Agricultura, Sociedad y Desarrollo

# ANALYSIS OF MEZCAL PRODUCTION IN SAN DIEGO LA MESA TOCHIMILTZINGO, PUEBLA (SIERRA DEL TENTZO RESERVE), MEXICO

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**Citation:** Barrera-Cobos S, Maimone-Celorio MR, Salomé-Castañeda E, González-Canchola A, Herrera-Pérez L. 2023. Analysis of mezcal production in San Diego la Mesa Tochimiltzingo, Puebla (Sierra del Tentzo Reserve), Mexico.
Agricultura, Sociedad y Desarrollo
https://doi.org/10.22231/asyd.v20i1.1525

ASyD 20(1): 66-91

**Editor in Chief:**
Dr. Benito Ramírez Valverde

Recived: February 7, 2022.
Approved: August 25, 2022.

**Estimated publication date:**
March 22, 2023.

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## ABSTRACT

There is a high pressure on wild populations of *Agave* spp. leading to possible extinction in the region of San Diego La Mesa Tochimiltzingo, located at the Natural Protected Area "Sierra del Tentzo", due to the increasing demand for mezcal production during the last 10 years. An analysis of the production process of mezcal was carried out through a socio-environmental diagnosis and the general population structure of wild Agave in order to determine actions for the sustainable use of mezcal production in the community. Techniques for participatory development were carried out with mezcal producers and field ecological techniques were used to assess an *Agave* population in the core area of the Reserve. It was determined that the main problem is the increasing scarcity of *Agave*, due to the extraction of wild specimens without suitable management techniques that allow the recovery of the resource, as well as the lack of training to grow their own plantations. An aggregate distribution was observed with individuals of different ages of *A. angustifolia*. A population density of 460 plants/ha was calculated, a value 60% lower than that recommended. No individuals of *A. potatorum* were found. An overexploitation of the resource was recorded, so it is urgent to establish measures for the conservation of wild *Agave* populations in the region.

**Keywords:** *Agave*, biodiversity, conservation, Mexico, Puebla.

## INTRODUCTION

The *Agave* genus belongs to the Asparagaceae family and Agavoideae subfamily, in which 9 genera with 300 plant species are recognized (Bautista and Smit, 2012), most of which are endemic to Mexico (Narváez *et al*., 2016). In Mexico, 42 species of *Agave* are used to produce mezcal, which are mostly extracted from wild populations and, in most cases, without reproduction techniques and management of their use that preserve them from extinction (Torres *et al*., 2013). According to the Mezcal Regulatory Council (CRM, 2015), the States having denomination of origin of mezcal, are Oaxaca, Durango, Guerrero, Guanajuato, Michoacán, San Luis Potosí, Tamaulipas, Zacatecas, and Puebla in 2015 (DOF, 2015). Later, Morelos, Aguascalientes, and the State of Mexico in 2018, and recently Sinaloa in 2021 (DOF, 2021).

In the mezcal regions of Puebla, two wild species of *Agave* used to make mezcal are *Agave potatorum* Zucc., commonly known as papalómetl, papalomé, or tobalá (García-Mendoza, 2010), and *Agave angustifolia* Haw. known as espadín. The mezcal made with *A. potatorum* is considered to be of high organoleptic quality and is one of the most appreciated in the country. This is one of the most vulnerable species, because of high extraction rates of *A.*

*potatorum* plants, the growing demand for mezcal, its particular reproductive biology, and the limited management efforts. It is estimated that in the Tehuacán-Cuicatlán Biosphere Reserve alone, between 54% and 87% of reproductive individuals are removed annually, generating projections that suggest *Agave* populations are in danger in the short term at the Puebla area (Torres *et al*., 2013).

The accelerated increase in the demand for mezcal during the last 10 years (CRM, 2019), generated greater pressure on the wild populations of *Agave*, increasing its risk of extinction. This is due to the fact that, for the elaboration of mezcal, complete plants are extracted before flowering occurs, as flowering decreases the amount of sugars present in the stem, which are necessary for the distillate. By collecting *Agave* plants before the flowering stage, reproduction is limited and the generation of seeds is completely canceled (Delgado-Lemus, 2008; Torres, 2009; Torres *et al*., 2013). Each *Agave* plant in reproductive age can produce between 2,000 and 9,500 seeds, which are lost when they are extracted for the production of mezcal. Inhabitants of different communities have expressed their concern when observing the fragmented populations of *Agave*, a situation forcing them to collect in places that are increasingly far from their places (Torres *et al*., 2013). The reproduction of agaves is also difficult due to their long life cycle, which lasts from 6 to 10 years (Bautista and Smit, 2012).

Another problem identified in cultivated and wild species is the existence of free grazing, where it has been observed that cattle feed on the maguey flower and trample seedlings and young specimens, affecting plant survival (Baraza and Estrella-Ruiz, 2008; Delgado-Lemus, 2008; Zizumbo-Villarreal *et al*., 2009).

