Life Cycle Analysis of Sotol Production in Mexico

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Sotol is a Mexican distilled spirit produced in Northern Mexico. The estimated annual production of sotol is at around 5,200 hl per year. This industry grows at an average rate of 5% per year. The Mexican Sotol Council and the Sotol Certificate Council are regulatory bodies dedicated to monitoring that sotol producers comply with the Official Mexican Standard NOM-159-SCFI-2004. Currently, those regulatory bodies try to improve the sotol production process and good practice guidelines to contribute to cleaner production. This paper reports a case study of artisanal sotol production in Chihuahua State in Mexico. Life cycle assessment (LCA) technique was used to compute the environmental impact of sotol and its performance to identify system hotspots and propose improvement interventions. SimaPro software, v.9.1®, is used for the LCA, applying CML-IA baseline V3.05/EU25 method to evaluate and select environmental impact categories. The system boundary included the stages of harvest, cooking, milling, fermentation, distillation, bottling, and packaging. The findings indicate that each of the stages required for sotol beverage processing significantly affects the marine ecosystem. The milling and bottling stages have the highest environmental impact. A 750-ml bottle of artisan sotol causes 5.92 kg CO$_2$ eq, based on empirical data. Sotol makers should focus on reducing energy consumption caused by input transportation and equipment for milling.

Keywords: life cycle assessment (LCA), sotol production, environmental impact (EI), Chihuahua wine, liquor

INTRODUCTION

The state of Chihuahua is located on the northern border of Mexico and adjoins the Southern United States of America. In the Mexican United States territory, Chihuahua is likewise just beyond the states of Durango, Coahuila de Zaragoza, Sonora, and Sinaloa. The area of the state accounts for 12.6% of the total territory of Mexico, with an area of 247,200 km$^2$ (Ortega-Ochoa et al., 2008). This area is predominated with ecosystems of desert scrub and grassland, covering about 65% of the total area of the state. Furthermore, 75% of its surface is predominated by the dry semi-arid and arid climate, with precipitation ranging from 300 to 500 ml per year (Alcalá de Jesús et al., 2014; Córdova and Romo, 2014).

Under the ecosystems mentioned above, a plant called sotol, of the genus Dasylirion, grows. This species develops at extreme temperatures that can range in winter from $-14$ to $30^\circ$C; in summer, temperatures are $\sim10$ to $42^\circ$C (Ortega et al., 2013). Native Mexicans used it to meet different needs,
such as for food (Ladyman, 2004; Riley, 2008) and household utensils (Becerra-López et al., 2020). This plant is currently primarily used in the artisanal production of the alcoholic beverage sotol. According to regulatory bodies, in 2002, this distilled liquor acquired the designation of origin, shared between Chihuahua, Coahuila, and Durango (Mexican states).

The craft of sotol begins with gathering the Dasylirion species and cutting it in the wild for 2 days; only the stem, also known as pineapple, is used as the raw material. Next, the elaborate process continues with the cooking of the pineapple in rudimentary ovens at ground level. After that, the cooked pineapples undergo a milling process to turn them into small pieces. Then, water is added to initiate a spontaneous fermentation process. Finally, a double-distillation process permits obtaining a final product at 45% alc. vol. The distilled liquor must be graduated to 40% alc. vol. to comply with the NOM-159-SCFI-2004 specifications for its sale to the public. This alcoholic beverage is classified in the market as white, rested, and aged, with the last two being stored in dark American oak barrels from 4 months to more than 12 months.

