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Sustainable Industrial Sotol Production in Mexico—A Life Cycle Assessment

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Abstract: Sotol is a distilled spirit made in the north of Mexico produced from the wild plant *Dasylirion wheeleri*. Although sotol was awarded the Designation of Origin (DO) in 2002 and has an economic influence on the DO region, its environmental profile has not been determined. For that reason, this paper reports a Life Cycle Analysis (LCA) of the industrial sotol production process in the Mexican state of Chihuahua to determine any significant environmental impacts caused by sotol production from raw material acquisition to the packaging stage. The LCA was modeled using SimaPro 8.5.2 software (PRé Sustainability, Amersfoort, The Netherlands) and the environmental impacts were calculated using the CML-IA baseline v3.03/EU25 impact assessment technique. The findings reveal that sotol beverage manufacturing considerably affects three of the eleven impact categories selected and that the harvesting and bottling stages have the greatest negative environmental impact of all the sotol production stages. According to empirical data, one bottle (750 mL) of sotol results in a higher carbon dioxide value than any other spirit evaluated in earlier LCA studies, with white, rested, and aged sotol generating 5.07, 5.12, and 5.13 kg CO_2 eq, respectively. Other drinks, such as mescal, classic gin, and whisky generate only 1.7, 0.91, and 2.25 kg CO_2 eq, respectively. In conclusion, sotol distillery companies should start to decrease road transport of raw materials used in the packaging stage and begin to cultivate sotol instead of extracting it from the wild as strategies to achieve cleaner production.

Keywords: LCA; environmental impact; carbon footprint; carbon emissions; sustainable production

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1. Introduction

Sotol is an alcoholic drink made from a wild plant of the genus *Dasylirion* that grows in several areas of the Chihuahuan Desert [1]. This spirit drink has economic significance in the community [2]. For instance, since the colonial era in Mexico, it has been marketed from the Mexican state of Chihuahua to New Mexico and Texas in the USA. After the Mexican Revolution, this alcoholic drink was used to prevent illnesses as it was recognized as having curative properties, even though it was banned at some point [3]. However, it was not until 2002 that sotol received the badge of Designation of Origin (DO). DO covers the Mexican states of Chihuahua, Durango, and Coahuila [4]. People in the DO region are increasingly interested in making money by buying sotol from sotol makers and selling this spirit drink under their brand, according to Sotol Certificate Council (CCS; acronym of the Spanish phrase Consejo Certificador del Sotol).

Similar to other Mexican spirits, such as tequila and mescal, sotol can be produced with artisanal or industrial manufacturing [5]. According to CCS, the sotol industry produces approximately 5200 hl per year. Of that amount, 70 percent corresponds to sotol industrial manufacturing. Despite that relevance, however, no one knows what type of environmental damage is associated with the industrial manufacturing of sotol. Most of prior research on sotol has been focused on developing *Dasylirion* cultivation, regulating the quality, and identifying volatile organic compounds and metals [6].

One way of estimating the harmful effects of making distilled spirits is using the life cycle assessment (LCA) method [7–9]. LCA has been used to report the causes of environmental impacts on the manufacturing process of artisanal gin [10], cognac [11], whisky [12], vodka production [13], artisanal mescal [14], and artisanal sotol [15]. Even though artisanal sotol has been researched for environmental issues, a literature search using the databases of Science Direct, EBSCOhost, and Wiley Online Library revealed that its industrial manufacturing and environmental impacts have not yet been reported in scientific journals.

Based on the aforementioned, this paper aims to reveal the environmental impact assessment of sotol industrial manufacturing in Mexico by applying the life cycle assessment (LCA) method. Regulatory bodies and other interested parties may use the findings from the LCA study to make sotol production less harmful to the environment.

2. Materials and Methods

The LCA study was modeled using Simapro 8.5.2 software (PRé Sustainability, Amersfoort, The Netherlands) and following ISO 14040/44 guidelines. The LCA method was mainly based on the following steps: goal and scope, functional unit (FU), system boundary, life cycle inventory (LCI), and the interpreting of the results [16,17]. Each step mentioned is described below according to the case study.

As a procedure to classify the empirical data gathered from the LCI step into impact categories, which makes it possible to evaluate the environmental impacts caused by sotol, the method of CML-IA baseline v3.03/EU25 was used. The impact categories consist of marine aquatic ecotoxicity potential (MAETP), global warming potential (GWP), fossil depletion potential (FDP), human toxicity potential (HTP), freshwater aquatic ecotoxicity potential (FAETP), acidification potential (AP), terrestrial ecotoxicity potential (TETP), eutrophication potential (EP), photochemical oxidation potential (POCP), abiotic depletion potential (ADP), and ozone-layer depletion potential (ODP). The CML-IA was selected because it looks at how farming [18] and process manufacturing [19,20] affect the environment in diverse ways.

2.1. Goal and Scope

The goal of this research is to identify the environmental implications of sotol industrial manufacturing considering the inputs from raw materials and auxiliaries to production and filling.

2.2. Functional Unit

The considered distillery produces about 7500 L of sotol per year, commercialized as three types: white, rested, and aged. The first one is diluted with water. The second one is stored for four months in oak barrels. The last one is stored for 14 months in oak barrels. Each type of sotol is packaged in 750 mL white glass bottles. Consequently, the functional unit (FU) selected was a 750 mL bottle of sotol.

