



Evaluating the environmental performance of mezcal production in Michoacán, México: A life cycle assessment approach

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Received: 7 June 2023 / Accepted: 20 September 2023 / Published online: 7 October 2023
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Abstract

Purpose The purpose of this work is to evaluate the environmental impacts of mezcal production from *Agave cupreata* in Michoacán, México. The central question is the influence of management options for vinasse, bagasse, and biomass energy.

Methods The study was conducted using life cycle assessment (LCA) based on the conceptual framework of ISO 14040, guidelines of ISO 14044, and material and energy flow analysis, in a cradle-to-gate approach. The functional unit considered is a packaged mezcal of 0.75 l produced in compliance with the official Mexican standard for this type of alcoholic beverage. Site measurements were conducted at two agave processing facilities, and descriptive surveys were carried out in collaboration with local producers. Related ecoefficiency indicators were evaluated and shown in a transparent and reproducible way. Environmental impact categories such as global warming potential (GWP), fine particulate matter formation (PMFP), freshwater eutrophication (FEP), and cumulative energy demand (CED) were calculated.

Results The results indicate that bioenergy is 87% of the cumulative energy for production. The main source of impacts from the PMFP category was the distillation process (50%). The vinasse contribution is around 60.4% for the FEP category. Bagasse's contribution to the GWP category is around 22.7%. Even though carbon dioxide produced from biomass is considered biogenic, the overall impact is still significant due to the presence of other compounds such as methane. We also evaluate barriers to the implementation of alternative waste management technologies for bagasse and vinasse.

Conclusions From this study, it is concluded that biomass energy plays a crucial role in the sustainable manufacturing of mezcal.

Keywords Agave spirits · Bagasse · Vinasse · Waste management · Ecoefficiency indicators · Life cycle assessment

1 Introduction

Agri-food systems are a critical sector in resource extraction and are essential to boost food security (Bombelli et al. 2019). It is estimated that around 44% of biomass is lost during harvesting, especially in less industrialized chains (El Bilali 2019). Through best practices such as cleaner production, these systems can support more sustainable conditions for all stakeholders (Giannetti et al. 2020). According to the

Sustainable Development Goals (SDG) 7 (affordable and non-contaminating energy) and 12 (responsible production and consumption), improving energy efficiency and resource use can help small and medium-sized businesses, particularly those in developing countries, gain access to and integration into value chains and markets (United Nations 2022).

As part of the agri-food systems, the production of distilled agave spirits in Mexico has increased 210% in the last 10 years and represents the second-largest sector of the alcoholic beverage industry (Instituto Nacional de Estadística y Geografía 2022; COMERCAM AC 2022; CRT AC 2022). Tequila and mezcal production in 2021 reached 527 and 8.1 million liters, respectively. Although mezcal represents only 1.5% of production, it increased by 170% in the last year (COMERCAM AC 2022; CRT AC 2022).

Sustainable production and consumption are essential components to avoid the detriment of environmental conditions due to industrial activities (Comisión Económica para América Latina y el Caribe 2018). In the agave distilled

Communicated by Matthias Finkbeiner.

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spirits industry, tequila manufacturing is industrialized and intensive, whereas mezcal production is mainly artisanal (Tetreault et al. 2021). Cultivation of *Agave tequilana* has generated soil erosion, chemical pollution, and displacement of traditional food crops and wild agave species (Zizumbo-Villarreal et al. 2013). Mezcal has sustainability challenges to limit uncontrolled growth in agave cultivation (Arellano-Plaza et al. 2022) which could lead to the same environmental problems as the tequila industry.

According to the NOM-070-SCFI-2016 standard, (Dirección General de Normas de la Secretaría de Energía 2016), mezcal is a Mexican alcoholic beverage 100% of agave harvested in established regions and obtained by distillation of fermented juices with spontaneous or cultivated microorganisms extracted from cooked agave heads. Numerous works have been published about the production chain and related procedures of this beverage (Kirchmayr et al. 2014; Rodríguez-Garay et al. 2009).

According to García-Mendoza Abisaí (2022), there are 150 species of agave in Mexico, in populations that are either wild or cultivated. The agave species can be differentiated by their morphological characteristics, such as general plant size, lateral teeth, terminal spines, flowers, and fruit size, among others (Rodríguez-Garay et al. 2009).

The work by Rivera-Lugo et al. (2018) examines four species and five varieties, including three species used for mezcal production. The domesticated and semi-domesticated populations of the agave genotypes used to make spirits are different from their wild counterparts and exhibit a reduced level of diversity (Rivera-Lugo et al. 2018). Extensive monovarietal cultivation of *Agave tequilana* is threatening the diversity of the germplasm used in traditional agave spirits production in west-central Mexico. Preservation of agave germplasm diversity requires increased cultivation and valuation of local agave species (Vargas-Ponce et al. 2007).

The common functional unit (FU) used is a 750-ml bottle with 40% alcohol volume. Guidelines for a sustainability strategy for the agave and tequila production chains was presented by Mario Molina Center, a non-profit association (Centro Mario Molina and Consejo Regulador del Tequila 2016). Their report includes an LCA of tequila production from *Agave tequilana* cultivation stage to the recycling of packaging materials, obtaining a total emission of 3 kg CO₂ eq/FU. They found that 44% of this value corresponds to direct emissions from production, while the remainder corresponds to raw materials, transportation, and distribution of the product. Madrid-Solórzano et al. (2021) conducted an LCA of an alcoholic beverage called sotol, from gathering and harvesting the *Dasyliirion* species (raw material) to the packaging stage (cradle-to-gate), considering an artisanal bottle. They found that the milling and bottling stages both contribute 78.04% of the total emission value, 5.92 kg CO₂ eq/FU. Martínez et al. (2020) outlined an

LCA of craft mezcal from *Agave cupreata* from the nursery of the plant to the final disposal of the packaging materials (cradle-to-gate). They considered a young craft mezcal bottle. They indicated that the energy demand of the craft mezcal resulted in 163.8 MJ/bottle. The stage with the highest contribution to the environmental impacts of mezcal was the manufacturing/processing, contributing 59.6% of them. Previous research studies have been limited by the absence of a comprehensive analysis of materials and energy usage and a failure to address treatment options for major byproducts.

