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Life Cycle Environmental Impacts and Energy Demand of Craft Mezcal in Mexico

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Abstract: Agave distillates, such as tequila and mezcal, are alcoholic spirits representative of Mexican culture. In recent years, the demand for mezcal has increased, and with it the requirement for raw materials, bringing with it a series of difficulties. The objective of this study was to evaluate the potential environmental impact and energy demand of the production of young craft mezcal from an endemic agave (*Agave cupreata*) found in the central and southern Pacific area of Mexico. The potential environmental impact of the mezcal studied was obtained through the life cycle analysis methodology using a midpoint approach by the ReCiPe method to calculate the potential environmental impact with SimaPro software (version 8.2.3.0., PRé Sustainability, Amersfoort, The Netherlands). The functional unit is a young craft mezcal bottle of 750 mL with 46% Vol. Alc. The stage of highest contribution to the environmental impact of mezcal was the manufacturing/processing, contributing 59.6% of them. The energy demand of the craft mezcal resulted in 163.8 MJ/bottle of 7.5 dl. The kg CO_2eq in mezcal (1.7) is higher than beer (0.63) or white wine (1.01), but lower than whisky (2.25) or pisco (3.62). These findings could allow the search for alternatives for the development of sustainable production.

Keywords: mezcal; craft alcoholic beverage; spirit drink; distilled spirit; *agave cupreata*

1. Introduction

Mezcal and tequila are distilled agave spirit drinks representative of Mexican culture. Linked to the global expansion of tequila, mezcal has increased in popularity in recent years. The production of this drink grew by 79% compared to 2017, bottling 7.14 million litres by 2019 [1].

In the specific case of the mezcal beverage, several states of Mexico, including Oaxaca, Durango, Guerrero, Michoacan, Puebla, Guanajuato, San Luis Potosi, Tamaulipas, and Zacatecas, have protected the designation of origin (PDO) "Mezcal" [1]. However, both raw materials and production practices differ noticeably between production regions, localities, and even factories, resulting in a set of highly distinctive products [2]. The mezcal production process, in general terms, begins with the cultivation of agave which can be of wild origin, semi-cultivated, or cultivated. Once the agaves are ripe, the leaves are cut, leaving what is known as the piña (succulent core). Only the piña of the agave plant is used to make mezcal. These piñas are baked, ground, and fermented. The product obtained from the ethyl fermentation is known as must, which is distilled to separate the residues and obtain the mezcal (Figure 1).

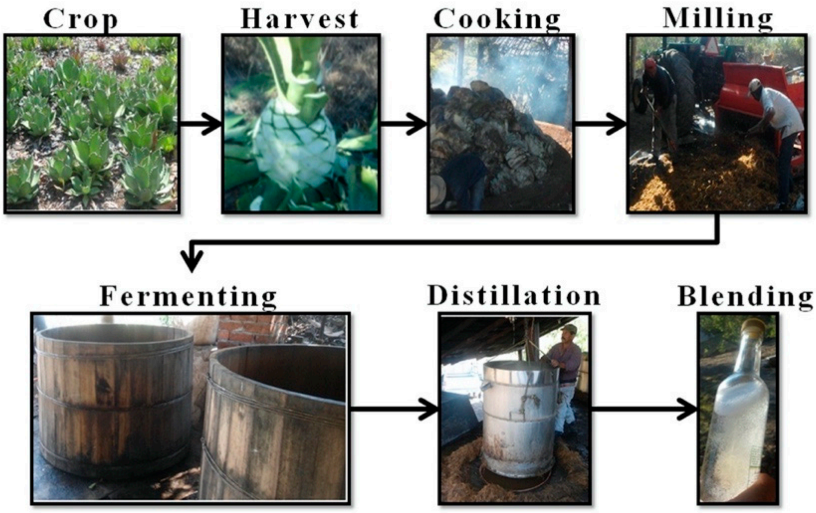

Figure 1. Mezcal production.

The regulation for mezcal production [3] declares certain categories according to the machinery, equipment, or infrastructure used in each production process. These range from industrialized production to craft production or even ancestral. In the same way, the classes of young or white mezcal are established: matured in glass, rested, aged, flared or distilled according to the process carried out after the distillation.

The increase of interest in mezcal has involved, as with tequila, several problems. Some authors pointed to the shortage of wild agave [4], overproduction of maguey [5], pests in plants [6], and even inappropriate waste management [7], both solid and vinasse, which are the residual liquids of distilling the fermented must [6]. The residual liquid effluents or stillage are classified as a polluting product because they are disposed of at temperatures close to 90 °C, with a pH lower than 5.0 and a high chemical oxygen demand (COD) (50–150 g O_2/L) [8]. By placing the stillage on the ground, the suspended solids cause a decrease in permeability, obstructing the pores of the soil [9].

In response to the problem of scarcity of raw materials in the agave–mezcal product system, sustainable practices have been proposed, focused mainly on the production of agave. For example, agroforestry management [10,11], the selection of potential areas for agave plantations [12], and even assisted plant reforestation programs, wet nurses, and agaves [13]. To reduce the problem of waste in the production of mezcal, studies have been carried out on the production of tiles made from a bio composite material, bagasse [14], and the production of biofuels through a treatment of bagasse [15] and adobes reinforced with agave fibre in Oaxaca [16].

The efforts made to solve the problems of mezcal, to date, have focused on specific stages of the production chain of said drink. However, there are still no reports that describe the environmental impact of mezcal production with a life cycle approach or indicators on the energy performance of the process.

There are several studies on the environmental impact of alcoholic beverages approached from the methodology of life cycle assessment (LCA), including wine and beer production in the UK [17,18], Spanish wine [19,20], whisky in Sweden [21], and Peruvian pisco [22], where the greatest impact comes from the agricultural stage. On the other hand, other LCA studies analysing alcoholic beverages point out that the main impact corresponds to the glass bottle production, as in the case of red wine in Catalonia, Spain [23] or white wine in Sardinia, Italy [24]. There is, however, a lack of life cycle perspective in the production stage of drinks obtained by distilling agave plants such as tequila or mezcal. To the best of the author's knowledge, no previous published studies are available that investigate impacts from a life cycle perspective.

On the other hand, Pimentel [25] points out that 25% of the world's fossil energy is used to produce food. The operation of current agro-ecosystems is based on two energy flows: the natural one corresponding to solar energy and an "auxiliary" flow, controlled by the farmer who resorts to the use of fossil fuels, either directly or indirectly, through the industrial inputs used in the production process. In addition to agro-ecosystems, studies have been carried out to find out the energy demand in other areas such as production processes. In the case of alcoholic beverages such as whisky [21], their primary energy consumption or energy obtained from either direct sources or combustible ones corresponded to 57.3 MJ/ 750 mL bottle (the energy equivalent of 1.63 L of gasoline). Olajire [26] mentions that a well-run brewery would use 1.125 MJ/ 750 mL of beer produced (the equivalent of 0.032 L of gasoline). In the case of agave distillates such as tequila or mezcal, this information was scarce within the bibliographic search carried out by the authors.