Previous research shows that four disciplines have been addressed by sotol issues. In agriculture and ecology, pre-germination treatments on the germination of Dasylirion spp seed., statistics models to estimate the mass to be harvested from the wild population (Olivas-García et al., 2013), and the effects of substrates and chemical fertilizer on sotol seedlings have been critical topics of interest (Arce-González et al., 2007; Sierra-Tristán et al., 2008; Reyes et al., 2013). In biotechnology (chemistry), several studies have focused on the fermentation and production process to improve the organoleptic properties and regulate the quality of the product (Cárdenas-Díaz et al., 2009; Gardea, et al., 2012). About health effects, it has been of interest to determine the quality of different brands of sotol, from characterizing volatile compounds and metals resulting from the distillation stage to the concentration of ethyl carbamate (De León-Rodríguez et al., 2008; Lachenmeier et al., 2009; Trujillo-Orozco et al., 2011). In an agro-industrial context, there has been an interest in diversifying the use of the Dasylirion species.

One example is to develop flour from planta seeds and manufacture probiotics and sugar substitutes from the fructans of the sotol stem (Orozco-Sifuentes et al., 2019). Sotol bagasse, a waste generated at the distillation stage, has undergone experimentation to be used in the solid-state fermentation process, although the result was negative (Flores-Maltos et al., 2014; Flores-Gallegos et al., 2019). Relying on the findings mentioned above, Figure 1 shows a Venn diagram presenting and suggesting directions for future research, with the latter highlighted in bold text. It presents the average percentage in which each of these research lines has been addressed in the texts analyzed—for example, agro-industrial and health account for 9 and 11% of scientific articles, respectively.

Regulatory bodies consider that around 500,000 L of this spirit drink is produced annually, and Chihuahua State generates 70% of total sotol production. Because sotol production is mainly artisanal, there is an increase of people who wish to diversify their monetary income through purchasing and marketing of

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**FIGURE 1** Contributions from study disciplines and future research.

- **Health**
  - 11% Ethyl carbamate concentration analysis
  - Knowledge of the volatile compounds and metals resulting from distillation
  - Quality is improved in the stages of milling, fermentation and distillation stages with the use of state-of-the-art technology

- **Regulating product quality**
  - 40% Standardize the fermentation process
  - Yeasts found: Cryptococcus albidus, Saccharomyces cerevisiae, Candida famata, Bacillus sp.
  - Adding enzymes to increase the sugar content and final ethanol concentration

- **Carbon footprint**
  - Identify the native yeasts by sotol species and the volatile compounds, that most influence the organoleptic properties of sotol
  - Specify the varieties of Dasylirion species as suitable in NOM-159-SCFI-2004

- **Seedling production**
  - 40% The percentage of effectiveness of various pre-germinative treatments is known
  - It is possible to estimate the kg to be obtained from a harvest of native plants
  - Knowledge on the effect of the application of substrates or chemical fertilizers to commercial plantations

- **To learn about plant production methods under the labor and economic conditions of farmers**
  - Investigate the stages of establishment, rapid growth, survival rate and hardening of a commercial plantation

- **To know about the biology of sotol plant growth in its natural habitat for successful reforestation**
  - Find alternatives for the utilization of sotol fructans

- **Develop agrochemical companies for the commercialization of sotol plants**
  - Production of flour from the seeds of the sotol plant

- **Finding applications for sotol bagasse**
  - Agroindustry 9%
the distillate under their trademark. The latter information can be reflected in the number of sotol producers and sotol liquor marketers registered in the Sotol Certificate Council (12 and 21, respectively). For that reason, the production of Dasylirion seedlings and regulating the quality of sotol drink add up to 80% of the research done. However, no evidence of work analyzing the carbon footprint and life cycle assessment in sotol liquor development was found so as to create proposals to mitigate its adverse effects on human health and the environment. Therefore, an assessment of greenhouse gas emissions during sotol processing would support these research lines to identify opportunities for improvement in the production process.

Regarding the latter, life cycle assessment (LCA) is a science-based tool often used to evaluate the environmental impact of alcoholic beverage processing (Leinonen et al., 2018; Baiano, 2021). The LCA methodology is ruled by international standards, such as ISO 14011:2004, ISO 14021, ISO/TR 14047, ISO/TE 14048, ISO/TR 14049, and ISO 14050, among others (Page, 2017; Patón-Romero et al., 2019; Jannah et al., 2020). In the literature, several examples of LCA application in wine, brewing, and distilled spirit industries are possible to find, as indicated below.