The two major byproducts of the production of plant-based alcoholic beverages, bagasse and vinasse, need to be managed properly. Alternatives have been investigated to propose new applications in which bagasse and vinasse from sugarcane or agave can be used as raw materials for the production of biofuels such as ethanol (Caspeta et al. 2014; Gómez-Guerrero et al. 2019), methane (Valdez-Vazquez et al. 2020), and electricity generation from combustion and gasification (Parascanu et al. 2017). Furthermore, research has been done on composite materials with bagasse, such as reinforcement and filler material for polylactic acid (PLA) green composites (Huerta-Cardoso et al. 2020) and bioactive compounds, membranes, and food packaging (Robles-García et al. 2018). These options have also been investigated through life cycle assessment (Silva et al. 2014; Kiatkittipong et al. 2009; Groot and Borén 2010) proposing an expansion of the waste management system into raw materials in other sectors through industrial symbiosis (Chertow and Ehrenfeld 2012).

The literature review indicates that the evaluation of the environmental impact of the production of mezcal with LCA is still in its early stages. The novelty and contribution of this study are that previous works have not shown a material and energy balance based on input–output analysis, an essential component to establishing a life cycle inventory. This study evaluates the environmental impact of mezcal production, comprising the quantification of energy flows, wastes, and raw material inputs and outputs involved in the agricultural, industrial, and waste management stages. The production system is modeled as part of a cradle-to-gate LCA, starting from the *Agave cupreata* cultivation to the packaging of mezcal and waste management scenarios for the end of life of bagasse and vinasse based on the current practices of local producers.

2 Materials and methods

Life cycle assessment was carried out on the production of mezcal using a “cradle-to-gate” approach based on the ISO 14044 principles and the ISO 14040 conceptual framework (ISO 14040:2006 2006; ISO 14044:2006 2006), using OpenLCA (Ciroth 2021), the leading free software

worldwide. Emissions from the life cycle inventory are provided by literature references and the Ecoinvent database version 3.6 (2019). ReCiPe midpoint (H) was selected as an impact assessment method to translate the inventory data into environmental impact categories. The following categories were selected based on their relevance to the product system: global warming potential (GWP), which helps us comprehend the impact of biomass as a primary energy source in comparison to fossil fuels; freshwater eutrophication (FEP), which addresses the effects of effluent discharge on soil and water bodies in the region; fine particulate matter formation (PMFP), due to the direct exposure of individuals to particulate matter from wood combustion; and cumulative energy demand (CED), which measures the total amount of energy needed.

The material and energy balances were made from in situ measurements. As mentioned below, the study includes the quantification of two agave processing facilities (APF) for operative materials, energy, fossil fuels, and wastes. As far as possible, quantitative information on all essential inputs and outputs connected to the unit process was gathered and/or modeled.

2.1 Study area

The study area is located in Madero, Michoacán (see Fig 1), one of the 29 municipalities that have the denomination of origin for mezcal production (Instituto Mexicano de la Propiedad Intelectual 2012). The mezcal industry has attracted tourism-related activities such as visits to the agave processing facilities, tours of the cultivation areas, and local consumption of mezcal beverages. There are 14 species of agave in the State of Michoacán, but only three are used to produce mezcal: *Agave angustifolia*, *Agave inaequidens*, and *Agave cupreata*. The main agave and mezcal-producing areas belong to the localities of Etúcuaro, Santos Marías, Parritas, El Zangarro, and Ucasiro (Instituto Nacional de Estadística y Geografía 2022). In this region, mainly *Agave cupreata* and *Agave angustifolia* have been established, and there are at least 89 owners involved in mezcal production and around 28 agave processing facilities.

2.2 Goal and scope definition

The functional unit considered is a packaged mezcal of 0.75 ls produced in compliance with the NOM-070-SCFI-2016



Fig. 1 Map of Madero, Michoacán. The municipality's main city is represented by the white pin. APF-1 and APF-2 are represented by the orange and yellow pins, respectively

standard. According to this standard, the alcoholic content is in the range of 35 to 55% according to this standard.

The study intends to be communicated to stakeholders so that they know the environmental strengths and weaknesses of this product. Results are intended to be used to identify critical points and the contribution of wastes to the environmental impacts of mezcal production.

2.3 Description system boundaries and scenarios

Figure 2 shows the system boundaries for the LCA that include agricultural, industrial, and waste management stages that apply to the APFs analyzed.

Since both APFs analyzed are in the same region, they share similarities in the process stages and only differ by the amount of electricity used and the mass yields between them. The stages of distribution and sales of the product are outside the scope of this work, and they are excluded from the analysis. The physical labor of people at all stages of the process is also excluded, even though his expertise is crucial to the mezcal culture. All activities related to the infrastructure and its maintenance were also excluded.

2.4 Data collection methods

Data for material and energy inputs and outputs were obtained from APF-1 and APF-2 through in-site measurements, which were carried out in collaboration with local producers.

Descriptive surveys were conducted with 13 local producers, including three leaders of mezcal associations. Verbal consent was obtained from all the participants in focus groups and interviews. Focused (semi-structured) interviews were conducted with the leaders of the associations to represent their perspectives on the management of vinasse and bagasse (Tarrés 2013).

There was no payment of any type given to the study participants. To protect confidentiality during data collection, no names were recorded. The aim of the study was informed to all participants who answered the questionnaire.

2.4.1 Cultivation

All mezcal producers use *Agave cupreata* as raw material; 80% also use *Agave angustifolia*, and 25% use *Agave inaequidens*. Local producers create a beverage assembly with improved organoleptic properties using the mezcal production generated from each agave. Only 10% reported using *Agave tequilana* in their production. Only 5% of the participants cultivate agave but do not make mezcal.

In the nursery, *Agave cupreata* is maintained for 1 to 2 years with water irrigation 24 h a day. After that, it is

transplanted to a cultivation area with rain-fed irrigation. The minimum time to harvest the agaves is 4 years. Some agaves are seed-germinated; consequently, they must not be considered for extensive agroindustrial exploitation (Gallardo-Valdez 2020).

No substances like fertilizers, insecticides, or herbicides are applied during the agave growing stage. In APF-1, the dry biomass around the agave plant is burned annually to control pests.

2.4.2 Harvest

The agave's leaves are chopped with a manual tool (called "Trinchera"). Then, the root was cut with a chainsaw that requires gasoline and two-stroke oil. After that, the agave heads are transported manually from stony and hillside terrain to a location that freight vehicles can access. The fuel consumption of the vehicles was considered. The considered distance, between the extraction zone and the mezcal production facilities, was 9.5 km for APF-1 and 14.4 km for APF-2. Once at the APFs, agave heads are cut into smaller pieces for a cooking process.

