frontiers in Sustainable Food Systems

ORIGINAL RESEARCH
published: 10 November 2021
doi: 10.3389/fsufs.2021.769478

Life Cycle Analysis of Sotol Production in Mexico

Juan Manuel Madrid-Solórzano[1], Jorge Luis García-Alcaraz[2], Emilio Jiménez Macías[3], Eduardo Martínez Cámara[3] and Julio Blanco Fernández[4]*

[1] Department of Design, Instituto de Arquitectura, Diseño y Arte, Universidad Autónoma de Ciudad Juárez, Ciudad Juárez, Mexico, [2] Department of Industrial Engineering and Manufacturing, Instituto de Ingeniería y Tecnología, Universidad Autónoma de Ciudad Juárez, Ciudad Juárez, Mexico, [3] Department of Electric Engineering, University of La Rioja, Logroño, Spain, [4] Department of Mechanical Engineering, University of La Rioja, Logroño, Spain

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

OPEN ACCESS

Edited by:
Zainul Akmar Zakaria, University of Technology Malaysia, Malaysia

Reviewed by:
Noor Intan Shafinas Muhammad, Faculty Civil Engineering Technology, Malaysia
Guadalupe Virginia Nevárez-Moorillón, Autonomous University of Chihuahua, Mexico

****Correspondence:***
Jorge Luis García-Alcaraz
jorge.garcia@uacj.mx

Specialty section:
This article was submitted to Sustainable Food Processing, a section of the journal Frontiers in Sustainable Food Systems

Received: *02 September 2021*
Accepted: *04 October 2021*
Published: *10 November 2021*

Citation:
Madrid-Solórzano JM, García-Alcaraz JL, Macías EJ, Cámara EM and Fernández JB (2021) Life Cycle Analysis of Sotol Production in Mexico. Front. Sustain. Food Syst. 5:769478. doi: 10.3389/fsufs.2021.769478

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°C; in summer, temperatures are ∼10 to 42°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