In wines, studies have handled a range of environmental concerns. The LCA methodology has been applied to the sustainability evaluation of wine among small-scale and large-scale wine producers, different qualities of wine, and organic and non-organic grapes wines (Iannone et al., 2016; Martins et al., 2018; Ponstein et al., 2019). Viticulture, vinification, and bottling/packaging are the main stages considered in the environmental evaluation of wine production. Frequently, it has been interesting to evaluate the environmental impact between different types of wine and varieties of grape wine (Amienyo et al., 2014; Ferrara and De Feo, 2018). Even the study of the environmental profile of the wine sector has scope in more specific production processes, such as assessing the environmental impact of an alternative process for keeping the organoleptic properties on wine (García-Alcaraz et al., 2020a) and the comparison of the techniques used for cleaning and disinfection of oak wine barrels (García-Alcaraz et al., 2020b).

Regarding the LCA of beer production, the bottling stage has the most significant impact. Diesel, as the energy source used in bottle production, is the primary driver of the global warming effect (Koroneos et al., 2005). The proposals to improve this manufacturing process include the use of thermal energy and different materials as primary packaging; for example, glass and polyethylene terephthalate are proposed (Cimini and Moresi, 2018).

The life cycle studies of distilled beverages such as gin, cognac, whisky, vodka, and mezcal have also been analyzed. The carbon footprint of both the production of a classic 700-ml gin bottle and that of the corporate has been calculated (Leivas et al., 2019). A cognac distillery (Becker et al., 2020) and one whisky distillery (Eriksson et al., 2016) have measured their carbon footprint. Vodka is another distilled beverage evaluated with LCA considering specific raw material varieties, high-volume distribution, and shipping for global market consumption (Bhattacharyya et al., 2019). About Mexican distilled liquor, the environmental impact of the artisanal process of mezcal (Maciel et al., 2020) has been evaluated.

Based on the abovementioned details, the environmental issues of wine have been mainly examined the most, followed by beer and distilled spirits. In the latter classification, Mexico has a wide variety of distilled beverages, of which the main environmental challenges of most of them are unknown. Hence, it is necessary to apply LCA in several of these because they differ in geographical conditions, the volume of production and sale, and raw material varieties. In order to gain a level of depth of analysis in the wine or brewery industry, it is considered essential to know the environmental impact of distilled beverages produced in the different regions of Mexico, such as sotol. Therefore, the main objective of this research is to identify the environmental profile of artisanal sotol production in Chihuahua, Mexico.

**METHOD**

The framework of ISO 14040 was the guidelines for carrying out the LCA study, and all its proposed stages are defined in the following paragraphs.

**Goal Definition**

The main goal of this case study is to identify the significant environmental impacts associated with the life cycle of artisanal sotol production.

**Functional Unit**

Producers of artisanal sotol agree that ~22 kg of wild sotol pineapple biomass is equivalent to one 750-ml white glass bottle of sotol with 40% alc. vol. (Regional Association of Foresters North Central Zone, 2019). For that reason, the functional unit chosen to reference all the inputs and outputs of the system was an artisan sotol bottle of 750 ml, which is the glass bottle size most used for sale.

**System Boundary**

An approach of cradle-to-gate was considered in the life cycle assessment of artisanal sotol production. The stages of harvest, cooking, milling, fermentation, distillation, bottling, and packaging were included in the system boundary, as shown in Figure 2. At the initial stage, gathering and cutting the Dasylirion species (raw material) and its transportation to the Vinata were included. Vinata is a rudimentary building where the alcoholic beverage is made and is located far from the urban area; therefore, sanitary facilities and electrical energy services are lacking. The work equipment for transporting raw material to the Vinata includes a gasoline-powered pick-up vehicle towing a 5-ton capacity cattle livestock trailer (two-axle).