2.4.3 Hydrolysis

In the cooking process, the hydrolysis of the agave biomass is carried out. In this region, this process is made in a ground kiln with an average capacity to process 4.65 tons of agave heads. Wood is used in the ground kiln to raise the temperature of volcanic stones, which hold heat during combustion and pyrolysis and release it after hydrolysis. The whole cooking process takes between 5 and 6 days.

The humidity of the agave head was measured with a Hobotest HT632 humidity meter at a room temperature of 28 °C. An average humidity of 8.58% was obtained. After the hydrolysis process, a moisture value of 9.51% was obtained on the agave heads.

2.4.4 Milling and fermentation

For ancestral mezcal, the cooked agave is crushed with wood or steel mallets to extract the juice, whereas for craft mezcal, the cooked agave can be milled with an agricultural shredder machine.

According to data analysis from surveys, 83% of mezcal producers employ an agricultural shredder machine to mill the cooked agave heads, but there is also a manual technique. The process can take several hours, depending on the total number of tons of agave. The juices and bagasse that come out of this process are placed in wood and stainless steel fermentation tanks.

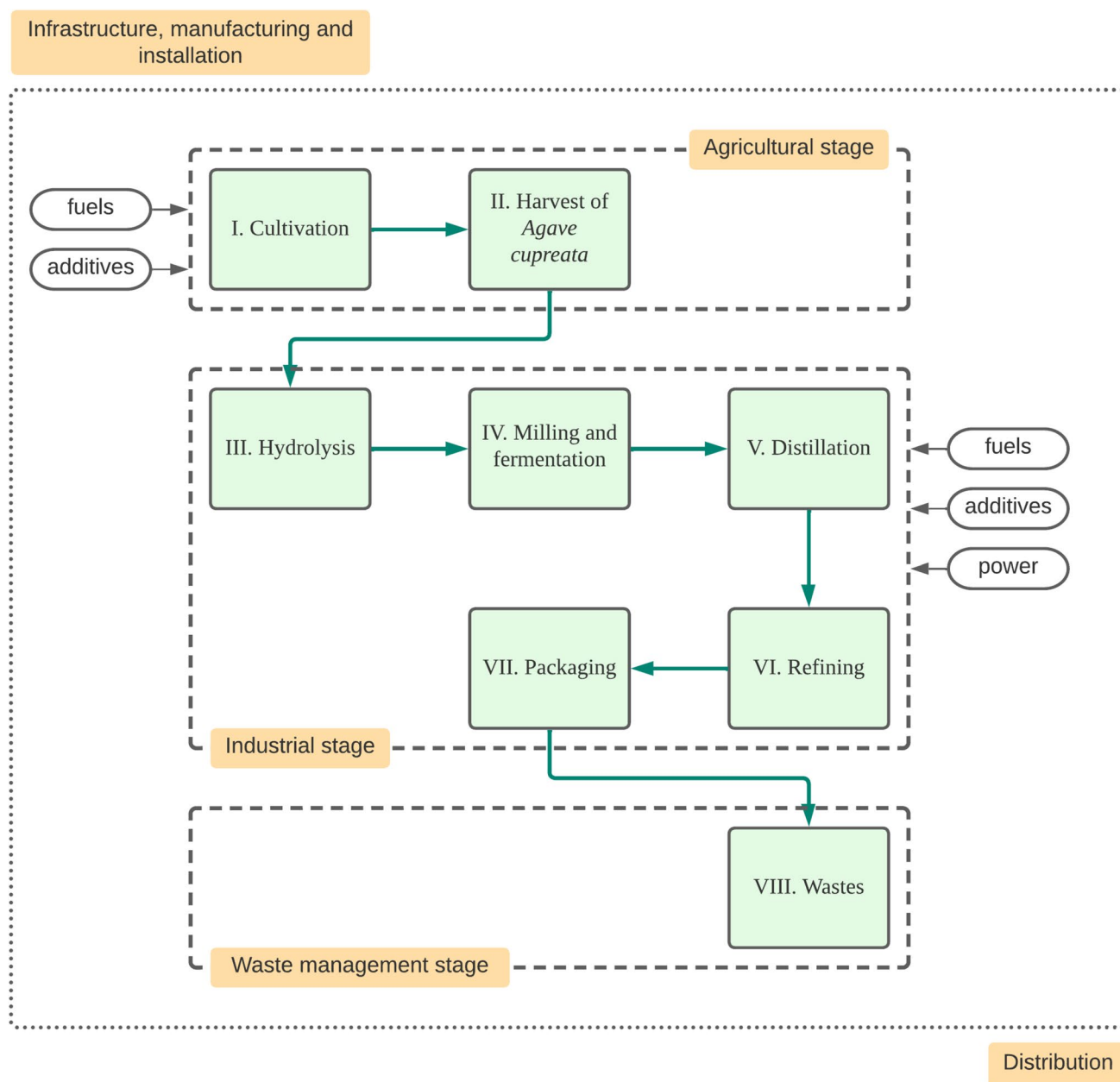


Fig. 2 System boundaries for craft mezcal production and waste management

Fermentation is done spontaneously, and only water is used in addition to the milled agave. There was no sugar or commercial yeast used. Microorganisms in the wort carry out the fermentation; their activity impacts the finished product's organoleptic characteristics. During fermentation, which lasts about 9 days, the wort is only stirred twice. The agave juice is around 29 °C and has a pH of 4.5. The CO_2 produced during fermentation is considered biogenic. The alcohol content of the fermenting wort is separated and concentrated during distillation.

2.4.5 Distillation and refining

Fermenting wort is placed in a copper pot, which has a capacity of about 250 ls. It is covered by a still device called “alambique,” made of stainless steel. It is sealed as the wood fuel underneath starts to heat up and distillation begins. Following NOM-070-SCFI-2016, the first 2 ls of the distillate are separated. Subsequently, 25 to 30 ls of distillate are recovered for each pot still processed, which is a continuous operation in three stills until all the wort

is distilled. The wood consumed is generally *Quercus* spp. with an approximate consumption of 50 kg for each processed ladle. Afterward, the distillate is refined, where approximately 400 ml of each liter is converted into marketable mezcal.