The present work evaluated the production of *Agave cupreata* mezcal in a vinata (the place where agave is processed to obtain a non-industrialized mezcal) of the community of Etucuaro. It is a drink of the artisan category, that is to say, it uses ancestral equipment and is of low technology in its production. It is classified as young because it is not subject to any type of post-distillation process, resulting in a colourless and translucent product [3]. The objective of the study was to identify the critical points of environmental impact from the point of view of LCA and to calculate the energy demand of the product including direct and indirect energy in order to calculate the productivity of the process. This information will serve as a basis for finding alternatives that increase the productivity of inputs and reduce the impact on the environment by improving the sustainable development of the activity.

2. Materials and Methods

The study evaluates two aspects of the craft mezcal production chain. First the information related to the LCA is shown and then the calculation of the energy demand. For both aspects the same stages and processes of mezcal production were taken.

2.1. Study Zone

The selected zone was Etucuaro, municipality of Madero, Michoacan de Ocampo, Mexico (Figure 2). The municipality is bordered to the north by Morelia, the state capital. According to National Institute of Statistics and Geography (NISG) [27], luvisol (38%) and regosol (35%) soils predominate in the municipality. The climates that predominate are semi-warm and temperate sub humid (33 and 27% respectively) with rainfall ranging from 800 to 1300 mm. Its vegetation is mainly composed of forest (82%) with low use of agricultural (6%) and urban land (0.17%). Most of the population (54%) is dedicated to primary activities [28].

Figure 2. Study zone [29].

2.2. Definition of the Scope and Objectives of the Craft Mezcal Life Cycle

2.2.1. Goal

Identify the critical points of environmental impact in the craft mezcal production chain under the LCA methodology.

2.2.2. Scope

The present study included everything from obtaining raw materials (cradle) to the end of life or waste disposal (grave) as shown in Figure 3. The data for the system analysis were collected directly in the field by the authors and correspond to the production of a young mezcal batch in 2017. The analysis was performed under the ReCiPe method to calculate the potential environmental impact using Simapro software (version 8.2.3.0., PRé Sustainability, Amersfoort, The Netherlands). The impact categories evaluated for the analysis were those considered mid-point by the ReCiPe method, although the results only express those considered significant, that is, when they represent more than 75% of potential impact.

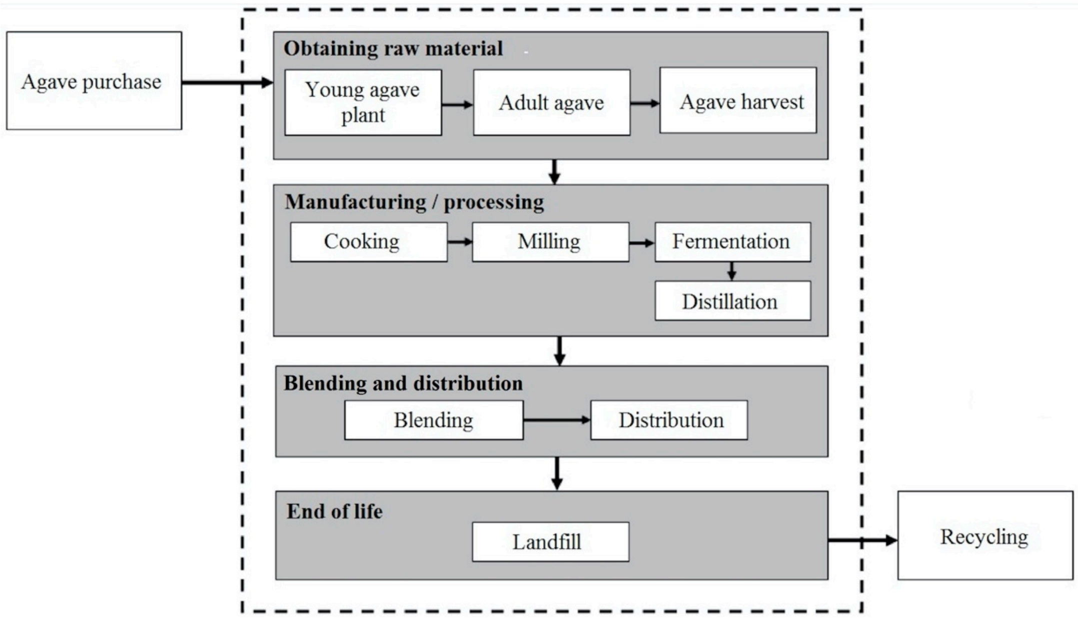

Figure 3. System limits of craft mezcal production.

The functional unit (FU) is a young craft mezcal bottle of 750 mL with 46% Vol. Alc. made from a vinata in Etucuaro, Michoacan. The stages of the production process studied were: (1) obtaining raw material, (2) manufacturing/processing, (3) blending and distribution, and (4) end of life.

In the analysis, it was considered that obtaining raw materials takes approximately seven years, from the germination of the seed until the agave reaches sexual maturity and is harvested just before flowering, when the sugar concentration is at its maximum [30]. The agave used for mezcal production was semi-cultivated, remaining three years in the nursery and four years in the wild. The processing stage together with the packaging stage lasts approximately two months. For the cooking of the agave hearts, it was identified that oak firewood obtained from the region is used because it provides organoleptic properties to the mezcal, while the double distillation uses residual wood obtained from a nearby lumber warehouse. For the milling, the inputs used by the tractor are included, but the impact of the manufacture of the equipment is not. Since data were collected in 2017, mezcal production was governed by the indications of NOM-070-SCFI-1994 [31], which allowed the production of type I mezcal with 100% agave sugars and type II which allows up to 20% use of other carbohydrates. The studied vinata produced type II mezcal, and sugarcane was added. Currently, the NOM-070-SCFI-2016 [3] is in force, which only allows the production of 100% agave mezcal. For the end of life, a landfill scenario was considered due it being the final disposal site for 78.5% of the waste in Mexico [32]. It includes the transport used in production from obtaining raw materials to the distribution of the final product.

The purchase of agave in the stage of obtaining raw materials was not considered for the present analysis, neither was the recycling of waste in the end of life stage because it only represents the destiny of 9.6% of the waste in Mexico [32]. The potential impact of the production of machinery, equipment, or infrastructure in the craft mezcal category (the oven for cooking, the tractor for grinding, the fermentation vats, the type or material of the stills) was not included. Transport used after the distribution of the final product was not considered either because the location of the final consumer and the distance between the consumer and the waste disposal site is unknown.

2.3. Types of Mezcal Considering in the Study

Craft Mezcal Type II: This is the product obtained from the distillation and rectification of musts whose formulation are up to 20% of other carbohydrates allowed by the corresponding legal provisions [31].