2.3. System Boundary

All activities and tasks, from cradle to gate, were included within the system boundary, as shown in Figure 1. The LCA study starts with the *Dasylirion* species collection from wild populations (cradle) and the transportation of raw materials and auxiliaries to the distillery. After that, it includes the 6-stage manufacturing process in the Vinata: cooking, milling, fermentation, distillation, bottling, and packaging (gate). However, some activities were eliminated for several reasons from the system boundary of the LCA study. Essentially, the activities that were not considered are those described below.

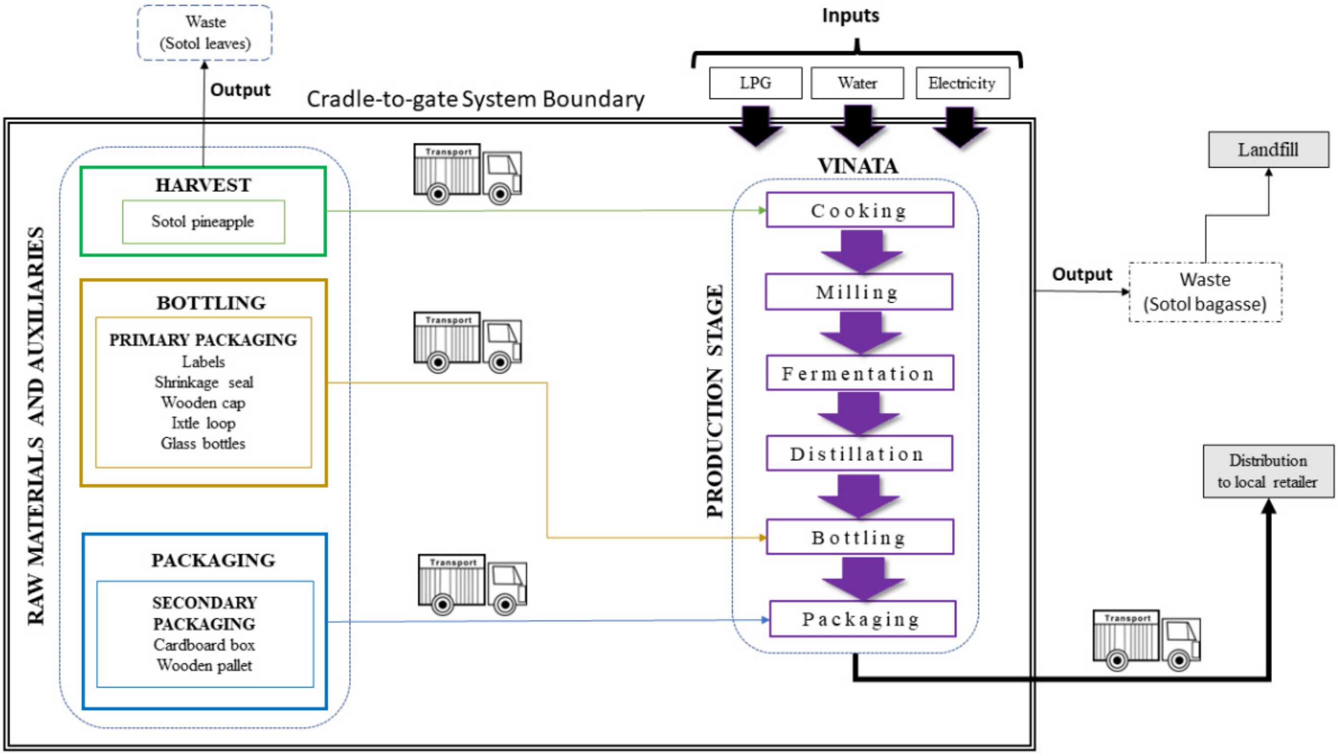

Figure 1. System boundary of sotol production.

Dasylirion plantation: After an experimental period of *Dasylirion* plant cultivation performed by researchers from Universidad Autónoma de Chihuahua for 16 years, *Dasylirion* cultivation is just beginning to be promoted among sotol makers. As a result, CCS and sotol makers have no data on *Dasylirion* plantations.

Distribution of the final product: It is not clear how to calculate the amount of pollution caused by buying sotol. Since people buy more than one good item when they go shopping, it is not clear how to count the carbon emissions of a bottle of sotol during shopping. The effects on the environment caused by shopping time should be spread among those things bought.

Maintenance of equipment and tool operation: Before starting sotol production, maintenance activities are made within two weeks, and no power is needed for maintenance tasks. They are scheduled as interrupted tasks during that time.

Working tools: During the manufacturing process, the inputs derived from tools used to make things were left out because their carbon footprint is less than 1% of the total carbon footprint.

Labor force: It was assumed that the workforce did not contribute to significant environmental impact. There is no agricultural system, such as there is for wine production, where labor is needed [21]. Three people collect sotol pineapples for three days, and it takes a month to process 15 tons. In the case of making sotol, three people work on the production process operations.

Transport for transfer: This factor was not thought to be linked to the environment because only one employee drives to work, and the rest moves on public transport.

Activities related to waste management: The sotol bagasse residue generated in the milling stage was not considered in the LCA study. It is randomly placed in open spaces next to the distillery. Generally, it is used as organic matter for different land uses. In addition, solid waste in the Vinata is collected by a waste collection service.