For the mezcal, the average percentage of alcohol was 41.1%, measured with a digital density meter, indicating that the production batch satisfies the NMX-V-013-NORMEX-2019 standard (Dirección General de Normas de la Secretaría de Energía 2020).

2.4.6 Packaging

The mezcal is stored in 20-l high-density polyethylene drums. Commonly, there is no maturation period, and mezcal is typically sold after a few weeks of being produced. It is packaged in 0.75-l glass bottles with a plastic cap and security seal. Product information is placed on vinyl labels. The bottling process is carried out mostly manually; in the case of APF2, they have a bottling machine, which requires electricity consumption. The bottles are packed in cardboard boxes for handling and transportation.

2.4.7 Treatment options

There are no extensive waste management activities in this region. Eighty-nine percent of the survey participants mentioned that they let the bagasse lose moisture for later open burning, and only around 11% of participants used it to generate compost. In 95% of the cases, during their distillation processes, vinasse is discharged to the soil through direct filtration. The other alternative is discharged into water (5%), with a temperature measured in-site between 80 and 85 °C. Most of the producers interviewed say that if bagasse and vinasse had economic value, they would prefer to manage them individually or, in any case, sell them for use in compost or as livestock feed. Current practices such as bagasse combustion, degradation of agave leaves, and direct filtration of vinasse into the soil were considered waste management scenarios.

3 Life cycle inventory and relevant data assumptions

3.1 Life cycle inventory

Raw data collected in each process of mezcal production is entered as the values of the flows in the life cycle inventory, as shown in Table 1. The values corresponding to the

functional unit are presented in the structure of a product system and unitary processes. We define in each process a reference flow, which represents the amount obtained. The input and output flows were obtained from direct measurements in the field. LCI emissions are evaluated based on the reference specified in the last column. A total of 8 unitary processes were considered for each APFs. The evaluation of total impacts is carried out through an assembly (see Table 1).

The main raw materials are agave, wood, and water. The main wastes are bagasse, vinasse, and leaves. On average, from both APFs, 5.6 kg of agave heads are used to produce a bottle of mezcal (see Table 1), generating 3.1 kg of bagasse and 7.7 kg of leaves. There are some agave head losses, but they do not even represent 0.5% on average. The main source of energy for craft mezcal production is wood, using 5.58 kg/FU. The fermentation process does not use energy; only water is added in a proportion close to 50%. The use of water is 7.68 kg/FU and generates 7.4 kg/FU of vinasse. Based on the surveys, on average, 7 batches are made in a year on the APFs, producing around 574 ls of mezcal.

3.2 Characterization factors

The Ecoinvent database 2019 (Wernet et al. 2016) was used to obtain emission factors for petrol, lubricating oil, biowaste, seeds, and charcoal. For wood combustion during distillation and refining, carbon dioxide emissions to the air were considered biogenic, and only methane emissions to the air were taken into account. The values reported by Morales-Máximo et al. (2022) were considered for wood emission rates during combustion measured for *Quercus* spp. in a stove. Vinasse waste from the distillation process, which causes emissions to the soil and water, was modeled with values reported by Robles-González et al. (2012) as shown in their review of treatment options for this waste. Those factors are used in the software OpenLCA 1.11 with the ReCiPe midpoint [H] methodology.

For the cumulative energy demand method, the higher heating values (HHVs) were considered as follows: 46.3 MJ/kg for gasoline and 45.5 MJ/kg for heavy diesel (Heywood 2018) and 19.3 MJ/kg for wood (Rutiaga-Quñones et al. 2020) and 32 MJ/kg for charcoal (Bustamante-García et al. 2013). The latent heat of evaporation for water was taken as 2.26 MJ/kg; the same value was considered for the mezcal distillate due to its high water content. Duran García et al. (2021) found that the calorific value of bagasse from *Agave tequilana* ranges between 7.72 to 9.63 MJ/kg; the average value (8.67 MJ/kg) was considered in this work.

Table 1 Life cycle inventory for APF-1 and APF-2 with the description of material and energy flows in each process for the stages: agricultural (cultivation and harvest), industrial (hydrolysis, milling, and

fermentation, distillation, refining, and packaging), and waste management (wastes). The reference flows of each process in the product system are indicated in blue

Process	Description	APF-1	APF-2	Unit	Provider
I. Cultivation	Water, river	64.287	23.257	kg	Elementary flow
	Grass seed, organic, for sowing	1.698	1.208	mg	Wernet et al. (2016)
	Treatment of waste wood, untreated, open burning	1.639	0.000	kg	Wernet et al. (2016)
	Agave plant	12.780	13.895	kg	User defined flow
	Petrol, unleaded, burned in machinery	1.689	1.049	MJ	Wernet et al. (2016)
	Petrol, unleaded, burned in machinery	0.317	0.122	MJ	Wernet et al. (2016)
	Lubricating oil production	0.014	0.015	MJ	Wernet et al. (2016)
II. Harvest	Waste, organic	7.533	7.927	kg	Wernet et al. (2016)
	Waste, organic	0.061	0.014	kg	Wernet et al. (2016)
	Agave heads	5.247	5.968	kg	User defined flow
	Petrol, unleaded, burned in machinery	0.676	0.583	MJ	Wernet et al. (2016)
	Petrol, unleaded, burned in machinery	0.106	0.036	MJ	Wernet et al. (2016)
	Lubricating oil production	0.005	0.005	MJ	Wernet et al. (2016)
	Charcoal production	0.184	0.347	kg	Wernet et al. (2016)
III. Hydrolysis	Cooked agave heads	4.013	4.746	kg	User defined flow
	Petrol, unleaded, burned in machinery	0.222	0.000	MJ	Wernet et al. (2016)
	Diesel, burned in agricultural machinery	0.000	0.261	MJ	Wernet et al. (2016)
	Water, river	8.819	6.559	kg	Elementary flow
IV. Milling and fermentation	Agave juice and bagasse	12.832	11.304	kg	User defined flow
	Electricity mix, MX	0.000	0.033	kWh	Wernet et al. (2016)
V. Distillation	Wood combusted	3.049	3.688	kg	Morales-Máximo (2022)
	Methanol	0.112	0.103	l	Elementary flow
	Distillate	1.764	2.316	l	User defined flow
	Wood combusted	0.711	0.863	kg	Morales-Máximo (2022)
	Electricity mix, MX	0.000	0.015	kWh	Wernet et al. (2016)
VI. Refining	Wastewater	1.181	1.566	l	Elementary flow
	Mezcal	0.750	0.750	l	User defined flow
	Packaging glass production, white	575	590	g	Wernet et al. (2016)
	Market for polyethylene, high density, granulate, recycled	1.5	1.5	g	Wernet et al. (2016)
	Market for polyethylene, low density, granulate	0.249	0.249	g	Wernet et al. (2016)
	Polyvinylchloride production, bulk polymerization	1.5	1.44	g	Wernet et al. (2016)
	Kraft paper production, bleached	1.44	1.44	g	Wernet et al. (2016)
	Corrugated board box production	13.125	13.125	g	Wernet et al. (2016)
	Electricity mix, MX	0.000	0.019	kWh	Wernet et al. (2016)
	Packaged mezcal	1.000	1.000	items	User defined flow
VII. Packaging	Treatment of waste wood, untreated, open burning	3.190	3.010	kg	Wernet et al. (2016)
	Vinasse, filtration to soil	8.802	6.107	l	Robles-González et al. (2012)
VIII. Wastes	Wastes	12.079	9.178	kg	User defined flow