Craft Mezcal: The formulation consists of 100% agave. The cooking of agave is in a floor oven, stone or masonry. The traditional equipment used for milling uses human strength or power tools. The distillation is with direct fire in copper stills, clay pot, or stainless steel, and the process can include the maguey fibre (bagasse) [3].

Ancestral mezcal. The production is in a rustic way with a 100% agave formulation. The cooking of agave is in a conical oven on the floor (earth). For milling, is used only the force of man or animals without electrical tools. The distillation only uses direct fire in the clay pots and must include the fibre of the maguey (bagasse) [3]. The price of this type of mezcal is higher compared to a craft mezcal. This because of the losses in the process and the added value of being made manually.

2.4. Life Cycle Inventory Analysis

The inventory considered the system inputs and outputs by production stage required per FU (Table 1). The raw materials included the agrochemicals and water used, the inputs required to prepare the soil for transplanting, the equipment for harvesting the agave stems (also called hearts), and the transport from the field to the vinata (three trips). Inputs for cooking, milling, fermentation, and distillation were included in the processing. The blending and distribution of the final product considered a 750 mL transparent glass bottle, label and screw cap assembled by hand, for distribution a trip was considered to cover the delivery route. The end-of-life scenario was the disposal of waste in a landfill.

Table 1. Life cycle inventory.

Obtaining Raw Material			
Inputs from Nature	**Amount per FU ***	**Unit**	**Description**
Occupation, unspecified, natural	4.1×10^{-6}	ha	Land
Water, fresh	1.05	m^3	Water
Inputs from Technosphere	**Amount per FU ***	**Unit**	**Description**
Grass seed, organic, for sowing {RoW}|production|Alloc Def, U	2×10^{-3}	kg	Seeds
Ammonium sulphate, as N {RoW}|ammonium sulphate production |Alloc Def, U	3×10^{-3}	kg	Fertiliser
Glyphosate {RoW}|production|Alloc Def, U	7×10^{-2}	kg	Herbicide
Pesticide, unspecified {RoW}|production|Alloc Def, U	7.8×10^{-3}	kg	Insecticide
Transport, freight, lorry 3.5–7.5 metric ton, EURO3 {GLO}|market for|Alloc Def, U	5.68×10^{-2}	t/km	Transport
Electricity, low voltage {CZ}|electricity voltage transformation from medium to low voltage|Alloc Def, U	2.2×10^{-3}	kWh	Energy

Table 1. *Cont.*

Final Waste Flow	Amount per FU *	Unit	Description
Packaging waste, plastic	1.62×10^{-2}	kg	Plastic bottles
Waste, organic	3×10^{-3}	t	Agave leaves
Manufacturing/Processing			
Inputs from Nature	**Amount per FU ***	**Unit**	**Description**
Water, river, MX	2.54×10^{-2}	m^3	Water
Inputs from Technosphere	**Amount per FU ***	**Unit**	**Description**
Forest residue, processed and loaded, at landing system/ton/RNA	2.4×10^{-3}	t	Firewood
Diesel, burned in building machine {GLO}|market for|Alloc Def, U	13.26×10^{-2}	MJ	Energy
Electricity, low voltage {MX}|electricity voltage transformation from medium to low voltage|Alloc Def, U	6×10^{-3}	kWh	Electricity
Transport, freight, lorry 3.5–7.5 metric ton, EURO3 {RER}|transport, freight, lorry 3.5–7.5 metric ton, EURO3|Alloc Def, U	14.65×10^{-2}	t/km	Transport
Sugar, from sugarcane {GLO}| market for|Alloc Def, U	1×10^{-3}	t	Sugar
Residual wood, dry {GLO}| market for|Alloc Def, U	5×10^{-3}	t	Wood
Final Waste Flow	**Amount per FU ***	**Unit**	**Description**
Wood ashes	1×10^{-4}	t	Ashes
Wastewater/m^3	1.65×10^{-2}	m^3	Residual water
Packaging waste, plastic	5.96×10^{-6}	kg	Plastic bottles
Waste, organic	11×10^{-3}	t	Vinasses and bagasse
Blending and Distribution			
Inputs from Technosphere	**Amount per FU ***	**Unit**	**Description**
Packaging glass, white {GLO}|market for|Alloc Def, U	3×10^{-4}	t	Bottle
Polypropylene, granulate {GLO}|market for|Alloc Def, U	2.65×10^{-6}	t	PP screw cap
Polypropylene, granulate {GLO}|market for|Alloc Def, U	5.96×10^{-7}	t	Paper tag
Corrugated board boxes, technology mix, prod. mix, 16.6% primary fibre, 83.4% recycled fibre EU-25 S	2.45×10^{-5}	t	Cardboard box
Transport, freight, lorry 3.5–7.5 metric ton, EURO3 {GLO}|market for|Alloc Def, U	4.73×10^{-2}	t/km	Transport
End of Life			
Inputs from Technosphere	**Amount per FU ***	**Unit**	**Description**
Packaging glass, white {GLO}|market for|Alloc Def, U	3×10^{-4}	t	Bottle
Polypropylene, granulate {GLO}|market for|Alloc Def, U	2.65×10^{-6}	t	PP screw cap
Printed paper {GLO}|market for|Alloc Def, U	5.96×10^{-7}	t	Paper tag
Corrugated board boxes, technology mix, prod. mix, 16.6 % primary fibre, 83.4 % recycled fibre EU-25 S	2.45×10^{-5}	t	Carton box
Final Waste Flow	**Amount per FU ***	**Unit**	**Description**
Wastewater/m^3	1.643×10^{-2}	m^3	Residual water
Waste, organic	1.458×10^{-2}	t	Organic waste
Wood ashes	1×10^{-4}	t	Ashes
Packaging waste, plastic	1×10^{-5}	kg	Plastic bottles

Note: * FU: 750 mL bottle of 46% volume of alcohol.

2.5. Energy Demand of Craft Mezcal Production

The energy demand of a production process is the energy used to create a production unit (kg, L, bottle, piece, among others). For the calculation of the total energy demand in the production of craft mezcal, the same FU was taken as for the LCA, and therefore the same stages apply. Direct and indirect energy sources were considered for each production stage. Energy equivalence data for inputs were obtained from literature reviews plus our own calculations from these or field data (Table 2). For some data such as firewood or wood, polypropylene (PP) and cardboard, the calorific potential was used, as well as own calculations. In the processing stage, the agave input was no longer included in the calculation to avoid double counting, because it was the result of the raw material stage.

Table 2. Energy equivalence of inputs for craft mezcal production by stage.