2.4. Life Cycle Inventory

The LCI (life cycle inventory) was based on a distillery north of Chihuahua State that supplied statistics on material flow and energy consumption. Table 1 displays the primary empirical data for research obtained from the sotol-producing house. The LCI shows that the time necessary to gather the materials needed to prepare 1250 L of sotol with a 47% alcohol concentration was 30 days. All the empirical data supporting this study's findings are available in Supporting Material S1. The empirical data come from the seven stages of the elaboration of sotol. Below are those stages.

Table 1. Main empirical data for LCI.

Stage	Data (Input)	Unit	Quantity
Harvest			
	Transportation	km	617
(Stage I)	Sotol pineapple biomass	kg	15,000
	Output		
	Dasylirion leaf biomass	kg	4500
Cooking	*Input*		
	LPG	kg	3600
	Water	L	3500
(Stage II)	*Output*		
	Muddy water	L	19
	Water	L	20
Milling	*Input*		
	Water	L	2500
(Stage III)	*Output*	L	
	Bagasse	kg	12,000
Fermentation	*Input*		
(Stage IV)	Water vapor	kg/cm^2	100
Distillation	*Input*		
(Stage V)	Evaporative cooling tower: water consumed	L	900
Bottling	*Input*		
	Transport	km	1664
	Water	L	50
	Distilled water	L	160
(Stage VI)	Glass bottle	kg	0.878 per bottle
	Output		
	Rested sotol loss from barrels	L	10
	Aged sotol loss from barrels	L	40
Packaging	*Input*		
(Stage VII)	RSC box	kg	0.48 per box

The first stage is to harvest the sotol stems. The *Dasylirion* plant is collected from wild populations, and its leaves are removed until just the *Dasyliron*'s stem remains. The stem is called "sotol pineapple" by workers. As a harvesting method, no equipment powered by gasoline engines is used. Afterwards, the raw material (sotol pineapple) is carried by trucks to the sotol distillery (Vinata).

The second stage is cooking the sotol pineapples. Once they arrive at the processing facility, they are cooked in an autoclave, which can cook three tons of sotol pineapples in eight hours. The autoclave uses a 50 horsepower (HP) steam boiler fed by a water pump. The steam boiler consumes liquefied petroleum gas (LPG) as an energy source.

The third stage is milling the sotol pineapples. The cooked pineapples are crushed in a mill driven by a 10 HP electric engine. In this step, water is mixed with crushed pineapple to obtain juice rich in sugar for use in the fermentation stage. The waste in this stage is sotol bagasse, which is moved from the Vinata to an improvised outdoor space. The distillery uses bagasse as organic matter in the soil around the Vinata.

The next stage is fermentation. The juice from the earlier stage is transferred to stainless steel tanks for the open fermentation process. Sugar is fermented using native wild yeast, which turns it into alcohol (ethanol) and other chemical compounds that give taste and smell.

After the fermentation stage, distillation is the stage that follows. The juice coming from the fermentation stage is distilled using a stainless steel still. The distillate flow is cooled using an evaporative cooling tower, which consumes 900 L of water per month and works with a 3 HP electric motor and a 1.5 HP electric pump.

On completing distillation, the bottling stage starts. This stage involves bottling the types of sotol (white, rested, and aged) in 750 mL glass bottles. Each container is pre-washed in hot water and cleaned in a washing machine. Afterwards, a semi-automatic machine operating at 200 bottles per hour is used to fill bottles. The bottling of white sotol occurs directly after the distillation stage. Furthermore, depending on whether it has been rested or aged, sotol is kept in barrels for four and fourteen months, respectively. Distilled water is used to regulate the degree of alcohol in sotol. The bottling stage is finished when labeling and bottle arrangement, using an ixtle loop, are conducted by hand.

Finally, the last step is packaging. Twelve bottles are stored in standard slotted container (RSC) boxes. No electric power equipment is used. All the boxes are kept on wooden pallets while they await delivery.

3. Results

The findings show no significant differences between the three types of sotol. According to the empirical data, the lowest GWP (global warming potential) is that of white sotol (5.07 kg CO_2 equivalent); aged sotol has the highest GWP (5.13 kg CO_2 equivalent), showing a standard deviation of 0.03 L. The contribution rate to each stage of the distilled beverage manufacturing in terms of greenhouse emissions per type of sotol is shown in Figure 2. Therefore, it takes an average of 5.10 kg of CO_2 equivalent to produce one bottle of sotol from when *Dasylirion* plants are collected to when the bottle is in the packaging.