4 Material and energy balance

Figure 3 is a flow chart elaborated with STAN 2.6.801, and it displays all input and output flows from the harvest to the refining process.

Based on the material balance, related ecoefficiency indicators can be calculated in a transparent and reproducible way. The following indicators were calculated: the mass yield from harvest, moisture loss, and carbon production during hydrolysis, water usage, the energy efficiency from

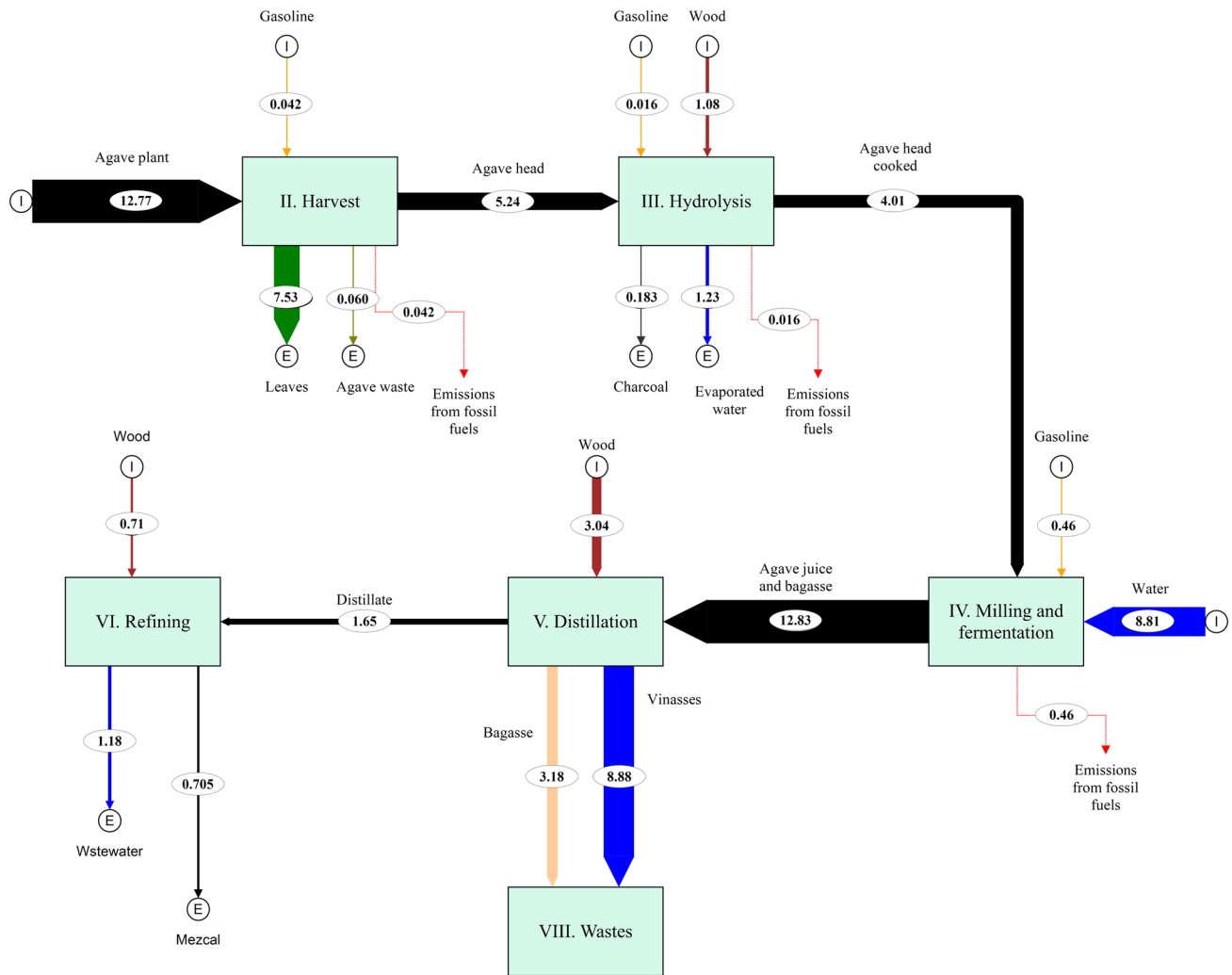


Fig. 3 Mass balance diagram of mezcal production from APF-1 in STAN. Material flows related to water were highlighted in blue, intermediate products in black, wood in brown, emissions from the

combustion of firewood and fossil fuels in red, and biomass wastes in green. All data are expressed in kilograms and per functional unit

the ground kiln, distillation, and refining, the rate of waste generation, and the agave material use efficiency.

The mass yield y_i is the ratio of the process output m_{out} to the mass m_{in} of the input, and it describes how much of the original mass remains in the process. The mass yield for agave harvest, agave cooked, and carbon production in the ground kiln is defined as follows:

$$y_{harvest} = \frac{m_{head}}{m_{plant}} \quad y_{cooked} = \frac{m_{cooked}}{m_{head}} \quad y_{charcoal} = \frac{m_{char}}{m_{wood_1}} \quad (1)$$

Fuel-related materials are evaluated according to their energy content in order to determine the energy efficiency of the processes. The energy efficiencies from the ground kiln, distillation, and refining are calculated as follows:

$$\eta_{kiln} = \frac{(m_{head} - m_{cooked})L}{m_{wood_1} * HHV_{wood} - m_{char} * HHV_{char}}, \quad \eta_{dest} = \frac{m_{dest}L}{m_{wood_3} * HHV_{wood}} \quad (2)$$

The amount of water evaporated is equal to the loss of mass after the cooking process, where L is the enthalpy of vaporization of the water and HHV_{Wood} is the higher heating value of the wood. Sensible heating is not considered.