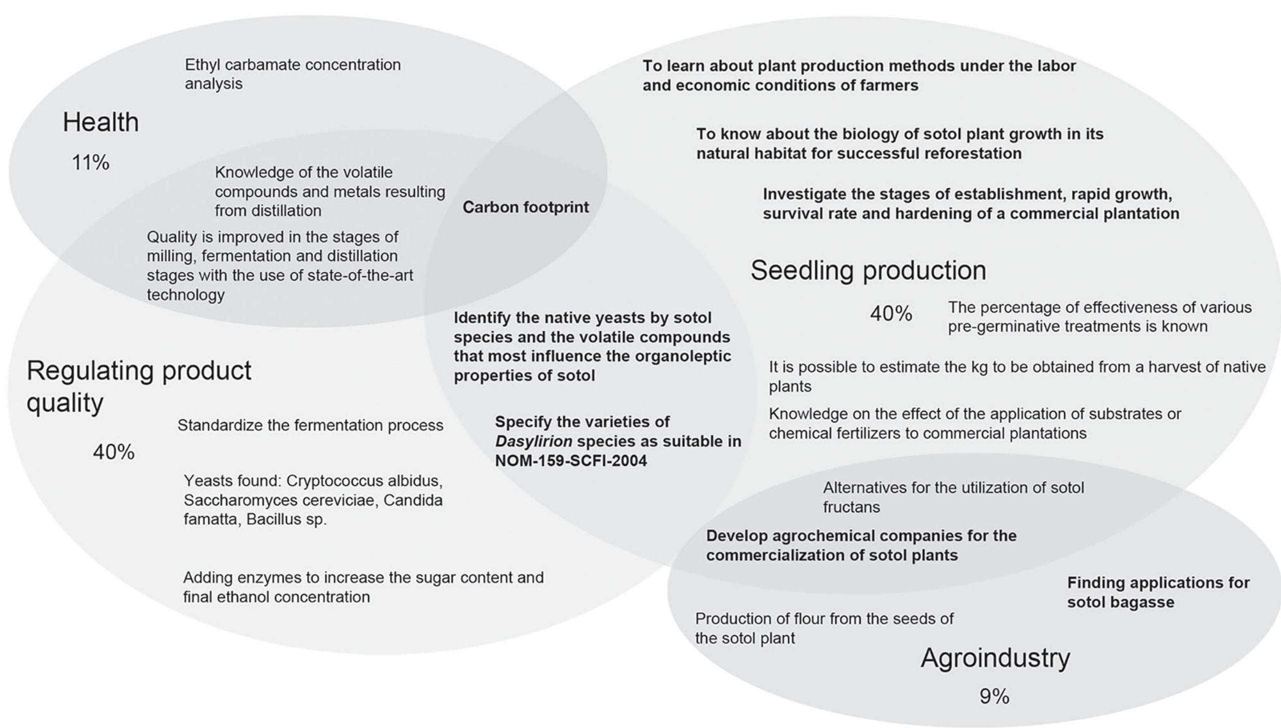

FIGURE 1 | Contributions from study disciplines and future research.

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 $\sim$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,

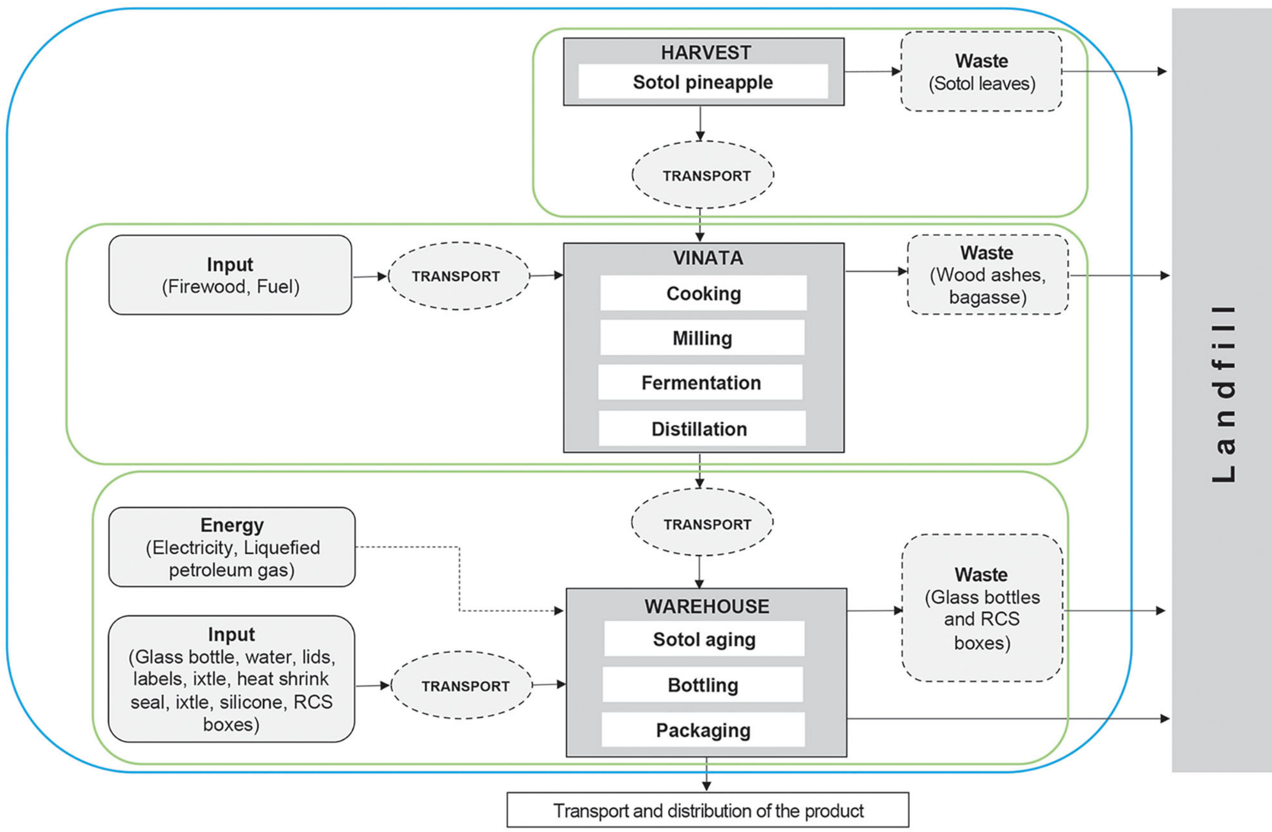

FIGURE 2 | System limits of artisanal sotol production.