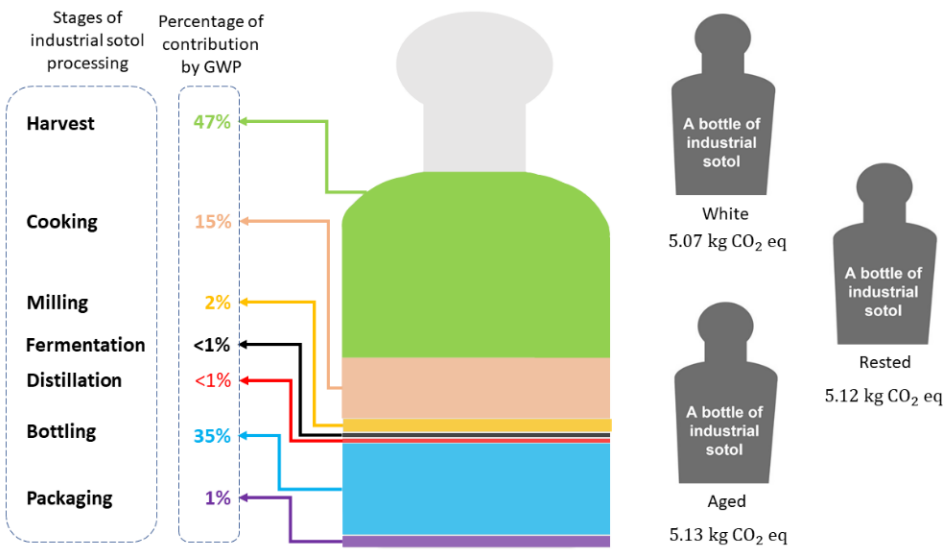

Figure 2. GHG emissions per sotol variety.

The highest amounts of CO_2 are released during the harvest and bottling stages, which account for 47% and 35%, respectively, as seen in Figure 2. These stages comprise a large part of the total carbon footprint caused by the sotol-making process, as they use high energy consumption to move raw materials and auxiliaries, for instance, transport using diesel. Another stage that makes a significant difference (15%) is cooking, because the energy consumed by the autoclave plays a crucial role. In short, the harvest, cooking, and bottling stages account for 97% of the GWP.

Even though raw commodity transport in the bottling stage is the main contributor to environmental damage, the glass bottle used by the sotol company has an equally strong negative impact on the environment. Because the weight of the bottle is large more material and energy are needed to make it. Hence, the current glass bottle should be reconsidered since it affects the environment to a great degree.

The findings show that the time spent in barrels by rested and aged sotol significantly causes a minor variation in the impact categories per FU. For example, the MAETP (marine aquatic ecotoxicity potential) varies by 0.89 percent depending on the sotol type. However, the bottling stage causes the most significant variation; the highest percentage variation is 5.8% in the HTP (human toxicity potential), and the lowest is 1.7% in the MAETP impact category. In addition, there are no differences (0 percent) in the total environmental effect of any sotol type in the harvest, cooking, milling, fermentation, distillation, and packaging stages. For further information, see the extra (Supporting Information S2), which show the total LCA results by type of sotol.

Another promising finding is that sotol industrial manufacturing causes considerable damage to aquatic and terrestrial ecosystems. The damage to the ecosystem is explained by the high values obtained in the impact categories of MAETP, FAETP, and TETP. Table 2 summarizes the findings per functional unit in each impact category for white sotol.

The high values shown for the impact categories of FDP (72.119 MJ) and HTP (3.24 kg 1,4-DB equivalent) are linked to fossil fuel consumption. As raw commodity suppliers in the spirit industry are far away from the sotol distillery location, a land transportation service is necessary. As a result, the current use of fossil fuels must be considered a key issue.

In general, the production input of transport has a significant impact, and so does the glass bottle weight (0.878 kg per bottle) used by the sotol distillery. Therefore, discussing effective suggestions to reduce the harmful effects is necessary.

Table 2. Environmental impact categories of the sotol industrial production process.

	Stages of Sotol Alcoholic Beverage Processing								
Impact Category	**I**	**II**	**III**	**IV**	**V**	**VI**	**VII**	**Total**	**Unit**
Marine aquatic ecotoxicity (MAETP)	1078.08	237.946	137.637	40.332	79.995	1855.13	110.282	3539.41	kg 1,4-DB eq
Fossil depletion (FD)	34.7170	12.242	1.04012	0.12131	0.16912	23.3215	0.50739	72.1189	MJ
Global warming (GWP)	2.4093	0.7929	0.08515	0.01231	0.01585	1.72182	0.04089	5.07841	kg CO_2 eq
Human toxicity (HTP)	0.8685	0.6711	0.30004	0.19472	0.20369	0.98547	0.01703	3.24063	kg 1,4-DB eq
Freshwater aquatic ecotoxicity (FAETP)	0.3450	0.15420	0.09317	0.03602	0.04711	0.33822	0.02474	1.0385	kg 1,4-DB eq
Acidification (AP)	6.09×10^{-3}	1.05×10^{-3}	4.01×10^{-4}	6.76×10^{-5}	1.48×10^{-4}	8.94×10^{-3}	1.31×10^{-4}	0.01684	kg SO_2 eq
Terrestrial ecotoxicity (TETP)	3.68×10^{-3}	1.33×10^{-3}	7.95×10^{-4}	2.33×10^{-4}	3.03×10^{-4}	2.70×10^{-3}	2.27×10^{-4}	9.29×10^{-3}	kg 1,4-DB eq
Eutrophication (EP)	1.44×10^{-3}	2.69×10^{-4}	1.68×10^{-4}	2.06×10^{-5}	7.44×10^{-5}	1.60×10^{-3}	8.94×10^{-5}	3.67×10^{-3}	kg PO4-eq
Photochemical oxidation (POCP)	4.00×10^{-4}	9.44×10^{-5}	2.07×10^{-5}	4.21×10^{-6}	8.14×10^{-6}	4.06×10^{-4}	8.16×10^{-6}	9.42×10^{-4}	kg C2H4 eq
Abiotic depletion (AD)	1.33×10^{-5}	1.28×10^{-6}	6.12×10^{-7}	3.16×10^{-7}	6.78×10^{-7}	6.66×10^{-6}	7.12×10^{-8}	2.30×10^{-5}	kg Sb eq
Ozone-layer depletion (ODP)	4.07×10^{-7}	8.74×10^{-8}	5.90×10^{-9}	5.80×10^{-10}	7.72×10^{-10}	2.27×10^{-7}	3.38×10^{-9}	7.32×10^{-7}	kg CFC-11 eq