Regarding the use of agricultural technologies, in the State of Jalisco it has been confirmed that the industrial production of tequilas and mezcal has caused pollution, soil erosion, reduction of genetic diversity, and displacement of native cultivars (Zizumbo-Villarreal *et al*., 2009). Furthermore, in Oaxaca, it has been shown that traditional peasant agricultural knowledge and practices contribute to environmental and productive sustainability (Bautista and Smit, 2012).

A study carried out at the Mixteca region of Puebla indicated that *Agave* populations subjected to a greater intensity of exploitation present a lower reproductive success, due to the fact that the scarce floral supply does not attract pollinators. Therefore, the extraction of plants not only poses a risk for mezcal *Agave* plants, but also represents risks for other plants in the area having dependence on the same animal guilds for their pollination (Baraza and Estrella-Ruiz, 2008).

In San Luis Atolotitlán (Tehuacán-Cuicatlán Biosphere Reserve), the extraction of reproductive plants of *A. potatorum* leads to a decrease of wild populations. Agaves developing under more stressful environmental conditions, such as low humidity and high solar radiation, show higher mezcal yields due to the increased availability of sugars to ferment and distill. In addition, it is established that the plants collected during the rainy season do not ferment properly. As a measure to protect the plant resource, a ban on the extraction of *A. potatorum* has been imposed in certain regions of San Luis Atolotitlán,

a situation that could be followed by other communities (Delgado-Lemus, 2008).

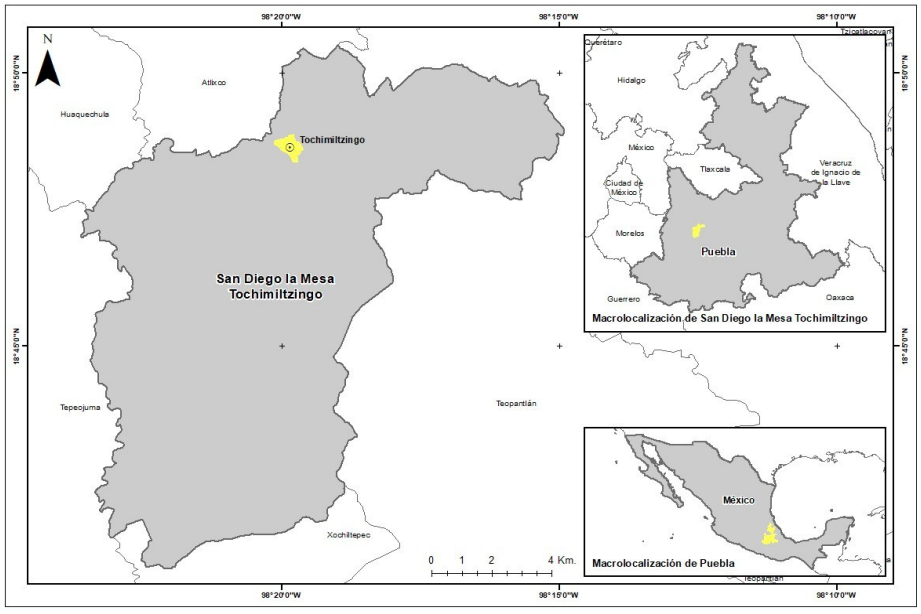
Under the present context described, various investigations in different agave regions of the country propose solutions to the overexploitation of *Agave* and control the production of mezcal, such as establishing genetic reservoirs and carrying out the reproduction of the species in nurseries for their subsequent reintroduction into the wild.

In this investigation, an analysis of the production process of mezcal was carried out through a socio-environmental diagnosis and the population structure of wild *Agave* to determine actions for sustainable use in the production of mezcal at San Diego La Mesa Tochimiltzingo in the State Reserve Sierra del Tentzo.

## METHODOLOGY

### Area of study

The municipality of San Diego La Mesa Tochimiltzingo is located in the center west of the State of Puebla, and it has an area of 91.90 km$^2$. It is located 47 km from the city of Puebla (Figure 1). Its altitude is 1,780 meters above sea level within the "Sierra del Tentzo" State Reserve. The Reserve comprises a total area of 57,815.283 ha, of which San Diego La Mesa Tochimiltzingo occupies 17.6% (SDRSOT, 2011). It has a mountainous relief ranging from 1,800 to 2,300 meters above sea level, belonging to the Atoyac River basin and has a perennial stream, the Río Grande (Government of the State of Puebla, 2014). The landscape structure corresponds to an open thicket with groups of trees of short or medium size, located mainly in the ravines or on some slopes having more humidity.




Source: own source.