In the system boundary, the tools used at each stage of the production process were not considered as inputs to system assessment; it was considered that their contribution to the total carbon footprint is ~1%. Similarly, activities to deliver the finished product at the distribution network were outside the system boundary because they related to consumer behavior.
TABLE 1 | Data included and excluded for sotol life cycle assessment.

| Included                                                                 | Excluded                                                                                           |
|--------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------|
| • The transportation from Vinata to the harvest area and back to it      | • The transportation and distribution of the final product to points of sale                        |
| • Gathering the Dasylirion species and cutting it in wild populations    | • The maintenance of operations of equipment and tools                                             |
| • The stages of harvest, cooking, milling, fermentation, distillation,   | • Labor force and transport for transfer                                                           |
|   bottling, and packaging                                                | • Activities related to waste management                                                          |
| • Warehouse activities, which include the transport of the final product | • Material flow from natural resources that do not have a transformation process                   |
|   in Vinata to the warehouse, sotol aging, and packaging                 |                                                                                                    |
| • Waste that is generated at the distillation stage                      |                                                                                                    |
| • Production losses triggered by the process of bottling and the         |                                                                                                    |
|   packaging stage                                                       |                                                                                                    |

Life Cycle Inventory
The present study was carried out in a sotol production house located in the desert region of northwestern Chihuahua State that has mostly an arid, semi-warm climate (62.4%). The predominant soil in the region is Calcisol (45.5%) and Leptosol (22.3%), with annual rainfall in the range of 200 to 400 mm. Desert scrub (72.9%) and grassland (22.6%) are the predominant vegetation type, where land use for agriculture is 3.4 and 0.1% for urban areas (INEGI, 2020).

Although the empirical data were gathered from only one sotol production house to assess the environmental impact of this distilled beverage, the artisanal production process studied...
is similarly replicated by many sotol producers. For that reason, owners may use the LCA results to guide best practices to achieve a quality item with the lowest environmental impact.

Sotol manufacturers usually produce the elaborate alcoholic beverage three times a month, starting their beverage production in late September and ending in February (Regional Association of Foresters North Central Zone, 2019). It is essential to mention that, if the sales are good, sotol production occurs in each of the months, which means a total of 6 months uninterrupted.

The sotol production house provided material flow and energy data. The primary data collection covers a 30-day period, where 9,000 kg of sotol pineapples are harvested, equivalent to 750 l of sotol at 45% alc. vol. The life cycle inventory, with each stage of production of the distilled beverage, is detailed below. Table 2 shows the primary empirical data provided by the artisanal sotol production company for this research.

The software SimaPro v.9.1® was used for LCA and CML-IA baseline V3.05/EU25 methodology to evaluate and select environmental impact categories because this is the most complete midpoint method in LCA with 11 categories, giving a general idea regarding all impacts. This method is also the most commonly used in LCA applied to agriculture production process (Merchan and Combelles, 2014) and product industrialization (Bobba et al., 2016; Li et al., 2018).

### Harvest

The production of the distilled liquor begins in autumn because it is when the stem of the sotol plant contains between 20 and 35° Bx (Reyes-Valdés et al., 2019). A worker cuts down Dasylirion using a hatchet and hoe. No gasoline engine-powered equipment is used in the harvesting stage as a harvesting mechanism. It is harvested three times a month, where to collect 9 tons of sotol pineapple biomass, two trips are made on different days to cover a total distance of 210 km. It is considered a quality raw material to produce this beverage from the Dasylirion species of 15 years (Sierra-Tristán et al., 2008). The harvested sotol pineapples are transported to the Vinata.

### Cooking

Once the sotol pineapples arrive at the Vinata, they are cooked in a rudimentary oven made at ground level. At the bottom of the oven are placed layers of volcanic stones (known as malpáis). The oven is heated with firewood from Prosopis velutina, commonly known as mesquite. On top of the red-hot stones are placed the heads of sotol pineapples. During the cooking process, to prevent the leakage of heat and vapors, a type of cover with wooden and earth beams is built. Water is added for cooking to generate steam to help better cook the sotol pineapples for 72 h.