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 • Gathering the *Dasylirion* species and cutting it in wild populations • The stages of harvest, cooking, milling, fermentation, distillation, bottling, and packaging • Warehouse activities, which include the transport of the final product 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	• The transportation and distribution of the final product to points of sale • The maintenance of operations of equipment and tools • Labor force and transport for transfer • Activities related to waste management • Material flow from natural resources that do not have a transformation process

supply capacity, and demand, and this is a common decision reported in other studies (Amienyo et al., 2014).

Management of waste generated at each stage of the production process was not considered for two reasons. First, outdoor spaces such as solid or liquid waste deposits are improvised—for example, leftover sotol leaves from the cut *Dasylirion* are abandoned outdoors in the harvest area. Sotol bagasse resulting from the first distillation of fermented work is likewise deposited in a space close to the Vinata. Second, solid waste generated in the warehouse is collected by the municipal garbage collection service. **Table 1** presents the parts that are included and excluded from the sotol production process.

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

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
	Output		
	Dasylirion leaf biomass	kg	2,700
Cooking (stage II)			
	Input		
	Firewood	kg	3,000
	Water	L	40
	Transport	km	15
	Output		
	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
	Output		
	Sotol bagasse biomass	kg	7,200
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

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 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-Alcaraz, 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.

TABLE 3 | Main categories of environmental impact of the ACV of a 750-ml bottle of sotol.

Impact categories	Stages of sotol alcoholic beverage processing							Total	Unit
	Harvest	Cooking	Milling	Fermentation	Distillation	Bottling	Packaging		
MAETP	245.39	352.29	8,450.46	73.69	359.94	1,879.08	110.47	11,471.35	kg 1,4-DB eq
FD	4.53	5.81	35.30	0.40	6.16	21.72	0.504	74.45	MJ
HTP	0.38	0.17	33.47	0.35	0.30	1.10	0.016	35.80	kg 1,4-DB eq
FAETP	0.14	0.10	6.67	0.06	0.12	0.35	0.024	7.49	kg 1,4-DB eq
GWP	0.32	0.44	2.99	0.02	0.46	1.61	0.040	5.92	kg CO_2 eq
TETP	7.1E-04	1.5E-03	0.041	4.2E-04	1.7E-03	2.7E-03	2.2E-04	0.04	kg 1,4-DB eq
AP	9.2E-04	2.2E-03	0.167	1.4E-04	2.4E-03	8.8E-03	1.3E-04	0.03	kg SO_2 eq