Inputs	Unit	Energy Equivalence (MJ/Unit *)	References
Obtaining Raw Materials			
Adult agave	kg	8.11	This report
Human work	h	1.96	Mandal et al. [33]
Chainsaw	h	4.3	Technical data sheet
Gasoline transport	kg	32.4	Rivera et al. [34]
Chemicals			
Fertiliser (ammonium sulphate CAS: 7783-20-2)	kg	45	Audesley et al. [35]
Herbicide (rival CAS number: 1071-83-6)	kg	238	Gündogmus [36]
Pesticide (cypermethrin CAS number: 52315-07-8)	kg	199	Gündogmus [36]
Water	m^3	0.63	Yilmaz et al. [37]
Barley seeds	kg	14.7	Ziaei et al. [38]
Manufacturing/Processing			
Inputs	**Unit**	**Energy Equivalence (MJ/Unit *)**	**References**
Agave hearts	piece	4.31	This report
Human work	h	1.96	Mandal et al. [33]
Tractor/mechanical mills	MJ	185.4	Technical data sheet
Gasoline transport	kg	32.4	Ecoinvent 2010 from Rivera et al. [34]
Diesel transport	L	56.31	Mohammadi and Omid [39]
Electric power	kWh	3.6	
Firewood and wood	t	14486	SENER [40]
Water	m^3	0.63	Yilmaz et al. [37]
Sugar	t	3083.3	Vu et al. [41]
Blending			
Inputs	**Unit**	**Energy Equivalence (MJ/Unit *)**	**References**
Bottles	bottles	8.5	Gazulla et al. [20]
PP screw cap	kg	44	Arandes-Esteban et al. [42]
Paper tag	t	16.5	SENER [40]
Cardboard box	t	14.5	SENER [40]

Note: * The unit is the one represented for each input.

From the total energy demand used and the total product produced, the specific energy (SE) (Equation (1)) and the energy productivity (EP) (Equation (2) were calculated, which represent the relationship between a product and the energy invested in a production process, valued in megajoules (MJ) [43].

$$SE = \frac{Energy\ used\ (MJ)}{Product\ produced\ (unit\ for\ measurement)} \quad (1)$$

$$EP = \frac{Product\ produced\ (unit\ for\ measurement)}{Energy\ used\ (MJ)} \quad (2)$$

3. Results and Discussion

3.1. Environmental Impact Assessment of Craft Mezcal Production

Table 3 shows the percentage of environmental impact contribution by each stage of the production process of a 750 mL bottle of young craft mezcal (46% Vol. Alc.), compared to two other similar categories in the current standard (NOM-070-SCFI-2016). The category "mezcal" is usually industrialized, so comparing these results was not considered. In all three categories, the stages with the greatest environmental impact were manufacturing/processing and obtaining raw materials. The use of sugar in type II mezcal generated changes in the distribution of the impact of the process stages, unlike the use of mechanical mills which did not represent a substantial change in the environmental impact of the process.

Table 3. Percentages of potential impact contribution by production stage in various mezcal categories.

Production Stage	**Mezcal Category**		
	Craft Mezcal Type II *	**Craft Mezcal ****	**Ancestral Mezcal ****
	Percentages (%)		
Obtaining Raw Materials 	19.7	28.7	28.8
Manufacturing/Processing 	59.6	37.8	37.4
Blending and Distribution 	10.1	17.2	17.3
End of Life 	10.2	16.4	16.5

Notes: * Mezcal made under NOM-070-SCFI-1994; ** mezcal made under NOM-070-SCFI-2016.

Table 4 indicates the categories of environmental impact that were significant with a value greater than 75% in the production of mezcal for the stages of obtaining raw materials and manufacturing/processing. In type II craft mezcal, the use of sugar provides three additional impact categories regarding the category of craft and ancestral mezcal in manufacturing/processing stage. On the other hand, in the raw materials stage, it has the lowest percentage regarding the contribution of water depletion at 86.5%.

Table 4. Contribution by significant * impact category in various mezcal categories.

Impact Category	**Craft Mezcal Type II**		**Craft Mezcal**		**Ancestral Mezcal**	
	RM	**M**	**RM**	**M**	**RM**	**M**
	Contribution Percentage (%)					
Marine eutrophication	–	90.2	–	–	–	–
Photochemical oxidant formation	–	82.2	–	–	–	–
Terrestrial ecotoxicity	–	99.2	–	–	–	–
Agricultural land occupation	–	95.4	–	93.9	–	93.9
Urban land occupation	–	86.9	–	85.5	–	85.5
Natural land transformation	–	77.8	–	75.0	–	75.0
Water depletion	86.5	–	99.5	–	99.5	–

Note: * Value greater than 75% considered to be significant. RM: Raw materials stage, M: Manufacturing/processing stage.

Table 5 indicates that, for the type II craft mezcal category, in the manufacturing/processing stage, the processes that presented a greater environmental impact were fermentation and distillation, contributing 56.3% and 40.9%, respectively. In the alternative mezcal categories, the fermentation process was less than 5% impact while distillation contributed about 90%. The second stage with the greatest impact on mezcal production was obtaining raw materials (Table 3). The process that most contributed to the environmental impact within that stage was the production of young agave plants (55.8%). This process comprises the germination of the seed to obtain the three-year-old plant, which can be transplanted in the field.

Table 5. Contribution percentage of potential impact by processes in two production stages in the mezcal categories.

Production Stage	Mezcal Category		
	Craft Mezcal Type II	Craft Mezcal	Ancestral Mezcal
	Percentages (%)		
Obtaining raw materials			
Young agave plant		55.8	
Adult agave		38.8	
Agave harvest		5.2	
Manufacturing/processing			
Cooking	2.2	4.4	4.5
Milling	0.6	1.7	0.09
Fermentation	56.3	3.9	3.9
Distillation	40.9	89.8	91.3

3.2. Interpreting the Potential Impact of Craft Mezcal Production

The stage with the greatest impact on mezcal production in the categories mentioned in Table 3 was manufacturing/processing. In the production of type II craft mezcal, the potential impact of the manufacturing/processing stage was related to the use of sugarcane. Table 6 reveals that within the fermentation process, the sugarcane input contributed 96% of the environmental impact and had a representation of more than 95% in 13 of 18 impact categories. For the distillation process, the wood used contributed 94% of the environmental impact and represented over 95% in 10 of 18 impact categories. For the young agave plant, the use of the herbicide provided 82% of the environmental impact and contributed over 95% in 10 of 18 impact categories.

Unlike some LCA studies applied to alcoholic beverages, where their agricultural stage provided the greatest environmental impact, in the present study it was found that for mezcal the production the manufacturing/processing stage provides it. For example, Gazulla et al. [20] reported that the impact of their agricultural stage on wine production is due to greenhouse gas (GHG) emissions produced by the use of fertilisers. They found a use of 0.7 kg per year of fertiliser per 750 mL bottle. For mezcal production, they use 0.003 kg of fertiliser per bottle of the same size, but unlike grapes, agave uses fertiliser only in the first three years of the seven-year production cycle.

Table 6. Significant contributions (>95%) by impact category in various inputs of mezcal production.