**Figure 1**. Location map of the area of study, San Diego La Mesa Tochimiltzingo.

Several representative species of the area are *Quercus* sp., *Ipomoea murucoides*, *Acacia* sp., *Juniperus deppeana*, *J. flaccida*, *Taxodium mucronatum*, and *Brahea dulcis*. In the area nomadic cattle grazing is carried out, these foraging and browsing habits contribute to the formation of compact groups of plant species that are protected under the defenses of spiny species (SDRSOT, 2011).

San Diego La Mesa has a population of 1,132 inhabitants in a rural community, with 549 men and 583 women, which represents a population density of 9 inhabitants/km$^2$. Among main development indicators, it presents a high degree of social backwardness, being in the 39th place at the State level in degree of marginalization, and the 446th place at the national level. The predominant activity is agriculture, main crops being beans and maize, raising poultry, goats, cattle and horses, and the production of mezcal made by family and ancestral tradition. Marble is also extracted from existing deposits, which is well accepted in the State market (Gobierno del Estado de Puebla, 2014).

**Socio-environmental diagnosis of the mezcal production process**

The socio-environmental diagnosis was carried out during March to October 2019, based on three stages: a) prospective visits; b) semi-structured dialogue with key informants and field trips; and c) participatory workshops.

a) Prospective visits. Two prospective visits were made during March 2019 to the town of San Diego La Mesa Tochimiltzingo, in order to establish the first contact with mezcal producers and to identify potential key informants for selecting the appropriate tools for diagnosis. Informal conversations and interviews were held with the municipal president and mezcal masters from three local factories, in order to learn about the region, which later allowed the design of the diagnostic instrument.
b) Semi-structured dialogue with key informants and field trips. The semi-structured dialogue technique aimed to collect general or specific information through conversation with individuals or groups, allowing flexibility to explore the information to be collected in greater detail (Geilfus, 2009). An interview guide was established to carry out the diagnosis of mezcal production. The guide covered socioeconomic characteristics of the producers, raw materials, production yields, waste management, product marketing, problems about the elaboration of mezcal, and complementary economic activities. For the application of the semi-structured dialogue technique, key informants were selected, who were initially recognized in the prospective visit stage. Six mezcal masters from the "Tepenahuazo" factory were chosen. Selection criteria were based on their experience (greater than 10 years), and their availability to participate in the research. The dialogue was carried out individually. This dialogue took place at the time the mezcal was being distilled, combining the activity with field trips and recognition and documentation of the production process.
c) Participatory workshops. Three participatory workshops were subsequently carried out during October 2019 with 10 participants (1 *Agave* producer, 3 mezcal producers,

5 mezcal marketers, and the municipal president), in order to obtain more specific information on the problem. The techniques were brainstorming, problems tree (Martínez and Fernández, 2008), and characterization of management practices. Main topic discussed in the brainstorming technique was that participants expose relevant problems faced by all those involved in the *Agave*-mezcal production chain. At the end of the exercise, the participants discussed among themselves the list of problems generated and chose the most pressing, setting up the basis for the following dynamic. After brainstorming, the participants chose the most important problem regarding the *Agave*-mezcal production chain, being the starting point to build the problems tree. At the end of the exercise, the participants achieved a better understanding of the situation studied, identifying its causes and effects, while reflecting on possible solutions. As the last activity of the participatory workshop, the characterization of management practices used was carried out. In this work, the tool aimed to identify, characterize and diagnose the management practices of cultivated *Agave*, as well as those from *Agave* extracted from the wild. The focused group was asked to draw the differing existing practices in the cultivation of *Agave* and the jimado (removing of leaves) of wild *Agave*. During this activity, moderators asked about how and why they do them, delving into the issues and noting the information shared. Finally, the information collected was reviewed and classified.

On the basis of diagnosis and background of the topic in Mexico, the most relevant actions to be developed by the community in a context of sustainability were determined.

### Population structure of wild *Agave* in the core area of the Sierra del Tentzo State Reserve

With the help of local guides and mezcal producers, field trips were made in the area aiming at locating wild populations of *Agave*. The interest was focused on conserved populations showing the lowest possible degree of human impact. After several trips, it was possible to locate a population of *A. angustifolia* in the Paraje de los Ahogados (San Diego La Mesa Tochimiltzingo), within the core zone of the natural protected area (ANP) Sierra del Tentzo State Reserve, being the population chosen to describe the population structure. However, this population presented human intervention, so it was not possible to find real conserved wild *Agave* populations.

In the selected place, a quadrant of 1,300 $m^2$ was drawn. All *Agave* plants found were labeled and mapped by registering their Cartesian coordinates. The following parameters were recorded for each plant: species, rosette height, rosette diameter, and number of leaves (Mostacedo and Fredericksen, 2000). Moreover, the terrain and vegetation within the quadrant were described. The registered individuals of *Agave angustifolia* were classified into classes according to their size, allowing to determine the structure of the population. The Sturges statistical formula (K= 1+3.322log N) was used to calculate the number of classes into which data are grouped (Palaniswamy and Palaniswamy 2006).