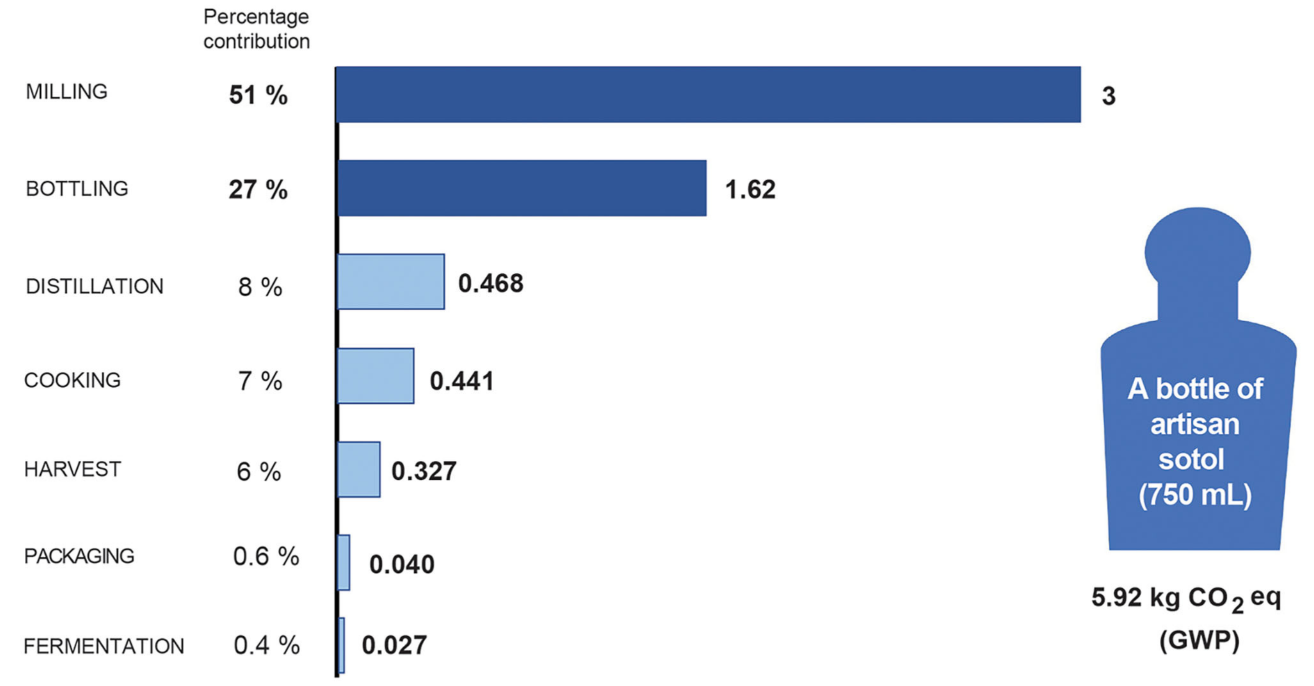

FIGURE 3 | Contribution details for each craft sotol processing process in the GWP (Global-warming Potential) index.

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 CO2 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 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

TABLE 4 | A comparison of the results of this study with previous research projects.

Distilled beverages	Presentation	Emissions kg CO_2 eq	Key points that contribute to environmental impact	References
Craft Sotol	750 ml	5.92	Machinery used for milling Use of glass bottle Distances traveled for the transport of matter and inputs for packaging	This article
Pisco	700 ml	3.62	Machinery and equipment used for viticulture and distillation Use of organic and inorganic fertilizers in the viticulture stage Distances traveled for the transport of the raw material Use of glass bottle	Vázquez-Rowe et al., 2017
Craft Mezcal	750 ml	1.7	Use of sugar for the fermentation stage Use of firewood for the distillation stage Use of herbicides in the production of agave plants to be transplanted in the field	Maciel et al., 2020
Whisky	750 ml	2.25	Waste transport Transportation of the product to other destinations Use of fossil fuel for agriculture and packaging production Barley cultivation	Eriksson et al., 2016
Classic gin	700 ml	0.57	Transport of inputs Use of cardboard boxes for packaging Electricity Use of glass bottles	Leivas et al., 2019

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 CO_2 eq., 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

The authors appreciate the help and collaboration of a Sotol Production House in Chihuahua, Mexico, for relevant artisanal production information.

REFERENCES

Alcalá de Jesús, M., Pando, M. M., Reyes, V. M. G., and Núñez, D. L. (2014). "Soil science," in *Biodiversity in Chihuahua: A State-of-the-Art Study*, eds A. N. Barajas, J. A. Cruz, P. Valero, and J. C. Treviño (Chihuahua: National Commission for the Knowledge and Use of Biodiversity (CONABIO)), 46–50.

Amienyo, D., Camilleri, C., and Azapagic, A. (2014). Environmental impacts of consumption of Australian red wine in the UK. *J. Clean. Prod.* 72, 110-119. doi: 10.1016/j.jclepro.2014.02.044

Arce-González, L., Valdés, J., Valdés, A., Gallegos, A., and Padilla, G. (2007). *Germination Tests on Sotol (Dasylirion cedrosasanum Trel.) Seeds Using Dry Extracts of Lechuguilla (Agave lechuguilla Torr.) Under Laboratory Conditions*. Universidad Autónoma Agraria Antonio Narro.