### Milling

After the cooking process, the next stage is milling. At this stage, the cooked sotol pineapples are chopped into tiny pieces using a mechanical mill powered by an agricultural tractor. The time used by the sotol producer to chop 3 tons of sotol pineapples is an average of 5 h in a day.

### Fermentation

The chopped pineapples are placed in stainless steel tanks to start fermentation, where water is added in a 1:1 ratio, and no yeast or sugars are added to this process. The average fermentation time is 72 h. However, this can be extended if the ambient temperature is several degrees Celsius below zero.

### Distillation

The distillation process is carried out in two steps. First, the result of the whole fermentation is placed in a still made of stainless steel. Firewood is used to heat the still, and water is used as a storage coil cooling system. The result of this first distillation is a by-product known as "wine," which does not have solid material—that is, it does not contain bagasse. The bagasse is eliminated at this step and is left in an impromptu

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**TABLE 2 | Empirical data for life cycle inventory.**

| Stage of the process | Data                      | Unit    | Quantity |
|----------------------|---------------------------|---------|----------|
| Harvest (stage I)    | Input                     |         |          |
|                      | Transportation            | km      | 210      |
|                      | Sotol pineapple biomass   | kg      | 9,000    |
|                      | Dasyllirion leaf biomass  | kg      | 2,700    |
| Cooking (stage II)   | Input                     |         |          |
|                      | Firewood                  | kg      | 3,000    |
|                      | Water                     | L       | 40       |
|                      | Transport                 | km      | 15       |
|                      | Ash                       | kg      | 90       |
| Milling (stage III)  | Input                     |         |          |
|                      | Fossil fuel               | L       | 90       |
| Fermentation (stage IV) | Input                   |         |          |
|                      | Stainless steel tanks     | kg      | 150      |
|                      | Water                     | L       | 9,000    |
| Distillation (stage V) | Input                           |         |          |
|                      | Stainless steel still     | kg      | 149      |
|                      | Firewood                  | kg      | 3,000    |
|                      | Stainless steel bottle washer | kg     | 12.5     |
|                      | Stainless steel packaging equipment | kg | 55 |
|                      | Distilled water           | L       | 80       |
|                      | Glass bottle              | kg      | 0.878 per bottle |
| Bottling (stage VI)  | Input                     |         |          |
|                      | Transport                 | km      | 1,217    |
|                      | Stainless steel tanks     | kg      | 117      |
|                      | Stainless steel bottle washer | kg     | 12.5     |
|                      | Stainless steel packaging equipment | kg | 55 |
|                      | Distilled water           | L       | 80       |
|                      | Glass bottle              | kg      | 0.878 per bottle |
| Packaging (stage VII) | Input                     |         |          |
|                      | Regular slotted container box | kg     | 0.48 per box |
outdoor area adjoining the Vinata. There are reports that the farmers in the area have employed bagasse as an organic fertilizer without success. As a result, leaving bagasse near the Vinata is a reasonably frequent occurrence. The second step refers to proceeding again to a distillation process to obtain a final distillation product of about 55% alc. vol. The total time required at this stage is 21 h.

**Bottling**

Once the distillation stage is completed, the product is transported to the warehouse in polyethylene drums. A warehouse is a place located in the urban area where public services are available. The distillate liquor is stored in stainless steel tanks for aging, depending on the amount of time of aging. There are three types of sotol: white sotol (diluted with distilled water), rested sotol (stored for 4 months in barrels), and aged sotol (stored for 14 months in barrels).

Before bottling, the distillers will get the standardization of the graduation by adding water to get sotol with a range of around 40% alc. vol. These types of sotol are packaged in glass bottles that have been pre-washed with hot water and whose final cleaning is carried out in washing equipment. A semi-automatic bottle packer is used for filling sotol, with a capacity of 200 bottles per hour. This equipment is made of stainless steel. Manually, each bottle is placed with its lid, shrinkage seal, and labels. It likewise receives a handcrafted decoration for the consumer to appreciate its good visual appearance; this consists of placing an *ixtle* loop rolled around the neck of the bottle and covering the central part of the lid.