## RESULTS AND DISCUSSION

### Diagnosis of the Mezcal production process

#### Mezcal factory selection

In the initial recognition of the studied area, 10 mezcal factories were identified, distributed in the towns of San Bartolomé Chimalhuacán (1), La Soledad Tepehuaxtitla (1), Guadalupe Amolocayan (4), and Tochimiltzingo (4). Four Tochimiltzingo factories are: La Perla, Río Blanco, Huizache, and Tepenahuazo, which have a total of 88 mezcal producers use same facilities sequentially. Producers indicated that all mezcal companies carry out artisanal processes, using wild *Agave* prepared in the field, the so called "jimado" involving removal of leaves. Mezcaleros work as an informal organization. Each partner makes an initial monetary contribution to build and equip the traditional factory. The Tepenahuazo factory was selected in Tochimiltzingo, where 14 partners participate producing an average of 800 liters of mezcal per year per partner.

#### Mezcal production process

The mezcal production process, described through semi-structured dialogue and field trips, is divided into 5 stages: 1) *Agave* gathering, 2) Baking, 3) Choping, 4) Fermentation, and 5) Distillation. Baking is the only phase carried out collectively. We now describe each stage of the local production process.

***Agave* gathering**. In the *Agave* gathering stage, mezcal masters go to the wild environment to collect *Agave* plants needed for their production. Main species collected are the "maguey espadín" (*A. angustifolia*) and the "maguey tobalá" or "papalómetl" (*A. potatorum*). Mature *Agave* plants are selected empirically, *i.e*. based on their acquired experience. Two main agricultural implements are used: the machete to cut *Agave* leaves, and the hoe to obtain the *Agave* pineapple, which is the only part of interest for the mezcal masters. The *Agave* inflorescences of plants in a reproductive state are cut in order to induce a longer life cycle. The cut allows the plant to grow in size and to concentrate sugars, which generates higher yields in the production of mezcal. The *Agave* gathering is carried out during December to May, in the dry season, because *Agave* plants concentrate a greater amount of sugars in the distillate. *Agave* pineapples are transported from the field to the mezcal factory using mules or trucks (Figure 2A).

**Baking or cooking of the *Agave*.** This is made in an underground oven of 7 tons capacity of *Agave* pineapples, having brick walls and cobblestone floor (Figure 2B). This stage is carried out collectively by participant partners, so they all place their *Agave* pineapples in the oven simultaneously. Each producer labels his *Agave* plants, making initials, line or symbols with a machete in order to identify *Agave* pineapples easily. Producers collect green wood from "huizache" (*Acacia farnesiana*), "mesquite" (*Prosopis* spp.), "huaje" (*Leucaena leucocephala*), and "espino" (*Acacia*, *Mimosa*). Around 1.3 tons of green firewood and 2 tons of rock are necessary for cooking 7 tons of maguey, although rocks can be used during an entire season (December to May). The


Source: own photos.
**Figure 2**. A) Wild *Agave* pineapples collected in the field. B) Underground oven. C) Ignition of the oven with dry palm. D) A mat called "petate" to cover *Agave* pineapples in the underground oven.

underground oven is filled in layers; a layer of green wood is placed covering the entire bottom of the oven, arranging logs vertically, similar to a campfire. Subsequently, greater trunks are placed and the firewood is lit using dry palm (*Brahea dulcis*). Volcanic rock is placed on top when the wood is burning (Figure 2C). The oven is left to smoke for approximately 6 hours, until rock ignites and firewood is consumed, allowing the rock to settle, providing enough space to place the *Agave*. The 7 tons of *Agave* are then placed on top of red-hot volcanic rock, and covered with a wet mat called "petate". The oven is completely covered with soil, as a hermetic seal. As a last step, a hole is made at the center of the oven, 40 liters of water are then added, and the oven is sealed again with soil. The cooking time for *Agave* pineapples lasts 4 days, as reported by Espinosa-Meza *et al*. (2017), which is a traditional practice of mezcal masters conferring a smoky flavor to the final product.

**Chopping.** After baking, the cooked *Agave* is extracted, each mezcal master recognizes its labelled raw material. The oven is cleaned and the ashes are collected and scattered on plantations. It is important to note that this collective process concludes here, and is then continued individually. Therefore, each producer is responsible for chopping their own *Agave*. Some of them involve their wives or family at this stage, the cooked *Agave* is

processed to obtain a shredded product, using a gasoline crusher with a 25 horsepower motor, and then it is placed in plastic tubs (Figure 3A).

**Fermentation.** At this stage, the chopped *Agave* is placed in plastic tubs of 1 ton capacity, and left to rest for 7 days. It is important to keep track of the start date on each tub. Rocks are added to prevent overflow. After the rest time, 300 liters of well water are added to each tub, and left to ferment for approximately 8 days, although this may vary according to environmental conditions (Figure 3B). Each producer is responsible for monitoring their tubs, using a kitchen density meter or a syrup weigher in Brix degrees. When the instrument shows 1 to 2 °Brix, the *Agave* must is ready to be distilled.