Production Process	Fermentation with Sugar	Distillation	Young Agave Plant
Impact Category/Input	**Sugarcane (96%) ***	**Residual Wood (94%) ***	**Herbicide (82%) ***
Climate change	–	–	–
Ozone depletion	–	–	•
Terrestrial acidification	•	–	-
Freshwater eutrophication	•	•	•
Marine eutrophication	•	–	-
Human toxicity	•	–	•
Photochemical oxidant formation	•	•	–
Particulate matter formation	•	•	–
Terrestrial ecotoxicity	•	–	•
Freshwater ecotoxicity	•	•	•
Marine ecotoxicity	•	•	•
Ionising radiation	–	–	•
Agricultural land occupation	•	•	–
Urban land occupation	•	•	–
Natural land transformation	•	•	•
Water depletion	–	•	–
Metal depletion	•	•	•
Fossil depletion	–	–	•
Total significant categories	13	10	10

Note: * Percentage contribution in processing for each input.

In mezcal production, the environmental impact resulted from the addition of sugarcane used in the processing stage. Figure 4 shows the origin of the impact of sugarcane obtained from the Simapro software database (version 8.2.3.0., PRé Sustainability, Amersfoort, The Netherlands). It is observed that irrigation and the use of nitrogenous fertilisers are the inputs with the greatest impact in the agricultural phase, contributing approximately 41.9%. Within its industrial part, transport stands out. In total, 0.344 kg of CO_2eq was generated per kg of sugarcane.

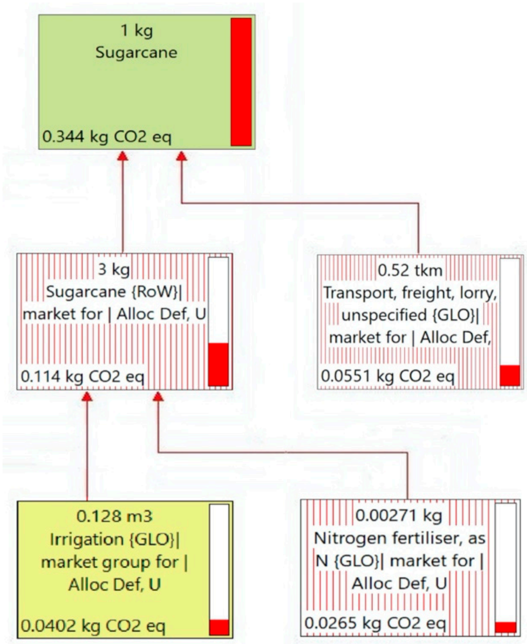

Figure 4. Inputs with the greatest impact on the sugarcane production.

In the category of craft and ancestral mezcal subject to NOM-070-SCFI-2016 that do not use sugar in their process, they present a different distribution of environmental impact. The input that contributes most is the wood used during distillation within the processing stage. Obtaining this input involves a forestry process and an industrial process. Figure 5 shows the nitrogen products, electricity and resins as the inputs with the greatest impact on the production of waste wood, generating a total of 52 kg of CO_2eq per m^3 of waste wood.

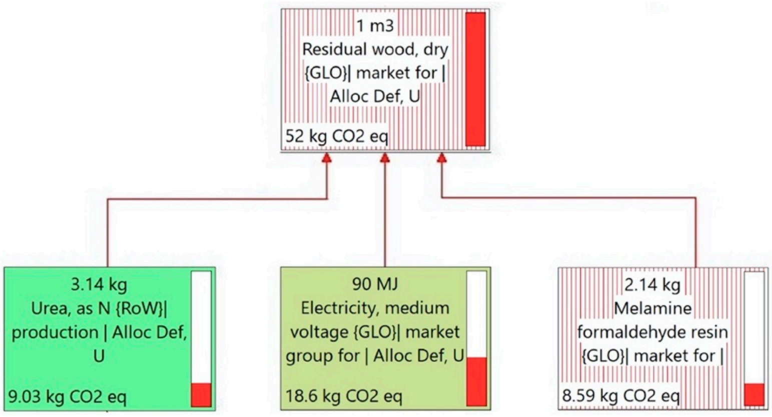

Figure 5. Inputs with the greatest impact on the residual wood production.

In a comparative study of LCAs in various Peruvian pisco producers, Vázquez-Rowe et al. [22] show that the impact on the distillation stage varies significantly depending on the fuel. When using wood, about 15 g CO_2eq are generated per 500 mL bottle, while fossil fuels generate about 350 g. In the case of the craft mezcal studied, a comparison was made between two fuels that cover the energy demand in the FU distillation (72.43 MJ). Table 7 shows the significant categories of GHGs generated if 5 kg of wood or 1.6 kg of propane is used. Values of less than 1 kg of contribution in the impact category were not considered significant. Wood was found to have a lower impact on the environment than propane. It is important to mention that the difference between the amount of fuel used is not negligible and its choice depends on other factors, such as costs, storage, transport, and other considerations of each producer. Eriksson et al. [21] reported that 24.9% of the energy in their process is invested in distillation, which comes mostly from renewable sources, such as biomass combustion, thus reducing the environmental impact of this stage.

Table 7. Contribution by impact category of two different fuels in the distillation stage.

Impact Category/Input	Residual Wood	Propane
Amount of Fuel (kg)	**5**	**1.6**
	72.43 MJ	
Climate change kg carbon dioxide-eq (CO_2-eq)	–	1631.8
Terrestrial acidification kg of sulphur dioxide-eq (SO_2-eq)	–	2.8
Human toxicity kg de 1,4 dichlorobenzene-eq (1,4-DB-eq)	–	870.1
Photochemical oxidant formation kg of volatile non-methane organic compounds (NMVOC)	–	2.8
Freshwater ecotoxicity kg 1,4 dichlorobenzene-eq (1,4-DB-eq)	–	7.2
Marine ecotoxicity kg 1,4 dichlorobenzene-eq (1,4-DB-eq)	–	7.1
Agricultural land occupation m^2	6.3	–
Fossil depletion kg oil-eq	–	525.6

In the stage of obtaining raw materials, the use of the herbicide has great representation during the obtaining of the young agave plant, a process that lasts three years and uses 0.07 kg of herbicide per 750 mL bottle of mezcal. In other studies, the use of fertilisers or pesticides is more represented than herbicides, such as in the production of pisco [22] or wine [18]. Figure 6 shows the most representative inputs in the impact of the production of 1 kg of herbicide, whose process generates 10.2 kg of CO_2eq.