4. Discussion and Recommendations

The data show that one bottle of sotol has a higher value of GWP than any other spirit evaluated in earlier LCA studies, such as mescal, gin, and whisky. For example, while one bottle of craft white mescal results in 1.7 kg CO_2 equivalent [14], one bottle of craft white sotol has a value of 5.92 kg CO_2 equivalent [15]. In addition, from an industrialized process point of view, our findings evidence that one bottle of white sotol emits more carbon dioxide (5.07 kg CO_2 equivalent) than classic gin (values ranging from 0.85 to 0.91 kg CO_2 equivalent) [10,22] and malt whisky (2.25 kg CO_2 equivalent) [12]. In terms of carbon dioxide, a 750 mL bottle of sotol has among the highest emissions among distilled spirits.

The results show that transporting raw commodities is a key environmental issue. However, what it is also seen as a key issue is the use of heavy single-use glass bottles as primary packaging. Both key issues affect the sotol-making process, making it one of the most polluting. As a result, the findings suggest that sotol makers need to decrease transport needs and use alternative primary packaging.

As proposed in the literature on sustainability in the food and beverage industry [23–26], decreasing the transportation input is a strategy to reduce environmental risks resulting from the alcoholic beverage industry. The sotol company, however, similar to many other similar sotol distilleries, does not have a way to decrease transport needs for two reasons. First, as the sotol market size is smaller than that of other famous Mexican spirit markets, suppliers in the alcoholic beverage industry are not interested in settling in the region, as it is not an attractive market for them. For example, while the mescal market in 2020 produced approximately 7.9 million liters (information available at www.statista.com, accessed on 26 September 2022), the sotol market manufactured barely 0.520 million liters (according to CCS). Therefore, the necessity to travel over long distances between raw commodity suppliers and sotol distilleries will probably remain unchanged. Second, as there are no *Dasylirion* plantations, sotol makers must travel to native plantations to cut and collect *Dasylirion* plants and bring them to the distillery. Therefore, until *Dasylirion* plantations are available, sotol makers might have to reduce the travel distance to obtain raw material. Thus, the sotol market size and *Dasylirion* plantation influence the efficiency of the sotol-making process. Therefore, it is assumed that a further increase in *Dasylirion* plantation would positively impact the expanding of the sotol market, because it would provide the opportunity to attract new stakeholders to commercialize sotol, as has been the case with mescal, according to CCS.

However, sotol distilleries can implement eco-friendly technologies for the road transport of inputs and byproducts, such as biofuels [27] and hybrid trucks [28]. Eriksson et al. (2016) mentioned that using biodiesel instead of diesel is a strategy to reduce CO_2 emissions generated when transporting raw materials and auxiliaries. Changing fossil diesel to biodiesel is a suitable alternative, but a variable that must be considered is that the biodiesel market in Mexico is not yet consolidated [29]. In other words, there are few biofuel stations, making it hard for truck drivers to obtain this type of fuel. Furthermore, with regards to hybrid trucks, most delivery companies use conventional gasoline vehicles in their fleet to transport bulk goods because they are cheaper than hybrid trucks [30]. Hence, using hybrid trucks to transport raw materials for distilleries is beyond their control.

Using alternative primary packaging materials is considered to be an effective strategy to reduce carbon emissions, such as substituting glass bottles with plastic bottles or aluminum cans [31,32]. Polyethylene terephthalate (PET) is the most common plastic used to replace glass in beverage bottles [33]. Even though PET is highly resistant to biodegradation, it has the environmental advantage of being refilled up to twenty-five times, which reduces CO_2 emissions by up to 70% [34]. In addition, Leivas et al. (2020) recommended that using plastic bottles minimizes energy and water consumption. PET is a material that can be used by sotol distilleries as alternative bottles; however, they are not regarded positively by consumers. Boesen et al. (2019) looked at how consumers judge the sustainability of distinct types of packaging made from varied materials. For example, even though PET bottles are less harmful to the environment than single-use glass bottles, plastic bottles are seen as the least sustainable material. Another suggestion is the use of aluminum cans instead of glass bottles [35]. Since aluminum cans are recycled an infinite number of times, they are identified as suitable for reducing emissions and preserving the quality of alcoholic beverages [35]. Aluminum cans are a more established alternative to glass weight and transport concerns [36]. Therefore, aluminum cans are a practical choice to replace glass bottles. During the COVID-19 pandemic, Mexicans increased their consumption of mixed drinks at home, such as margarita (tequila mixed with various ingredients), and most are packed in aluminum cans [37]. This trend in the alcoholic beverage market suggests that sotol consumers are more likely to agree with this market trend. Thus, sotol makers could consider using aluminum cans as a more environmentally friendly packaging.