**Distillation.** In this process, a copper still of 1/3 of a ton of *Agave* must capacity is used. This amount is placed in the copper pot, which is heated with direct fire using 28 kg of dry "copalillo" or "palo blanco" firewood as fuel for 6 hours of distillation. In the boiler, the alcohol from the *Agave* must evaporates and is conducted through the copper pipe until it reaches a coil heat exchanger, submerged in a tub of water at room temperature, where the mezcal is condensed and recovered in plastic containers (Figure 3C). "Tips" and "tails" are obtained from distillation, the tips are the product obtained in the first hour of distillation, which contains a higher degree of alcohol than that of tails obtained


Source: own photos.

**Figure 3**. A) Crusher. B) Chopped *Agave* resting in fermentation tubs. C) Artisanal distillation still. D) "Pearls" of mezcal indicate the degree of alcohol.

during last minutes of the process. At the end of distillation, the mezcal master mixes tips and tails until the desired degree of alcohol is obtained for the product, which varies from 35% to 55% alcohol by volume at 20°C. To determine the degree of alcohol in the mezcal, the producer makes a measurement using a gourd and a dry cane or reed as a pipette. When the mezcal is dropped into the gourd, the formation of "pearls" is observed on the surface. The percentage of alcohol is determined based on the size and quantity of "pearls" observed. These data are similiar to those reported by Bautista *et al*. (2015), who mentioned that this technique is performed empirically by mezcal masters (Figure 3D). This traditional measurement is verified with an alcohol meter. The mezcal is finally stored in 20-liter glass containers.

The distillation process continues until initial 7 tons of *Agave* are consumed. Each mezcal master obtains his own product, according to the amount of *Agave* initially contributed. In this phase, 11.11 kg of *Agave* are required to obtain 1 liter of mezcal, starting from an average pineapple weight of 30 kg. Solid residues of *Agave*, *i.e*. the bagasse, are collected and disposed as compost in the open air, taking about two years to be used. The complete process of artisanal production of mezcal from the Tepenahuazo factory is shown in Figure 4.

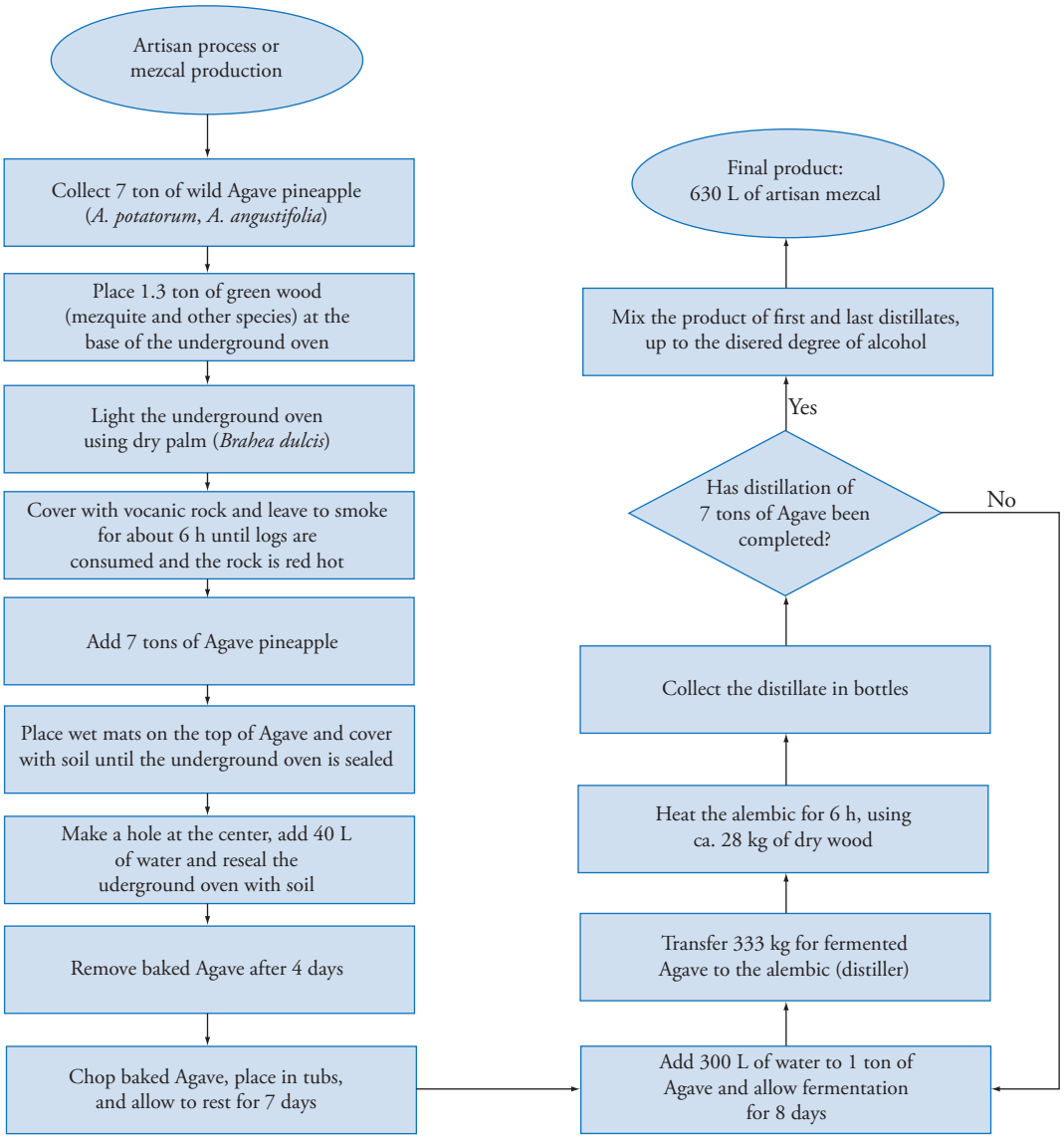
**Identification of community problems in the mezcal production process**