Using the mass balance approach, the waste disposed at the on-site landfill was considered. The core waste intensity indicator (e) is the total waste leaving the system boundary per unit of product delivery. In the case of bagasse and vinasse:

$$e_{bagasse} = \frac{m_{bagasse}}{m_{product}}, \quad e_{vinasse} = \frac{m_{vinasse}}{m_{product}} \quad (3)$$

Results for the process indicators for the APFs are shown in Table 2.

For the agave heads, the mass yield in the harvest stage is 41%. Iñiguez-Covarrubias et al. (2001) indicate that, from the total wet weight of an agave, 54% corresponds to the head of the plant, in the case of *Agave tequilana*. It is important to note that harvest has a small m_{loss} since some agave heads were contaminated by pests or handled improperly during transportation.

In the ground kiln, wood (m_{wood}) is used and some charcoal residues ($m_{charcoal}$) are produced in such a proportion that they reach around 16.5%, which is an efficiency comparable with the exclusive activities of charcoal production. Weber and Quicker (2018) report that the mass yield for low-efficiency carbon production processes is around 20%.

Energy from wood is used for the hydrolysis of the agave heads, obtaining 22% of moisture removal throughout the process. Considering the ground kiln as a cooking device, it reaches an efficiency of 16.2%. The skills of the people in charge of production are important to make the task more efficient, since sometimes they employ more wood for the process, obtaining fewer efficiencies. Most of the wood fuel is needed for distillation and refinement. The calculated efficiencies of those processes are 6% and 11%, respectively.

It is important to remark that previous indicators quantify the material and energy performance of the production process and do not adequately account for all environmental effects (Huijbregts et al. 2006). It is necessary to translate inputs and outputs into environmental impacts, indicating that LCA evaluations are still necessary.

5 Potential environmental impacts and cumulative energy demand

Figure 4 shows the environmental impact assessment for the mezcal production for both APFs considered in the life cycle inventory (Table 1). Results for each process are expressed as a percentage of the total impact.

Table 2 Eco efficiency indicators of mezcal production

Process	Indicator	APF-1	APF-2
II. Harvest	$y_{harvest}$	41.06	42.95
III. Hydrolysis	$y_{charcoal}$	16.92	19.65
	y_{cooked}	76.48	79.53
	η_{kiln}	18.47	12.01
IV. Milling and fermentation	Water use (%)	68.73	58.02
V. Distillation	$\eta_{distillate}$	6.37	6.91
VI. Refining	$\eta_{product}$	11.61	9.56
VIII. Wastes	$e_{bagasse}$	4.52	4.27
	$e_{vinasse}$	12.57	8.72

Total results corresponding to potential environmental impacts and cumulative energy demand are shown in Table 3 for the two APFs.

The cumulative energy demand (CED) of a product includes the energy consumed during the extraction, manufacturing, and disposal of the raw and auxiliary materials. Most often, agave crops are irrigated using a gravity-flow system during the first year of the cultivation stage; therefore, there is no energy consumption in this stage. Due to the proximity of the agave plantation areas to the APF-1 and APF-2, around 1% of the energy is used for transport during the harvesting process.

The consumption of wood in the hydrolysis, distillation, and refining processes accounts for 87% of the energy used, which shows how crucial biomass energy is to the culture of mezcal manufacturing. The price of wood ranks as the second-highest expense in the process of making mezcal (after the purchase of agave heads). Distributing the usage of forest resources across harvesting cycles can help with forest recovery (Gao et al. 2021), and it can be promoted as a good practice in this industry. The ratio of fossil fuel and biomass energy, on average, is around 5%. The package contribution, on average, is around 8% of the total energy of the mezcal production. Burning bagasse is considered a waste management base scenario; unfortunately, this energy is not harnessed. The total amount of energy per functional unit is 114.7 MJ and 142.2 MJ for APF-1 and APF-2, respectively. In the study carried out by (Martínez et al. 2020), traditional mezcal has a cumulative energy demand per bottle of 163.8 MJ, which is in accordance with the results.

Global climate change is predicted to increase heat, drought, and soil-drying conditions and thereby increase crop sensitivity to water vapor pressure deficits, resulting in productivity losses (Cushman et al. 2015). Climate change may influence the region's ability to access water and wood, as well as the spread of pests that may compromise the stability of the productive system (Silva et al. 2022; Morales-Barquero et al. 2014; Servín et al. 2014). Carbon emissions are increased when biomass is burned openly for pest control and land clearing during the growing phase of APF-1 (see the process I 2). For the harvest phase, the carbon footprint is due to the transportation of the agave heads from the cultivation area to the APFs. The production of charcoal is responsible for 11% of APF-1 and 21.3% for APF-2 of the CO_2 eq emissions during the hydrolysis process. Emissions from the wood burning process in distillation and refining processes consider carbon dioxide as biogenic; with this assumption, therefore, the contributions of burning are mainly due to biogenic methane emissions (Eggleston et al. 2006). CO_2 eq emissions are mostly a result of the use of fossil fuels. The packaging process accounts for around 29% of the impact on climate change in both APF-1 and APF-2. Bagasse combustion ends up adding three times fewer impacts than the