For the use of alternative primary packaging, there are two ideas for improvement, though with considerable restrictions. First, one way to reduce the environmental impact is to use lighter-weight glass bottles [22]. Nonetheless, reducing the weight of glass bottles makes them more susceptible to breakage. Likewise, it has been noticed that consumers believe heavy glass bottles to be better than light glass bottles [34]. Consequently, using lighter-weight glass is not a promising idea for its fragility and the consumer's belief [38]. Second, a workable possibility for mitigating greenhouse emissions is using recycled glass bottles [39]. Sovacool et al. (2021) reported that recycling materials such as glass, aluminum, and steel as primary packaging significantly decreases its carbon footprint compared to lighter-weight glass bottles. Unfortunately, Chihuahua distilleries deal with a lack of infrastructure and bottle-recycling systems [40]. In this context, switching consumer behavior to promote bottle recycling seems complex to achieve for a sotol maker in a brief time span [41].

Because of the above restrictions, our suggestions for achieving cleaner sotol production are as follows: Firstly, it is proposed that the sotol makers located in those regions that are a long way away from suppliers in the alcoholic beverage industry buy their products in bulk and act jointly. Buying in bulk would help to reduce the amount of greenhouse gas emissions that each CCS member produces, since pollution would be shared among the members, and the number of trips would decrease. Secondly, based on what happened at the first experimental *Dasylirion* plantations, sotol makers should be encouraged to grow their own *Dasylirion* crops to reduce fossil fuel use for the road transport of raw materials (sotol pineapples). Overall, if all the suggestions were considered, sotol industrial manufacturing could minimize its environmental impact quickly.

5. Conclusions and Future Research

Based on the literature review, this is the first LCA report conducted to determine the environmental profile of industrial manufacturing of a distilled beverage in Mexico. This research is limited to data gathered from a distillery located in the northern part of Chihuahua State. For the LCA study, empirical data were collected from the harvest to the packaging stages to estimate the damage that one 750 mL bottle of sotol can make to the environment. The findings of the sotol life-cycle assessment show that it is the distilled beverage that produces more greenhouse gases than any other, including those from other countries.

In conclusion, each stage of producing this distilled beverage affects freshwater ecosystems and human health due to high fossil fuel consumption. Most of the energy is consumed while transporting inputs for the sotol-making process on the road. Because of this, it is crucial to develop strategies to make the sotol industry less harmful to the environment. For that reason, to make the sotol industry less harmful to the environment, this LCA study recommends strategies to reduce its environmental impact, such as reducing transportation needs, substituting glass bottles with aluminum cans, and purchasing raw materials in bulk by acting jointly with other sotol producers, which are key aspects for minimizing the carbon footprint.

Finally, changing primary packaging and using solid residues are critical issues for future research. An effective strategy to reduce greenhouse emissions is switching from glass to plastic bottles. However, this strategy has limitations, which are mentioned above. For that reason, in future research, it might be possible to assess the feelings towards PET bottles of sotol consumers when plastic bottles display shapes different from the traditional ones on the liquor market, as in the case of the bottled water industry; for instance, the companies Ícelandic Glacial TM (www.icelandicglacial.com, accessed on 26 September 2022) and Ty Nant (www.tynant.com, accessed on 26 September 2022) offer PET containers using a non-conventional shape that is different from the usual ones on the market. Regarding the use of solid residues, the waste generated by the sotol industry, such as sotol bagasse, has not been used efficiently yet. Hence, future work should focus on generating economically practical options to take advantage of solid residues, for instance, the conversion of sotol bagasse into biogas as an energy source for the cooking stage.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture12122159/s1, Supporting Material S1: This supporting information contains all the empirical data supporting this study's findings. Supporting information is openly available in the "Mendeley data" repository at https://doi.org/10.17632/hh6c5s7sh2.2, accessed on 26 September 2022. Supporting Information S2: This supporting information provides the total LCA results by type of sotol (white, rested, and aged). Supporting information is openly available in the "Mendeley Data" repository at https://doi.org/10.17632/bxcmnpp424.1, accessed on 26 September 2022.