The problems obtained from participatory workshops (brainstorming, problems tree, and characterization of management practices) are described below.

Main problems identified from brainstorming were the following: 1) There is not enough raw material, both wild and cultivated *Agave* are scarce for the production of mezcal; 2) There is no homogeneous consumer price, it varies according to the producer, some have a very low price while others higher, leaving the former at a disadvantage despite being the same product; 3) Lack of water for *Agave* plantations; 4) Lack of organization among mezcal producers, it has been difficult for them to work together to obtain important certifications, as well as to agree on homogeneous prices and to establish resource management and conservation strategies; 5) There is no financing or technical advice, they have received little external support and they consider it important to continue expanding.

Among problems mentioned above, mezcal masters from three factories indicated that the main current problem is the shortage of *Agave* (*A. potatorum*, *A. angustifolia*), as raw material for the elaboration of mezcal. The problems tree showed in its lower part that causes of *Agave* shortage are: the common ownership of the land where the plants are found or cultivated, as well as the lack of training and technical assistance for the crop. Various effects are then derived, such as the purchase of plant in other States of the country, and that there is no guarantee of plant supply for the production of mezcal, thus increasing production costs and little growth in the local economy (Figure 5).

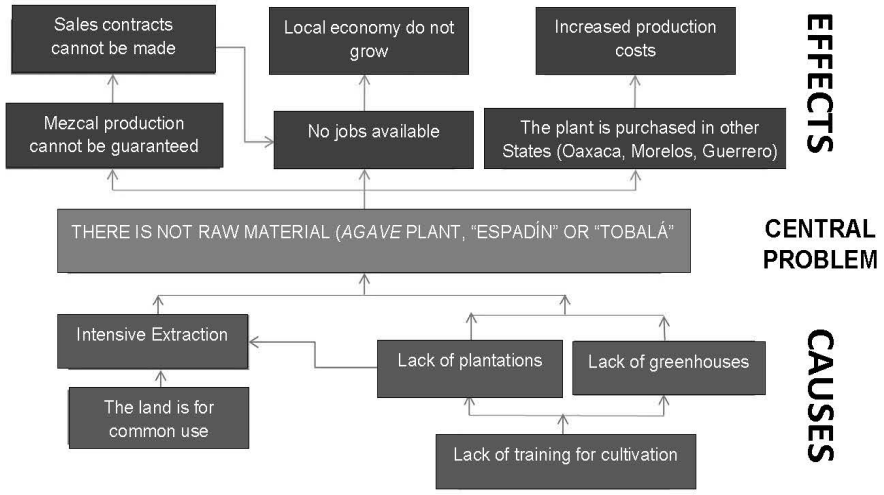
The characterization of management practices was divided into three types of information: 1) Current management practices for wild *Agave*; 2) Current management practices for cultivated *Agave*; and 3) Ideal scenario of the *Agave*-mezcal production system.




Source: own source.
**Figure 4**. Flow chart of the production process of artisanal mezcal.

### Current management practices for wild *Agave*

In current management practices of wild *Agave*, the participants indicated that 90-97% of mezcal masters carry out the extraction activity; however, a small percentage manages the *Agave* cultivation. The extraction of wild specimens of *A. angustifolia* and *A. potatorum* is carried out during December to May, due to the high concentration of sugars in the pineapple. The usable part of *Agave* is the so called pineapple, the rest of the plant is discarded at the extraction site. The removal of leaves from wild *Agave*, called "jimado",




Source: own diagram.
**Figure 5.** Problems tree of the maguey-mezcal chain.

are practices carried out manually. Furthermore, it was mentioned that firewood is also extracted from wild tres, such as "cazahuate" (*Ipomea murucoides*), cubata (*Acacia cochliacantha*), "espino" (*Acacia*, *Mimosa*), and "huizache" (*Acacia farnesiana*), for baking and distilling *Agave*.

