids upon contact with water vapor and adversely affect soil, aquatic systems, and biodiversity [11].Human toxicity assessments help identify harmful substances in the life cycle and support measures to mitigate human exposure to such substances. Studies comparing agave to other biomasses—notably sugarcane—consistently indicated that agave has a lower environmental impact [11,12]. Parascanu and colleagues (2021) state that these differences stem primarily from cultivation practices. Sugarcane requires higher inputs of chemical compounds and fertilizers, leading to greater emissions into water and air.

A notable difference in Water Consumption Potential (WCP) was also observed, as sugarcane cultivation depends heavily on irrigation, unlike agave [11]. This reinforces agave's advantage in terms of a lower water footprint.

Conclusion

The comprehensive literature review underscores the need for expanded Life Cycle Assessment (LCA) studies focused on the cultivation and processing of agave. The selected articles—most of which are recent—enabled a detailed analysis of the diverse methodological approaches used in this field.

This study highlighted a growing concern about the environmental impacts of agave throughout its life cycle. Agave has demonstrated consistently lower environmental impacts compared to other biomass sources, particularly regarding water use and carbon emissions. Nevertheless, areas for improvement remain. The results indicate the need for policy support to promote strategies that reduce environmental impacts and incentives to enhance the economic viability of agave-based bioproducts.

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