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References

1. Becerra-López, J.L.; Rosales-Serna, R.; Ehsan, M.; Becerra-López, J.S.; Czaja, A.; Estrada-Rodríguez, J.L.; Romero-Méndez, U.; Santana-Espinosa, S.; Reyes-Rodríguez, C.M.; Ríos-Saucedo, J.C.; et al. Climatic Change and Habitat Availability for Three Sotol Species in México: A Vision towards Their Sustainable Use. *Sustainability* **2020**, *12*, 3455. [CrossRef]
2. Flores-Gallegos, A.C.; Cruz-Requena, M.; Castillo-Reyes, F.; Rutiaga-Quiñones, O.M.; Torre, L.S.; Paredes-Ortíz, A.; Soto, O.N.; Rodriguez-Herrera, R. Sotol, an alcoholic beverage with rising importance in the worldwide commerce. In *Alcoholic Beverages: Volume 7: The Science of Beverages*, 1st ed.; Grumezescu, A.M., Holban, A.M., Eds.; Woodhead Publishing: Sawston, UK, 2019; Volume 7, pp. 141–160. [CrossRef]
3. Gutiérrez-Ortiz, J.A.; Gutiérrez-de Alba, E. *The Sotol War: From Pre-Hispanic Times to the Law Regulating Sotol Activity*, 1st ed.; Sispro: Chihuahua, Mexico, 2019.
4. Gardea, A.A.; Findley, L.T.; Orozco-Avitia, J.A.; Bañuelos, N.; Esqueda, M.; Huxman, T.H. Bacanora and sotol: So far, so close. Social Studies. *J. Contemp. Food Reg. Dev.* **2012**, *2*, 153–168. Available online: https://www.ebsco.com/ (accessed on 5 April 2020).
5. Reyes-Valdés, M.H.; Palacios, R.; Rivas-Martínez, E.N.; Robledo-Olivo, A.; Antonio-Bautista, A.; Valdés-Dávila, C.M.; Villarreal-Quintanilla, J.Á.; Benavides-Mendoza, A. The Sustainability of Mexican Traditional Beverage Sotol: Ecological, Historical, and Technical Issues. In *Processing and Sustainability of Beverages*, 1st ed.; Elsevier: Amsterdam, The Netherlands, 2019; pp. 103–137. [CrossRef]
6. Madrid-Solórzano, J.M.; Garcia-Alcaraz, J.L.; Valles-Rosales, D.J. The elaboration process of sotol: A systematic review. *Mundo FESC* **2021**, *11*, 107–117. Available online: https://www.fesc.edu.co/Revistas/OJS/index.php/mundofesc/article/view/917/723 (accessed on 17 July 2022).
7. Adhikari, B.; Prapaspongsa, T. Environmental Sustainability of Food Consumption in Asia. *Sustainability* **2019**, *11*, 5749. [CrossRef]
8. Rosado, M.A.G. Propuestas de prácticas sustentables en la industria vitivinícola de Baja California, México (tesís de maestria). Ph.D. Thesis, El Colegio de la Frontera Norte, Tijuana, Mexico, 2016. Available online: https://colef.repositorioinstitucional.mx/jspui/handle/1014/204 (accessed on 20 July 2022).