**Packaging**

The sotol production process ends with the packaging of the product. Regular slotted container boxes are used to store 12 bottles per box. Each box is stored on wooden pallets pending distribution at points of sale. From 9 tons of sotol pineapples, ~1,080 bottles of 750-ml sotol are packed per month. However, supply and demand controls how long it takes to do the packing.

### RESULTS AND DISCUSSION

The impact categories integrated in the CML-IA baseline V3.05/EU25 were fossil depletion (FD), global warming potential for a time horizon 100-year (GWP), ozone layer depletion, human toxicity potential (HTP), freshwater aquatic ecotoxicity (FAETP), marine aquatic ecotoxicity potential (MAETP), terrestrial ecotoxicity, photochemical oxidant creation potential, acidification potential (AP), and eutrophication potential. Table 3 shows the characterization of the results per functional unit in the impact categories in critical conditions. Each of the stages for sotol beverage processing significantly affects the marine ecosystem.

In line with the method to evaluate and select environmental impact categories (CML-IA baseline V3.05/EU25), MAETP is considered in the LCA study because this impact category on freshwater aquatic ecotoxicity indicates how the toxic substances to the air, water, and soil were generated on freshwater ecosystems in the Chihuahua Desert, where water is scarce and eroded soil is abundant. Though the marine ecosystem there is not in Chihuahua State, it represents a substantial portion of the harmful effects of the artisanal sotol process.

According to the study, there were no significant variations in environmental impact categories between the various types of sotol (white, rested, and aged). At the bottling stage, a minor difference between the values of the impact categories was due to the time spent in barrels by the rested and aged sotol. However, the time spent did not significantly affect the overall environmental impact of each type of sotol—for instance, MAETP has a difference of 0.38% in each value of MAETP by type of sotol. Several impact categories at the bottling stage have a difference of <5%. Human toxicity potential varies by 8.2% but does not surpass 10%.

[see the additional supporting material (S1) for further details in Madrid-Solórzano and García-Alaraz, 2021]. S1 displays the LCA findings or environmental impacts for each type of sotol: white, rested, and aged. Within each sotol process step, the value for each impact category is arranged in decreasing order. In S1, findings show the impact categories of a 750-ml sotol bottle, whatever the type of sotol. Table 3 shows the characterization of the results per functional unit in the impact categories in critical conditions. Each of the stages for sotol beverage processing significantly affects the marine ecosystem. Based on the analysis carried out, no significant differences in environmental impact categories were presented in analyzing the data between the different types of sotol (white, rested, and aged). In this way, the results show the impact categories of a 750-ml sotol bottle, whatever the type of sotol.

Nevertheless, if critical stages are not considered, the fossil fuel resource (FD) is significantly affected by the process of cooking (33%) and distillation (35%). The latter significantly affects the AP category by 41%. Additionally, sotol harvesting mainly affects the HTP and FAETP categories by around 31%. The cooking process affects the rest of the categories in a relevant way.

Figure 3 reports the contribution rate for each of the stages of production of the distilled beverage concerning greenhouse gases. The results revealed that a 750-ml sotol bottle produces 5.92 kg CO$_2$ eq. based on the empirical data. The stages that contribute the most to CO$_2$ emissions are milling and bottling, with 51 and 27%, respectively. If critical stages are not considered, it is distillation and cooking again that influence most the environmental impact of producing a sotol bottle.