Baiano, A. (2021). Craft beer: an overview. *Compr. Rev. Food Sci. Food Saf.* 20:2. doi: 10.1111/1541-4337.12693

Becerra-López, J. L. B., Rosales, R. S., Ehsan, M., Becerra, J. S. L., Czaja, A., Estrada, J. L. R., et al. (2020). Climatic change and habitat availability for three sotol species in México: a vision toward their sustainable use. *Sustainability* 12:8. doi: 10.3390/su12083455

Becker, S., Bouzdine, T. C., and Jaegler, A. (2020). The carbon neutrality principle: a case study in the French spirits sector. *J. Clean. Prod.* 274:122739. doi: 10.1016/j.jclepro.2020.122739

Bhattacharyya, N., Goodell, A., Rogers, S., and Demond, A. (2019). Environmental impacts of wheat-based vodka production using life cycle assessment. *J. Clean. Prod*. 231, 229-237. doi: 10.1016/j.jclepro.2019.05.226

Bobba, S., Deorsola, F. A., Blengini, G. A., and Fino, D. (2016). LCA of tungsten disulphide (WS2) nano-particles synthesis: state of art and from-cradle-to-gate LCA. *J. Clean. Prod*. 139, 1478-1484. doi: 10.1016/j.jclepro.2016.07.091

Cárdenas-Díaz, D. I., Castro, E. N., Aguilar, C., Soto, O. C., La, D., et al. (2009). *Sotol Fermentation; Enzymatic Treatment of Residues*. National Congress of Biotechnology and Bioengineering.

Cimini, A., and Moresi, M. (2018). Mitigation measures to minimize the cradle-to-grave beer carbon footprint as related to the brewery size and primary packaging materials. *J. Food Eng*. 236, 1–8. doi: 10.1016/j.jfoodeng.2018.05.001

Córdova, G. B., and Romo, M. L. A. (2014). "Socio-economic context," in *Biodiversity in Chihuahua: A State-of-the-Art Study*, eds A. N. Barajas, J. A. Cruz, P. Valero, and J. C. Treviño (Chihuahua: National Commission for the Knowledge and Use of Biodiversity (CONABIO)), 65–84.

De León-Rodríguez, A., Escalante, M. P. M., Jiménez, M. I. G., Ordoñez, L. G. A., Flores, J. L. F., and Barba de la Rosa, A. P. (2008). Characterization of volatile compounds from ethnic agave alcoholic beverages by gas chromatography-mass spectrometry. *Food Technol. Biotechnol*. 46, 448–455. Available online at: https://hrcak.srce.hr/30423

Eriksson, O., Jonsson, D., and Hillman, K. (2016). Life cycle assessment of Swedish single malt whisky. *J. Clean. Prod*. 112, 229–237. doi: 10.1016/j.jclepro.2015.07.050

Ferrara, C., and De Feo, G. (2018). Life cycle assessment application to the wine sector: a critical review. *Sustainability* 10:2. doi: 10.3390/su10020395

Flores-Gallegos, A. C., Cruz, M. R., Castillo, F. R., Rutiaga, O. M. Q., Torre, L. S., Paredes, A. O., et al. (2019). "Sotol, an alcoholic beverage with rising importance in the worldwide commerce," in *Alcoholic Beverages: The Science of Beverages, Vol. 7*, eds M. A. Grumezescu, and A. M. Holban (Cambridge: Woodhead Publishing), 141–160. doi: 10.1016/B978-0-12-815269-0.00005-2

Flores-Maltos, D. A., Mussatto, S. I., Contreras, J. C. E., Buenrostro, J. J., Rodríguez, R., Teixeira, J. A., et al. (2014). Typical Mexican agroindustrial residues as supports for solid-state fermentation. *J. Agric. Biol. Sci*. 9, 289–293. doi: 10.3844/ajabssp.2014.289.293

García-Alcaraz, J. L., Montalvo, F. F., Martínez, E. C., Sáenz-Diez Muro, J. C., Jiménez-Macías, E., and Blanco-Fernández, J. (2020b). Comparative environmental impact analysis of techniques for cleaning wood wine barrels. *Innov. Food Sci. Emerg. Technol*. 60:102301. doi: 10.1016/j.ifset.2020.102301