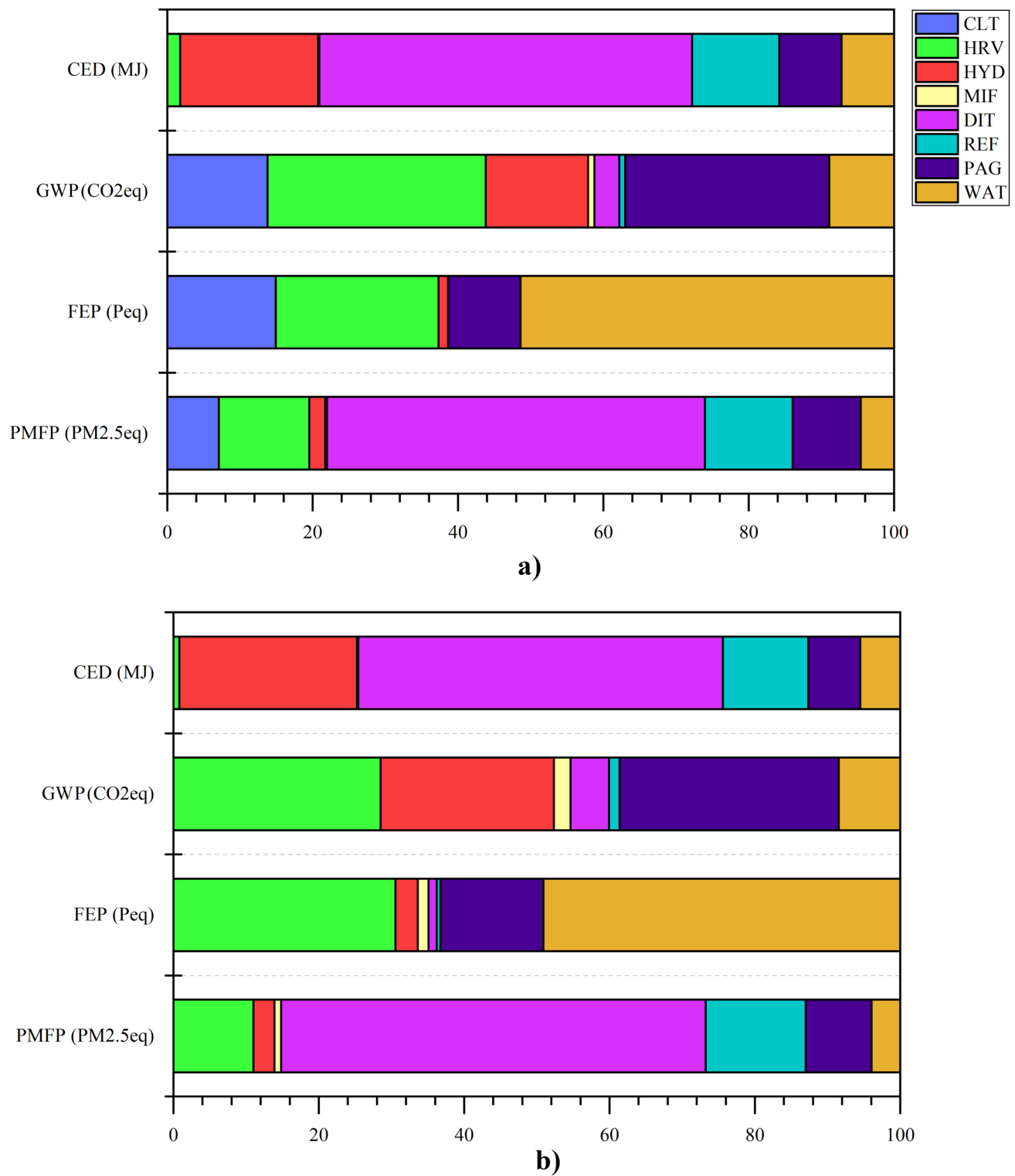


Fig. 4 Environmental impacts for APF-1 (**a**) and APF-2 (**b**) in the categories: CED, GWP, FEP, and PMFP. Values are expressed per functional unit and in percentage for each process: cultivation (CLT),

harvest (HRV), hydrolysis (HYD), milling and fermentation (MIF), distillation (DIT), refining (REF), packaging (PAG), and wastes (WAT)

Table 3 Potential environmental impacts and Cumulative Energy Demand of mezcal production in Michoacán, Mexico. Data expressed per functional unit

Impact category	Unit	APF-1	APF-2
Potential environmental impacts			
GWP	kg CO_2 eq	2.16E0	2.10E0
FEP	kg Peq	1.20E-3	9.00E-4
PMFP	kg $PM_{2.5eq}$	1.66E-2	1.79E-2
Energy consumption			
CED	MJ	1.14E2	1.42E2

packing process. The total GWP attributed to mezcal from the current work is 2.1 kg CO_2 eq/FU, which is equivalent to 70% of the impact of tequila compared to the reported results of 3 kg CO_2 eq by Centro Mario Molina and Consejo Regulador del Tequila (2016). The result from Martínez et al. (2020) is 1.7 CO_2 eq, but waste management was not included within the boundaries of the product system.

Eutrophication is a type of water pollution that can seriously harm aquatic ecosystems by overfeeding water bodies with excess nutrients, typically nitrogen or phosphorus. The burning of agricultural wastes contributes to eutrophication, and it is increased mainly by the use of fertilizer (15% for APF-1). Degradation of harvested biomass in the soil makes a limited contribution. The combustion of firewood in hydrolysis and distillation has a negligible contribution, but the ashes were not quantified, i.e., they were outside the limits of the system, and it is important to note that they can also contribute to this category (eutrophication) if their treatment is not adequate. The use of fossil materials generates small contributions to the packaging. Vinasse production in the distillation stage was the key hotspot, causing a significant contribution in the eutrophication category (41.7% for APF-1 and 37.4% for APF-2). Composting is one of the strategies to use the nutrients produced as fertilizer for crops instead of increasing aquatic biomass.

Burning biomass produces particle emissions. This category is essential to understanding the risk to human health by the extended use of wood in this production process to safeguard people. In the cultivation stage, the annual burning of dry biomass affects this category. In the milling and fermentation stages, transportation is where fossil fuel burning arises. This can increase if, in addition, the technology used is old. Hydrolysis is a process without the presence of oxygen, so the amount of smoke is minimal. The largest amount of PMFP emissions occurs in distillation (55% on average for both APFs). Refining and packaging have contributions of 12% and 9% respectively. Bagasse burning has a minor contribution. $PM_{2.5}$ has been confirmed through fieldwork that this is a major issue since the smoke restricts work activities inside the APFs. In the case of the

APFs studied, they are located in an area with a very low-density population.

6 Barriers for implementation of waste management technologies

Wastes contribute between 3 and 58% of the environmental impacts for the described categories for both APFs. There are many proposed alternatives to take advantage of the utility potential of waste, that do not require major changes in the craft manufacturing process.