### Current management practices for cultivated *Agave*

Regarding the management practices of the cultivated *Agave*, around 3-10% of mezcal masters have their own plantations and, on average, five years of experience on cultivation. *Agave* growers obtained seeds from wild *A. angustifolia* and *A. potatorum*. They mentioned that exclusion areas are designated in order to allow cultivated specimens to complete their reproductive cycle and seeds can be obtained. Germination takes place in seedbeds, where seedlings remain for 5 to 6 months, and are later transplanted into nursery bags. Little plants, 2 years old, are transplanted in the field, keeping a separation of 1.30 meters between plants for the "maguey espadín" (*A. angustifolia*), while 1 meter for the "maguey tobalá" (*A. potatorum*).

The plantations are established in a straight line, without contour lines or staggering. In reference to agricultural inputs, they use organic fertilizer, such as manure and dry leaves, while weed control is manual. The main pests reported are: the "gallina ciega" (white grub; *Phyllophaga* spp.) and the "picudo" (*Agave* weevil; *Scyphophocus intersticialis*), which they have not been able to control. They mentioned that grazing is a problem for the survival of *Agave* seedlings, since they are stepped on or eaten by animals. However, it is possible to integrate silvopastoral systems with *Agave* production. Herrera-Perez *et al.* (2017) reported on the efficiency of free grazing practice under certain conditions: livestock rotation between plantations, periodicity (after the rainy season), age of the plants (three years), and the type of livestock.

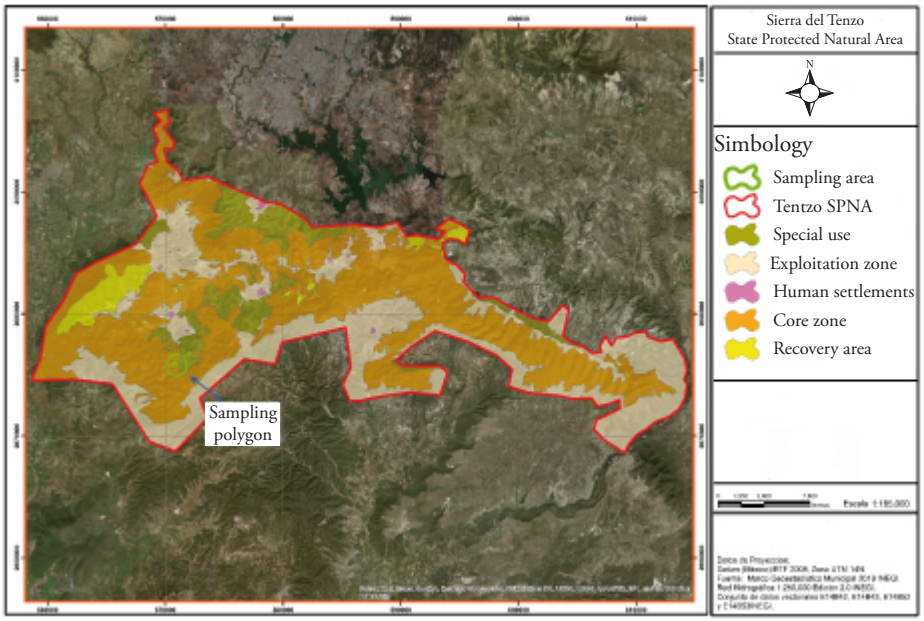
### Ideal scenario of the *Agave*-mezcal production system

Workshop participants made a diagram of an ideal scenario for the *Agave*-mezcal chain, which begins with a greenhouse or a germination area for *Agave* seeds, in order to obtain seedlings that will later be planted on the farmers' land. It should be verified that "the varieties of *Agave* can be planted together or independently by species", monitoring the age of plants for suitable removal of leaves (jimado). The need for continuous technical assistance and advice in *Agave* production stages is emphasized, to "control all factors and ensure the raw material and the product".

### Population structure of *Agave angustifolia* in the core zone of the Sierra del Tentzo State Reserve

The *Agave* population studied is located in the core area of the Sierra del Tentzo State Reserve, as can be seen in Figure 6 indicating zone and location of the sampling quadrant or polygon. Expanding the scale of the map from 1:10,000 to 1:4,000, the sampling site is observed as located on a slope near a ravine, an area far from human settlements and gathering zones.