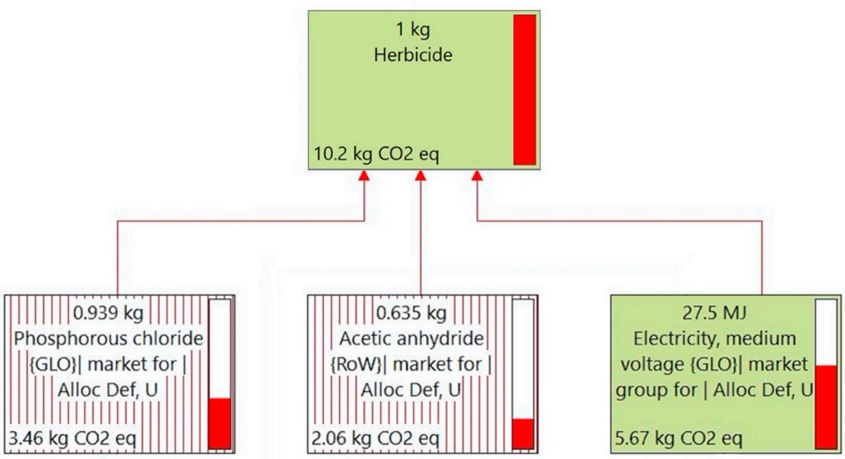

Figure 6. Inputs with the largest impact on the herbicide production.

Table 8 shows a comparison of CO_2 emissions for various alcoholic beverages. The studies corresponding to distilled beverages show values greater than 1.5 kg of CO_2 except as reported by Leivas et al. [44] for gin. The difference in beverage emissions is most likely due to variations in the product life cycle or system boundaries of each study. For example, gin has the lowest emissions value (0.58 kg CO_2) because its agricultural stage does not generate impacts since it obtains its botanical resources from the wild [41]. On the other hand, Vázquez-Rowe et al. [22] show for Peruvian pisco the average emissions of several wineries, with 3.37 kg of CO_2 being the highest value.

Table 8. Comparison of CO_2 emissions among alcoholic beverages.

Beverage (750 mL)	Emissions kg CO_2 eq	References
Craft mezcal	1.7	This report
Gin	0.62	Leivas et al. [44]
Beer	0.63	Amienyo et al. [17]
Crianza wine	0.93	Gazulla et al. [20]
Aged red wine	0.95	Meneses et al. [23]
White wine	1.01	Fusi et al. [24]
Austrailian red wine	1.25	Amienyo et al. [18]
Whisky	2.25	Eriksson et al. [21]
Ribeiro wine	2.64	Vázquez-Rowe et al. [19]
Pisco	3.62	Vázquez-Rowe et al. [22]

3.3. Energy Demand for Craft Mezcal Production

Agro-ecosystems are demanding energy from various sources, from solar energy for biomass development, to energy from fossil sources when they require heating such as in greenhouses or agricultural machinery. In the case of mezcal production, the various stages demand various sources of energy, either for primary use or for the processing of its inputs.

Table 9 shows the energy demand of type II craft mezcal production obtained from Table 2, by life cycle stage and by its relationship with the various inputs, as well as the percentage contribution of the latter. A total of 163.8 MJ/bottle (750 mL) was identified as required. The stage with the highest energy requirement was manufacturing/processing. This stage is a relatively short process that lasts from one to two months, which, nevertheless, demands 73.4% of the whole production process to obtain the mezcal product, due to the use of firewood and wood. The stage of obtaining raw materials, despite a duration of about seven years, requires 21.4% of the total energy for the production of agave hearts. This is due to the impact generated by the use of herbicides. The agave used in this study is semi-cultivated, which could explain why its greatest impact stage is not obtaining raw materials, as in other studies where a greater use of agrochemicals is required. In craft mezcal production, the main source of energy came from burning biomass. Other sources such as electricity or petroleum derivatives, e.g., agrochemicals and hydrocarbons for transportation, had less participation.

Table 9. Total energy inputs in the stages of mezcal production.

Stage	Power Inputs (MJ/FU)	Contribution (%)
Obtaining raw materials (agave)		21.4
Herbicide	16.7	47.6
Gasoline transport	12.0	34.3
Human work	3.9	11.1
Others **	2.4	6.9
Subtotal stage	35	
Manufacturing/Processing		73.4
Agave *	–	–
Firewood and wood	107.2	89.1
Gasoline transport	8.0	6.7
Sugar	3.1	2.6
Others **	2.0	1.6
Subtotal stage	120.3	
Blending		15.1
Bottles	8.5	99.5
Others **	0.04	0.5
Subtotal stage	8.5	
Total	163.8	100

Notes: * Total value of the previous stage so not counted in order to avoid double counting; ** Σ Others, included the following categories: use of chainsaw, fertiliser, pesticide, water, seeds, tractor, diesel transport, electric power, firewood and wood for agave heart cooking and distillation, PP screw caps, sticky paper labels, cardboard boxes.

The energy demand for mezcal production differed from other beverages such as whisky reported by Eriksson et al. [21] with 57.3 MJ/ 750 mL bottle. However, whisky production only considered energy obtained from direct sources (electricity and fossil fuels), while in this study, mezcal included the energy required for input production.

Table 10 shows the comparison of SE and EP in alcoholic drinks and spirits around the world, including water as a reference drink. The mezcal production process had an SE value of 21.8 MJ/dl and an EP of 0.05 dl of mezcal for each MJ. Of the references cited, the beer production analysed by Olajire [26] had the lowest value for SE (0.19) and the highest for EP (5.18), which means that more product is obtained with less energy. It should be noted that differences in the values of SE and EP may be due to differing processes, inputs or equipment used, their origin, and the source and type of energy (direct or indirect).

Table 10. Comparative table of SE and EP in some alcoholic and spirit drinks.

Product (7.5 dL)	SE (MJ/dL)	PE (dL/MJ)	Country	References
Craft mezcal Type II	21.8	0.05	Mexico	This report
Whisky	7.6	0.13	Sweden	Eriksson et al. [21]
Wine	3.0	0.33	United Kingdom	Amienyo et al. [18]
Gin	1.83	0.55	Spain	Leivas et al. [44]
Beer	1.75	0.57	United Kingdom	Amienyo et al. [17]
Beer	0.3	3.33	Latvia	Kubule et al. [45]
Beer	0.19	5.18	Nigeria	Olajire [26]
Drinking water	0.02	48.14	United States	Bukhary et al. [46]

Note: The values in this table were calculated according to the data in each reference. 750 mL = 7.5 dL. The decilitre unit is handled to facilitate the presentation of the data.

4. Conclusions

This study identified the critical points of environmental impact and energy demand for craft mezcal production, resulting in the manufacturing/processing stage for both cases, unlike other studies whose main impact comes from obtaining raw materials. During the comparison of mezcal categories, it was found that changing a key input, such as sugarcane, wood, or herbicide, redistributes the percentage contribution to environmental impact. The energy demand of craft mezcal production has a value of 163.8 MJ/bottle (750 mL) equivalent to 4.62 L of gasoline. The CO_2 emissions of spirits whose process is industrialised and whose life cycle includes everything from obtaining raw materials to the end of life show higher values than spirits whose process is carried out by hand or whose raw materials are obtained from the wild. In stricto sensu, the non-technical and ancestral production of mezcal is difficult to compare because of the variants in machinery, equipment, and infrastructure. In mezcal's life cycle, for example, some agaves are only obtained in the wild, while others, because they are endemic species, only develop in the space that meets the required characteristics, and there are also species that only reproduce through seed, like the agave mentioned in this study. However, in general terms, mezcal production has homogeneous stages. For this reason, we consider that this study could be valid for others vinatas or palenques with same technification level.