### Comparison With Other Research Projects

Based on findings, even though the craft sotol processing does not have a stage to produce sotol plants (*Dasylirion* spp.), the environmental impact of the craft sotol elaboration process is higher than those of other distilled beverages. In other studies, fertilizers and herbicides in plantation farming increase the greenhouse gas emissions (Ferrara and De Feo, 2018), and although in the production of sotol these resources are not integrated, given that it is extracted from a wild plant, its environmental impact is greater. Table 4 shows a comparison of the results of this study with previous research projects or LCA on distilled beverages, and it concludes that the transport of the raw material is a critical point in producing each spirit drink.
Maciel et al., 2020 concluded that a 750-ml handcrafted mezcal bottle yields 1.7 kg CO$_2$ eq., considering an ancestral technology in its milling stage. However, it is not specified whether the use of equipment for pre-washing and bottle washing was included in the ACV. It is then suggested that the environmental impact of mezcal may be more significant by including equipment for the bottling stage, as is the case in the current study. Similarly, an increase in the generation of greenhouse gases would occur if the transport of inputs for the adornment of the bottles for sale was included in the same way with that of the type of packaging used for transport to points of sale.

A 750-ml sotol bottle can reduce its impact on GWP by ~2.92 kg CO$_2$ eq., a value within the range that other LCA studies showed. This reduction of carbon emissions is possible by replacing the farm tractor used in the milling stage with existing machinery with less energy consumption—for example, a small mechanical mill would permit to reduce the energy consumed to chop 9 tons of cooked sotol pineapple per month. Table 4 presents the contribution of the emissions of CO$_2$ from different distilled beverages, such as craft mezcal and pisco with 1.7 and 3.62 kg CO$_2$ eq., respectively. Both craft sotol and pisco liquor share a common problem: employing machinery with higher energy consumption. This reduction of carbon emissions is possible by replacing the farm tractor used in the milling stage with existing machinery with less energy consumption—for example, a small mechanical mill would permit to reduce the energy consumed to chop 9 tons of cooked sotol pineapple per month.

**CONCLUSIONS AND RECOMMENDATIONS**

This study aimed to report the environmental evaluation of artisanal sotol production. Ten environmental indicators have
been considered for sustainability performance in this research project. The evaluation used mainly empirical data gathered from the sotol production house for a functional unit of 750-ml handcrafted sotol bottle. Data collection was carried out from harvest to packaging stage. The LCA study indicates that the milling and bottling stages are opportunities for improvements since together they contribute 4.62 kg CO₂eq., which is equivalent to 78.04% of the total emissions. It is also noted that the transport of inputs to produce the alcoholic drink is an unfavorable condition for sotol producers in the state of Chihuahua, as glass bottles, packaging cardboard, lids, and stamps are supplied from the center of the country, resulting in high energy consumption. In line with the results of the LCA, two suggestions are given, to be ruled by regulatory bodies to minimize system hotspots. First, it is suggested to regulate the type of machinery used in the milling stage, such that the capacity of the equipment is in line with the capacity of the liters to be produced per season, that is, that there is no unnecessary energy consumption as there is with the current process. Secondly, the weight of the generic bottles used to bottle the distilled beverage must be the lowest. These regulations will help avoid further impacts on the ecosystem. Finding applications for sotol bagasse is intended for future research. In the literature review, there is no proposal to produce by-products from sotol bagasse. Currently, this waste ends up in an unplanned outdoor space next to the Vinata. However, there is a proposed project by the sotol production house to make souvenirs, such as cup coasters, from sotol bagasse for consumers. In summary, this study argued that, with appropriate regulations in sotol processing, this spirit drink would be considered among those with the least negligible impact on the environment. It does not have a cultivation stage, as is the case with wine. Although according to the literature that addresses sotol production, there is an interest in generating commercial Dasylirion farming. Consequently, future research is needed to determine the carbon footprint for this type of farming. **DATA AVAILABILITY STATEMENT**

The data analyzed in this study is subject to the following licenses/restrictions: Information comes from a private company. Requests to access these datasets should be directed to jorge.garcia@uacj.mx. **AUTHOR CONTRIBUTIONS**

JM-S contributed to conceptualization, data curation, investigation, and writing (original draft). JG-A contributed to writing (review and editing). JF contributed to visualization and supervision. EC contributed to software, formal analysis, and data curation. All authors contributed to the article and approved the submitted version. **ACKNOWLEDGMENTS**

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