García-Alcaraz, J. L., Montalvo, F. J. F., Martínez, E. C., Pérez de la Parte, M. M., Jiménez-Macías, E., and Blanco-Fernández, J. (2020a). Economic-environmental impact analysis of alternative systems for red wine ageing in re-used barrels. *J. Clean. Prod*. 244:118783. doi: 10.1016/j.jclepro.2019.118783

Gardea, A. A., Findley, L. T., Orozco-Avitia, J. A., Bañuelos, N., Esqueda, M., and Huxman, T. H. (2012). Bacanora and sotol: so far, so close. Social Studies. *J. Contemp. Food Reg. Dev*. 2, 153–168. Available online at: https://www.redalyc.org/pdf/417/41724972007

Iannone, R., Miranda, S., Riemma, S., and De Marco, I. (2016). Improving environmental performances in wine production by a life cycle assessment analysis. *J. Clean. Prod*. 111, 172-180. doi: 10.1016/j.jclepro.2015.04.006

INEGI (2020). *Compendium of Municipal Geographic Information of the United Mexican States*. INEGI: Chihuahua.

Jannah, M., Fahlevi, M., Paulina, J., Nugroho, B. S., Purwanto, A., Subarkah, M. A., et al. (2020). Effect of ISO 9001, ISO 45001 and ISO 14000 toward financial performance of Indonesian manufacturing. *Syst. Rev. Pharm*. 11:10. doi: 10.31838/srp.2020.10.134

Koroneos, C., Roumbas, G., Gabari, Z., Papagiannidou, E., and Moussiopoulos, N. (2005). Life cycle assessment of beer production in Greece. *J. Clean. Prod*. 13:4. doi: 10.1016/j.jclepro.2003.09.010

Lachenmeier, D. W., Kanteres, F., Kuballa, T., López, M. G., and Rehm, J. (2009). Ethyl carbamate in alcoholic beverages from Mexico (Tequila, Mezcal, Bacanora, Sotol) and guatemala (Cuxa): market survey and risk assessment. *Int. J. Environ. Res. Public Health* 6, 349-360. doi: 10.3390/ijerph6010349

Ladyman, J. A. R. (2004). "Dasylirion wheeleri S. Wats. Wheeler sotol," in *Wildland Shrubs of the United States and its Territories: Thamnic Descriptions, Vol. 1*, ed J. K. Francis (Washington, DC: United States Department of Agriculture), 26.

Leinonen, I., MacLeod, M., and Bell, J. (2018). Effects of alternative uses of distillery by-products on the greenhouse gas emissions of Scottish malt whisky production: a system expansion approach. *Sustainability* 10:5. doi: 10.3390/su10051473

Leivas, R., Laso, J., Hoehn, D., Margallo, M., Palmer, P. F., and Aldaco, R. (2019). Product vs. corporate carbon footprint: a case study for the spirit drinks sectors. *Chem. Eng. Trans.* 76, 223–228. doi: 10.3303/CET1976038

Li, J., Ma, X., Liu, H., and Zhang, X. (2018). Life cycle assessment and economic analysis of methanol production from coke oven gas compared with coal and natural gas routes. *J. Clean. Prod*. 185, 299-308. doi: 10.1016/j.jclepro.2018.02.100

Maciel, J. M., Trejo, E. B., González, P. T., Virgen, Q. A., and Benavides, L. M. (2020). Life cycle environmental impacts and energy demand of craft mezcal in Mexico. *Sustainability* 12:19. doi: 10.3390/su12198242

Madrid-Solórzano, J. M., and García-Alcaraz, J. L. (2021). *LCA Results of 750 ml Artisanal Sotol*. doi: 10.6084/m9.figshare.16640383.v1

Martins, A. A., Araújo, A. R., Graça, A., Caetano, N. S., and Mata, T. M. (2018). Toward sustainable wine: comparison of two Portuguese wines. *J. Clean. Prod*. 183, 662–676. doi: 10.1016/j.jclepro.2018.02.057

Merchan, A., and Combelles, A. (2014). "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), 239–242.