5. Recommendations

Based on the results, we believe that it is possible to reduce the environmental impact and energy consumption for mezcal production, so the following recommendations are made for future research.

- Carry out a study in other vinatas or palenques of the equivalent category of mezcal to compare in other regions the critical points of environmental impact.
- Compare production processes with alternatives that may have less impact, for example, the use of renewable energies, organic agriculture, recycling, or waste management.
- Establish a guide of good environmental practices for craft mezcal production.

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References

1. Consejo Regulador Mezcal. *Informe Estadístico 2020*; Consejo Regulador Mezcal: Oaxaca, Mexico, 2020.
2. Kirchmayr, M.R.; Segura-García, L.E.; Lappe-Oliveras, P.; Moreno-Terrazas, R.; de la Rosa, M.; Gschaedler Mathis, A. Impact of environmental conditions and process modifications on microbial diversity, fermentation efficiency and chemical profile during the fermentation of Mezcal in Oaxaca. *LWT Food Sci. Technol.* **2017**, *79*, 160–169. [CrossRef]
3. STID (Former Secretariat of Trade and Industrial Development). *NOM-070-SCFI-2016. Norma Oficial Mexicana. Bebidas Alcohólicas-Mezcal-Especificaciones*; STID: Mexico City, Mexico, 2016. (In Spanish). Available online: https://dof.gob.mx/nota_detalle.php?codigo=5472787&fecha=23/02/2017 (accessed on 14 May 2020).
4. Martínez-Jiménez, R.; Ruiz-Vega, J.; Caballero-Caballero, M.; Silva Rivera, M.E.; Montes Bernabé, J.L. Wild and cultivated agaves used in the elaboration of mescal in Sola de Vega, Oaxaca, México. *Trop. Subtrop. Agroecosystems* **2019**, *22*, 477–485.
5. Bautista, J.A.; Antonio-Jose, A.A.; León-Nuñez, M.J. Socioeconomic and environmental effects of overproduction of maguey mezcalero in the mezcal region of Oaxaca, México. *Agric. Soc. Desarro.* **2017**, *14*, 635–655.
6. Cea Barcia, G.E.; Imperial Cervantes, R.A.; Torres Zuniga, I.; Van Den Hende, S. Converting tequila vinasse diluted with tequila process water into microalgae-yeast flocs and dischargeable effluent. *Bioresour. Technol.* **2020**, *300*, 122644. [CrossRef] [PubMed]
7. Chairez-Aquino, J.; Enríquez-del-Valle, J.R.; Ruíz-Luna, J.; Campos-Ángeles, G.V.; Martínez-García, R. Uso del bagazo de Agave spp y hoja de maíz para cultivar el hongo Pleurotus ostreatus. *Rev. Mex. Agroecosistemas* **2015**, *2*, 23–28.
8. Rodriguez Arreola, A.; Sanchez Tizapa, M.; Zurita, F.; Morán-Lázaro, J.P.; Castañeda Valderrama, R.; Rodríguez-López, J.L.; Carreon-Alvarez, A. Treatment of tequila vinasse and elimination of phenol by coagulation–flocculation process coupled with heterogeneous photocatalysis using titanium dioxide nanoparticles. *Environ. Technol.* **2020**, *41*, 1023–1033. [CrossRef]
9. Moran-Salazar, R.G.; Sanchez-Lizarraga, A.L.; Rodriguez-Campos, J.; Davila-Vazquez, G.; Marino-Marmolejo, E.N.; Dendooven, L.; Contreras-Ramos, S.M. Utilization of vinasses as soil amendment: Consequences and perspectives. *SpringerPlus* **2016**, *5*, 1007. [CrossRef]
10. Martínez Palacios, A.; Chávez Mendoza, S.; Reyes González, R.; Lobit, P.; Sánchez Vargas, N.; Prat, C. *Manejo Forestal Para El Cultivo De Agave Cupreata*; CIIDIR Unidad Oaxaca: Oaxaca, Mexico, 2017; p. 38.
11. Torres-García, I.; Rendón-Sandoval, F.J.; Blancas, J.; Moreno-Calles, A.I. The genus Agave in agroforestry systems of Mexico. *Bot. Sci.* **2019**, *97*, 263–290. [CrossRef]
12. Huerta-Zavala, J.; Sabino-López, J.E.; Ochoa-Miranda, R.; Damián-Nava, A.; Segura-Pacheco, H.R.; Hernández Castro, E. Áreas potenciales para plantaciones de *Agave angustifolia* Haw en Guerrero, Mexico. *Agro Product.* **2019**, *12*, 3–9. [CrossRef]
13. Rangel-Landa, S.; Casas, A.; Dávila, P. Facilitation of Agave potatorum: An ecological approach for assisted population recovery. *For. Ecol. Manag.* **2015**, *347*, 57–74. [CrossRef]
14. Olivera, A.A.; Caballero Caballero, M.; Alavéz Ramírez, R.; Chiñas Castillo, F.; Montes Bernabé, J.L.; Silva Rivera, M.E. Biocomposite tepexil cement reinforced with fibers of Agave angustifolia Haw. as a light mortar. *Rev. Mex. Cienc. Agríc.* **2018**, *9*, 4406–4415. [CrossRef]
15. Montiel Corona, V.; Razo-Flores, E. Continuous hydrogen and methane production from Agave tequilana bagasse hydrolysate by sequential process to maximize energy recovery efficiency. *Bioresour. Technol.* **2018**, *249*, 334–341. [CrossRef] [PubMed]
16. Caballero-Caballero, M.; Chinas-Castillo, F.; Montes Bernabé, J.L.; Alavéz-Ramirez, R.; Silva Rivera, M.E. Effect on compressive and flexural strength of agave fiber reinforced adobes. *J. Nat. Fibers* **2018**, *15*, 575–585. [CrossRef]
17. Amienyo, D.; Azapagic, A. Life cycle environmental impacts and costs of beer production and consumption in the UK. *Int. J. Life Cycle Assess.* **2016**, *21*, 492–509. [CrossRef]
18. Amienyo, D.; Camilleri, C.; Azapagic, A. Environmental impacts of consumption of Australian red wine in the UK. *J. Clean. Prod.* **2014**, *72*, 110–119. [CrossRef]