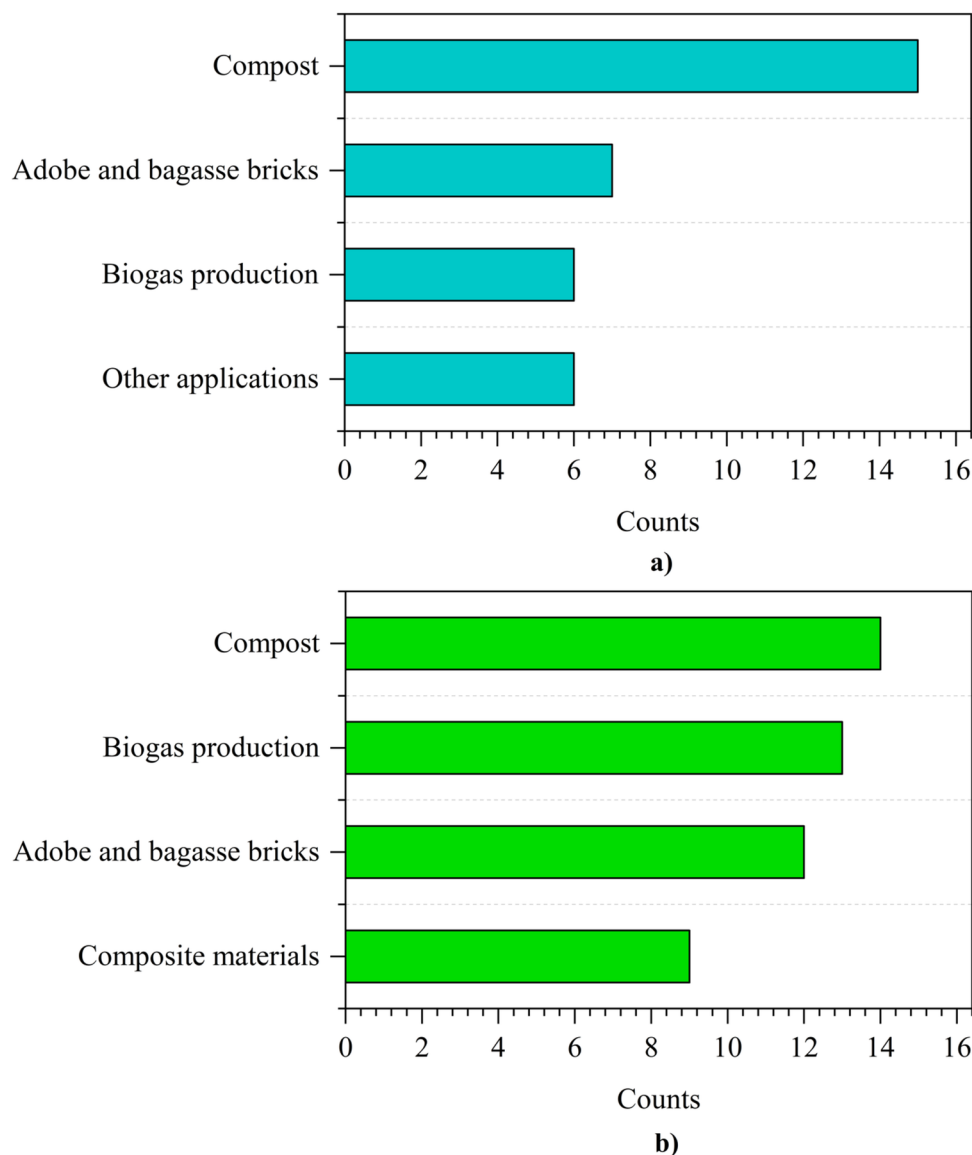
As shown in Fig. 5, producers responded in the survey which applications for bagasse and agave vinasse seemed most viable for their use in a local context, identifying the use of biomethane for cooking, composting for agave growth, and mixing bagasse with adobe for construction material as the main options. We explore the barriers that must be overcome for these treatment options to be implemented in the mezcal industry.

Although the potential of biogas technologies has been well demonstrated, some barriers in rural areas have been identified, such as high up-front installation costs, no access to financial support or incentives given by the government, and a lack of access to skilled workers for construction, operation, and repairs (Mittal et al. 2018). For cooking applications, obstacles include widely available fuelwood in the local area and low participation of women in decision-making.

Although composting may be utilized as a substrate, the volume of waste produced is greater than the rate of usage locally, requiring the development of a product that can be employed in other agricultural areas.

The generation of alternatives for use, such as adobe and bagasse, requires industrial synergy. Bagasse can be used as a raw material to make adobe, but first, it must be ensured that the conditions are suitable to replace the traditional fiber. Furthermore, the transport and processing of the fiber have additional impacts that limit this type of industry from growing outside the community.

Fig. 5 Survey results showing the preferences selected by producers for bagasse valorization that can benefit the community (a) or themselves (b)



7 Conclusions

This study provides a comprehensive and transparent evaluation of the environmental impacts of the production of mezcal in Michoacán, Mexico. Eco-indicators of the process were calculated based on a material and energy balance as well as LCA environmental impact categories such as GWP, FEP, PM2.5, and CED. The current results highlight the importance of biomass energy and also reveal the impacts of bagasse and vinasse management scenarios for the craft mezcal system. The sustainable manufacturing of mezcal could only be done in discontinuous batches due to the limited availability of natural resources and the traditional mezcal culture. The main regulations should focus on forest management to make sustainable use of wood

(FSC systems), improving road conditions to reduce fuel consumption, and encouraging practices such as avoiding the use of agrochemicals during the growth of the agave, promoting the application of agroforestry systems, and organic pest control that can benefit the maintenance of agave cultivation in the long term. The results of this research can assist producers in prioritizing the reduction of material intensity and environmentally damaging emissions and monitoring progress, or they can serve as the basis for choosing environmentally conscious agave products in purchase decisions. As a future perspective, the identification of hotspots along the production process suggests that efforts can be focused on (a) increasing the efficiency of combustion devices, (b) reducing product losses during distillation, and (c) increasing the percentage

of biomass utilized from bagasse and vinasse to make the system more sustainable.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11367-023-02237-y>.

Acknowledgements César Ruiz-Camou would like to acknowledge receiving a fellowship (CVU 1086052) from CONAHCYT. The authors would like to thank the Postgraduate Program in Sustainability Science of the National Autonomous University of Mexico, the project CONAHCYT-PRONACES 319333, and Nanakutzi, a brand belonging to the Association of Women of Mezcal and Maguey of Mexico.

Data availability The authors declare that the datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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