9. Olajire, A.A. The brewing industry and environmental challenges. *J. Clean. Prod.* **2020**, *256*, 102817. [CrossRef]
10. Leivas, R.; Laso, J.; Hoehn, D.; Margallo, M.; Fullana-i-Palmer, P.; Aldaco, R. Product vs Corporate Carbon Footprint: A Case Study for the Spirit Drinks Sectors. *Chem. Eng. Trans.* **2019**, *76*, 223–228. [CrossRef]
11. Becker, S.; Bouzdine-Chameeva, T.; Jaegler, A. The carbon neutrality principle: A case study in the French spirits sector. *J. Clean. Prod.* **2020**, *274*, 122739. [CrossRef] [PubMed]
12. Eriksson, O.; Jonsson, D.; Hillman, K. Life cycle assessment of Swedish single malt whisky. *J. Clean. Prod.* **2016**, *112*, 229–237. [CrossRef]
13. Bhattacharyya, N.; Goodell, A.; Rogers, S.; Demond, A. Environmental impacts of wheat-based vodka production using life cycle assessment. *J. Clean. Prod.* **2019**, *231*, 642–648. [CrossRef]
14. Martínez, J.M.; Baltierra-Trejo, E.; Taboada-González, P.; Aguilar-Virgen, Q.; Marquez-Benavides, L. Life Cycle Environmental Impacts and Energy Demand of Craft Mezcal in Mexico. *Sustainability* **2020**, *12*, 8242. [CrossRef]
15. Madrid-Solórzano, J.M.; García-Alcaraz, J.L.; Macías, E.J.; Cámara, E.M.; Fernández, J.B. Life Cycle Analysis of Sotol Production in Mexico. *Front. Sustain. Food Syst.* **2021**, *5*, 411. [CrossRef]
16. Löfgren, B.; Tillman, A.-M.; Rinde, B. Manufacturing actor's LCA. *J. Clean. Prod.* **2011**, *19*, 2025–2033. [CrossRef]
17. Page, R. *ISO 14000 Environmental Standards: Implementing Innovation in Management and Measures*; Edward Elgar Publishing: Cheltenham, UK, 2017. [CrossRef]
18. Merchan, A.; Combelles, A. Comparison of Life cycle Impact Assessment methods in a case of crop in Northern France. In Proceedings of the 4th international conference on Life Cycle approaches, Lille, France, 5–6 November 2014; pp. 239–242. Available online: https://orbi.uliege.be/handle/2268/179975 (accessed on 26 September 2021).
19. Bobba, S.; Deorsola, F.A.; Blengini, G.A.; Fino, D. LCA of tungsten disulphide (WS2) nano-particles synthesis: State of art and from-cradle-to-gate LCA. *J. Clean. Prod.* **2016**, *139*, 1478–1484. [CrossRef]
20. Li, J.; Ma, X.; Liu, H.; Zhang, X. Life cycle assessment and economic analysis of methanol production from coke oven gas compared with coal and natural gas routes. *J. Clean. Prod.* **2018**, *185*, 299–308. [CrossRef]
21. Rugani, B.; Vázquez-Rowe, I.; Benedetto, G.; Benetto, E. A comprehensive review of carbon footprint analysis as an extended environmental indicator in the wine sector. *J. Clean. Prod.* **2013**, *54*, 61–77. [CrossRef]
22. Leivas, R.; Laso, J.; Abejón, R.; Margallo, M.; Aldaco, R. Environmental assessment of food and beverage under a NEXUS Water-Energy-Climate approach: Application to the spirit drinks. *Sci. Total Environ.* **2020**, *720*, 137576. [CrossRef]
23. Cucurachi, S.; Scherer, L.; Guinée, J.; Tukker, A. Life Cycle Assessment of Food Systems. *One Earth* **2019**, *1*, 292–297. [CrossRef]
24. Espinosa, R.V.; Soto, M.; Garcia, M.V.; Naranjo, J.E. Challenges of Implementing Cleaner Production Strategies in the Food and Beverage Industry: Literature Review. In *Advances and Applications in Computer Science, Electronics and Industrial Engineering*; Springer: Berlin, Germany, 2021; pp. 121–133. [CrossRef]
25. Pan, W.; Pan, W.; Hu, C.; Tu, H.; Zhao, C.; Yu, D.; Xiong, J.; Zheng, G. Assessing the green economy in China: An improved framework. *J. Clean Prod.* **2019**, *209*, 680–691. [CrossRef]
26. Sovacool, B.K.; Bazilian, M.; Griffiths, S.; Kim, J.; Foley, A.; Rooney, D. Decarbonizing the food and beverages industry: A critical and systematic review of developments, sociotechnical systems and policy options. *Renew. Sustain. Energy Rev.* **2021**, *143*, 110856. [CrossRef]
27. Desta, M.; Lee, T.; Wu, H. Life cycle energy consumption and environmental assessment for utilizing biofuels in the development of a sustainable transportation system in Ethiopia. *Energy Convers. Manag. X* **2022**, *13*, 100144. [CrossRef]
28. Fernández, R.Á.; Pérez-Dávila, O. Fuel cell hybrid vehicles and their role in the decarbonisation of road transport. *J. Clean. Prod.* **2022**, *342*, 130902. [CrossRef]
29. Sosa-Rodríguez, F.S.; Vazquez-Arenas, J. The biodiesel market in Mexico: Challenges and perspectives to overcome in Latin-American countries. *Energy Convers. Manag. X* **2021**, *12*, 100149. [CrossRef]
30. Briseño, H.; Ramirez-Nafarrate, A.; Araz, O.M. A multivariate analysis of hybrid and electric vehicles sales in Mexico. *Socio-Econ. Plan. Sci.* **2021**, *76*, 100957. [CrossRef]
31. Perez-Martinez, M.M.; Noguerol, R.; Casales, B.; Lois, R.; Soto, B. Evaluation of environmental impact of two ready-to-eat canned meat products using Life Cycle Assessment. *J. Food Eng.* **2018**, *237*, 118–127. [CrossRef]
32. Boesen, S.; Bey, N.; Niero, M. Environmental sustainability of liquid food packaging: Is there a gap between Danish consumers' perception and learnings from life cycle assessment? *J. Clean. Prod.* **2019**, *210*, 1193–1206. [CrossRef]
33. Sazdovski, I.; Bala, A.; Fullana-i-Palmer, P. Linking LCA literature with circular economy value creation: A review on beverage packaging. *Sci. Total Environ.* **2021**, *771*, 145322. [CrossRef]
34. Otto, S.; Strenger, M.; Maier-Nöth, A.; Schmid, M. Food packaging and sustainability–Consumer perception vs. correlated scientific facts: A review. *J. Clean. Prod.* **2021**, *298*, 126733. [CrossRef]
35. Ruggeri, G.; Mazzocchi, C.; Corsi, S.; Ranzenigo, B. No More Glass Bottles? Canned Wine and Italian Consumers. *Foods* **2022**, *11*, 1106. [CrossRef] [PubMed]
36. Eco-Packaging Trends Across Spirits, Wine and Beer-IWSR. Available online: https://www.theiwsr.com/news-and-comment-radius-trend-eco-packaging/ (accessed on 21 May 2022).
37. Echeverría, M. ¿Qué bebieron los mexicanos en casa durante la pandemia? Muchos cocteles en lata. *Expansión* **2022**. Available online: https://expansion.mx/empresas/2020/10/02/que-bebieron-los-mexicanos-en-casa-durante-la-pandemia-muchos-cocteles-en-lata (accessed on 21 May 2022).

38. Orlowski, M.; Lefebvre, S.; Back, R.M. Thinking outside the bottle: Effects of alternative wine packaging. *J. Retail. Consum. Serv.* **2022**, *69*, 103117. [CrossRef]
39. Khan, W.S.; Asmatulu, E.; Uddin, M.N.; Asmatulu, R. 6-Recycling and reusing of glasses and ceramics. In *Recycling and Reusing of Engineering Materials*; Khan, W.S., Asmatulu, E., Uddin, M.N., Asmatulu, R., Eds.; Elsevier: Amsterdam, The Netherlands, 2022; pp. 105–118. [CrossRef]
40. Giner, M.-E.; Córdova, A.; Vázquez-Gálvez, F.A.; Marruffo, J. Promoting green infrastructure in Mexico's northern border: The Border Environment Cooperation Commission's experience and lessons learned. *J. Environ. Manag.* **2019**, *248*, 109104. [CrossRef]
41. Oke, A.; Osobajo, O.; Obi, L.; Omotayo, T. Rethinking and optimising post-consumer packaging waste: A sentiment analysis of consumers' perceptions towards the introduction of a deposit refund scheme in Scotland. *Waste Manag.* **2020**, *118*, 463–470. [CrossRef] [PubMed]