19. Vázquez-Rowe, I.; Villanueva-Rey, P.; Moreira, M.T.; Feijoo, G. Environmental analysis of Ribeiro wine from a timeline perspective: Harvest year matters when reporting environmental impacts. *J. Environ. Manage.* **2012**, *98*, 73–83. [CrossRef]
20. Gazulla, C.; Raugei, M.; Fullana-i-Palmer, P. Taking a life cycle look at crianza wine production in Spain: Where are the bottlenecks? *Int. J. Life Cycle Assess.* **2010**, *15*, 330–337. [CrossRef]
21. Eriksson, O.; Jonsson, D.; Hillman, K. Life cycle assessment of Swedish single malt whisky. *J. Clean. Prod.* **2016**, *112*, 229–237. [CrossRef]
22. Vázquez-Rowe, I.; Cáceres, A.L.; Torres-García, J.R.; Quispe, I.; Kahhat, R. Life Cycle Assessment of the production of pisco in Peru. *J. Clean. Prod.* **2017**, *142*, 4369–4383. [CrossRef]
23. Meneses, M.; Torres, C.M.; Castells, F. Sensitivity analysis in a life cycle assessment of an aged red wine production from Catalonia, Spain. *Sci. Total Environ.* **2016**, *562*, 571–579. [CrossRef]
24. Fusi, A.; Guidetti, R.; Benedetto, G. Delving into the environmental aspect of a Sardinian white wine: From partial to total life cycle assessment. *Sci. Total Environ.* **2014**, *472*, 989–1000. [CrossRef] [PubMed]
25. Pimentel, D. *Handbook of Energy Utilization in Agriculture*; Taylor & Francis Group: Boca Raton FL, USA, 2017; ISBN 978-1-315-89341-9.
26. Olajire, A.A. The brewing industry and environmental challenges. *J. Clean. Prod.* **2020**, *256*, 102817. [CrossRef]
27. NISG, National Institute of Statistics and Geography. Prontuario de Información Geográfica Municipal de los Estados Unidos Mexicanos. Madero, Michoacán de Ocampo. Available online: http://www3.inegi.org.mx/contenidos/app/mexicocifras/datos_geograficos/16/16049.pdf (accessed on 7 May 2020).
28. SEDESOL Census of Population and Housing. Microdata of the Sample. Madero, Michoacán de Ocampo. Geostatistical Code 16049. (In Spanish). Available online: http://www.microrregiones.gob.mx/zap/Economia.aspx?entra=nacion&ent=16&mun=049 (accessed on 8 April 2020).
29. NISG, National Institute of Statistics and Geography. Mexico in Numbers. Madero, Michoacán de Ocampo. Geostatistical Code 16049. (In Spanish). Available online: https://www.inegi.org.mx/app/areasgeograficas/?ag=16 (accessed on 8 May 2020).
30. Avendaño-Arrazate, C.; Iracheta-Donjuan, L.; Gódinez-Aguilar, J.; López-Gómez, P.; Barrios-Ayala, A. Morphological characterization of endemic *Agave cupreata* species of Mexico. *Int. J. Exp. Bot.* **2015**, *84*, 148–162.
31. STID (Former Secretariat of Trade and Industrial Development). *NOM-070-SCFI-1994. Norma Oficial Mexicana. Bebidas Alcohólicas-Mezcal-Especificaciones*; STID: Mexico City, Mexico, 1994. (In Spanish)
32. Maldonado-Rivas, P.; Pérez-Balan, R.; Aké-Canche, B.; Mex-Álvarez, R. Identificación de los Residuos sólidos urbanos con mayor reciclaje en la ciudad de San Francisco de Campeche, México. *Rev. Energ. Renov.* **2017**, *1*, 31–41.
33. Mandal, K.G.; Saha, K.P.; Ghosh, P.K.; Hati, K.M.; Bandyopadhyay, K.K. Bioenergy and economic analysis of soybean-based crop production systems in central India. *Biomass Bioenergy* **2002**, *23*, 337–345. [CrossRef]
34. Rivera, J.E.; Chará, J.; Barahona, R. Análisis del ciclo de vida para la producción de leche bovina en un sistema silvopastoril intensivo y un sistema convencional en Colombia. *Trop. Subtrop. Agroecosystems* **2016**, *19*, 237–251.
35. Audsley, E.; European Commission. *Directorate-General for Agriculture Harmonisation of Environmental Life Cycle Assessment for Agriculture: Final Report, Concerted Action AIR3-CT94-2028*; CE DG VI-Centre de Documentation: Brussels, Belgium, 1997.
36. Gündoğmuş, E. Energy use on organic farming: A comparative analysis on organic versus conventional apricot production on small holdings in Turkey. *Energy Convers. Manag.* **2006**, *47*, 3351–3359. [CrossRef]
37. Yilmaz, I.; Akcaoz, H.; Ozkan, B. An analysis of energy use and input costs for cotton production in Turkey. *Renew. Energy* **2005**, *30*, 145–155. [CrossRef]
38. Ziaei, S.M.; Mazloumzadeh, S.M.; Jabbary, M. A comparison of energy use and productivity of wheat and barley (case study). *J. Saudi Soc. Agric. Sci.* **2015**, *14*, 19–25. [CrossRef]
39. Mohammadi, A.; Omid, M. Economical analysis and relation between energy inputs and yield of greenhouse cucumber production in Iran. *Appl. Energy* **2010**, *87*, 191–196. [CrossRef]

40. SENER (Energy Secretariat). Lista De Combustibles 2018 Que Se Considerarán Para Identificar A Los Usuarios Con Un Patrón De Alto Consumo, Así Como Los Factores Para Determinar Las Equivalencias En Términos De Barriles Equivalentes De Petróleo. (In Spanish). Available online: https://www.gob.mx/cms/uploads/attachment/file/302306/Lista_de_combustibles_2018.pdf (accessed on 15 June 2020).
41. Vu, T.; LeBlanc, J.; Chou, C.C. Clarification of sugarcane juice by ultrafiltration membrane: Toward the direct production of refined cane sugar. *J. Food Eng.* **2020**, *264*, 109682. [CrossRef]
42. Arandes-Esteban, J.M.; Elorriaga, J.B.; Valerio, D.L. Reciclado de residuos plásticos. *Rev. Iberoam. Polímeros* **2004**, *5*, 3.
43. Tobasura, I.; Moreno, F.A.; Aya, S.; Mora, J. Productividad energética y financiera en fincas campesinas del departamento de Caldas: Tres estudios de caso. *Luna Azul* **2012**, 101–112.
44. 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] [PubMed]
45. Kubule, A.; Zogla, L.; Ikaunieks, J.; Rosa, M. Highlights on energy efficiency improvements: A case of a small brewery. *J. Clean. Prod.* **2016**, *138*, 275–286. [CrossRef]
46. Bukhary, S.; Batista, J.; Ahmad, S. Water -energy -carbon nexus approach for sustainable large-scale drinking water treatment operation. *J. Hydrol.* **2020**, *587*, 124953. [CrossRef]