Olivas-García, J. M., Anchondo, J. Á. N., Luján, C. A., and Hernández, J. S. (2013). *Sotol (Dasylirion spp.) Production Tables for the State of Chihuahua and Technical Manual for Use*. Universidad Autónoma de Chihuahua.

Orozco-Sifuentes, M. M., García, J. E. M., Arévalo, C. A. S., Ramírez, F. G., and Reyes, M. H. V. (2019). Nutritive potential of sotol (*dasylirion cedrosanum*) seeds. *Fitotec. Mex. Mag*. 42:4. doi: 10.35196/rfm.2019.4.385-392

Ortega, S. J. A., Ibarra, F. A. F., Melgoza, A., Gonzalez, E. A. V., Martin, M. H. R., et al. (2013). Exotic grasses and wildlife in northern Mexico. *Wildl. Soc. Bull.* 37:3. doi: 10.1002/wsb.325

Ortega-Ochoa, C., Martínez, J. N., Villalobos, C., Britton, C. M., and Sosebee, R. E. (2008). Chihuahua's cattle industry and a decade of drought: economical and ecological implications. *Rangelands* 30:6. doi: 10.2458/azu_rangelands_v30i6_ortega-ochoa

Page, R. (2017). *ISO 14000 Environmental Standards: Implementing Innovation in Management and Measures*. Cheltenham: Edward Elgar Publishing. doi: 10.4337/9781783470082.00029

Patón-Romero, J. D., Baldassarre, M. T., Rodríguez, M., and Piattini, M. (2019). Application of ISO 14000 to information technology governance and management. *Comput. Stand. Interfaces*. 65, 180-202. doi: 10.1016/j.csi.2019.03.007

Ponstein, H. J., Meyer, A. A., and Prochnow, A. (2019). Greenhouse gas emissions and mitigation options for German wine production. *J. Clean. Prod*. 212, 800-809. doi: 10.1016/j.jclepro.2018.11.206

Regional Association of Foresters North Central Zone (2019). *Study of the Coyame julimes Abasto Basin*. Ministry of Environment and Natural Resources.

Reyes, A. I. S., Morales, C. F. M., Pérez, M. E. R., and Molphe, E. P. B. (2013). *In vitro* propagation of Mexican nolinaceae. *Investig. Cienc.* 21, 12–20. Available online at: https://www.redalyc.org/articulo.oa?id=67428815002

Reyes-Valdés, M. H., Palacios, R., Rivas, E. N. M., Robledo, A. O., Antonio, A. B., Valdés, C. M. D., et al. (2019). "The sustainability of Mexican traditional beverage sotol: ecological, historical, and technical issues," in *Processing and Sustainability of Beverages*, eds A. M. Grumezescu, and A. M. Holban (Cambridge, MA: Elsevier Press), 103–137. doi: 10.1016/B978-0-12-815259-1.00004-5

Riley, T. (2008). Diet and seasonality in the lower pecos: evaluating coprolite data sets with cluster analysis. *J. Archaeol. Sci.* 35:10. doi: 10.1016/j.jas.2008.04.022

Sierra-Tristán, J. S., Lara, C. R. M., Carrillo, R. R., Mendoza, A. C., Morales, C. N., and Royo, M. H. M. (2008). *The Sotols Dasyliron spp of Chihuahua*. Agricultural and Livestock Research (INIFAP).

Trujillo-Orozco, A., Gómez, S. S., Bárcena, M. S., Carreon, A. A., Estrada, A. V., Prado, R. R., et al. (2011). Detection of Cu, Pb, Cd and Zn in Mexican spirituous beverages by differential pulse polarography (DPP). *ECS Trans*. 36:1. doi: 10.1149/1.3660630

Vázquez-Rowe, I., Cáceres, A. L., Torres-García, J. R., Quispe, I., Kahhat, R. (2017). Life cycle assessment of the production of pisco in Peru. *J. Clean. Prod.* 142, 4369–4383. doi: 10.1016/J.JCLEPRO.2016.11.136

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.