Vegetation found and identified in the polygon: "cuajiote rojo" (*Bursera* sp.), "cubata" (*Acacia cochliacantha*), "mala mujer" (*Cnidoscolus* sp.), "cacalosuchil" (*Plumeria rubra*), "gallinita" (*Tillandsia recurvata*), "maguey espadín" (*Agave angustifolia*), "nopal" (*Opuntia* sp.), palm (*Brahea dulcis*), "lantana" (*Lantana* sp.), and "cinco negritos" (*Lantana camara*).



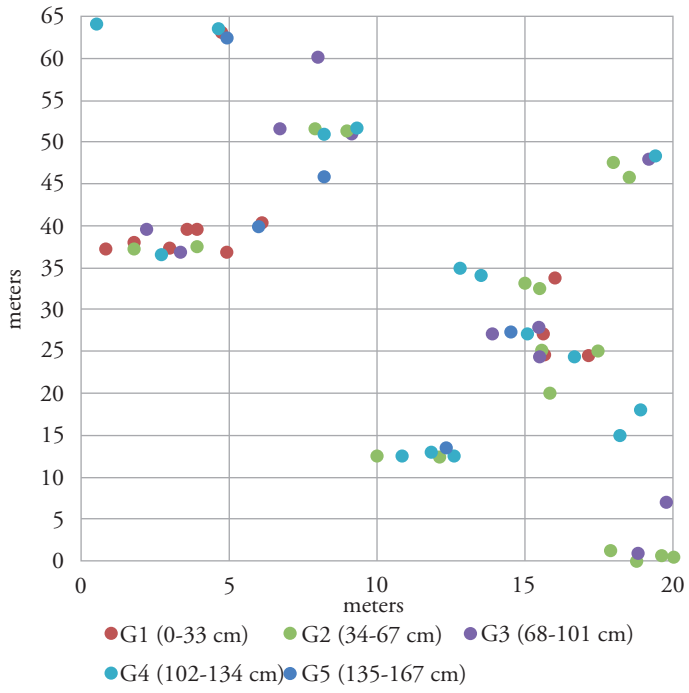

Source: own photo.

**Figure 6**. Zoning of the Sierra del Tentzo State Reserve (ANP), and location of the sampling polygon.

In the quadrant, 60 individuals of *A. angustifolia* of variable sizes were recorded. It is worth mentioning that no individual of *A. potatorum* was recorded. The calculated population density is 460 ind/ha (0.046 individuals per $m^2$), which is low compared to reports in the literature, in which densities of 1,080 to 1,340 ind/ha have been reported (Cervera *et al.*, 2018; Delgado-Lemus, 2008; Torres, 2009). Figure 7 shows the location of each individual within the polygon, where the aggregate distribution of *A. agustifolia* is evident, similar to other works previously reported (Cervera *et al.*, 2018). A higher frequency of individuals with a rosette diameter ranging from 34 cm to 67 cm was found.

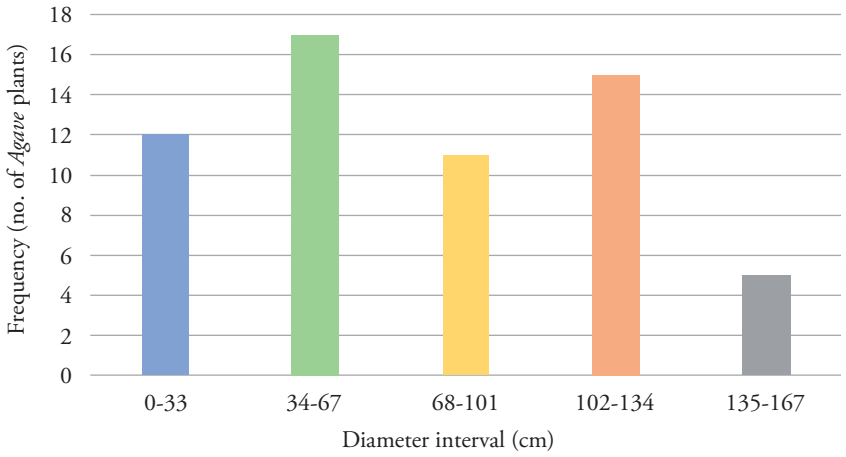
Evidences of the extraction of 9 adult plants were found in the entire quadrant, suggesting a loss of at least 18,000 seeds, according to the criteria of Torres *et al.* (2013). These data suggest overexploitation, even in conservation areas, and reinforce the need for a strategy for wild *Agave* conservation in the region.

Regarding the population structure of *A. angustifolia*, 5 size categories were determined based on data from the variables of rosette height, rosette diameter and number of leaves. The greatest abundance, in terms of height, were those plants measuring from 28 cm to 54 cm. Regarding the diameter of the rosette, the largest number of individuals present were those measuring from 34 cm to 67 cm (Figure 8).




Source: own graph.

**Figure 7**. Aggregate distribution of wild *Agave angustifolia* (1300 $m^2$), considering the diameter of the rosette. Paraje de los Ahogados, Sierra del Tentzo Protected Natural Area. July 25, 2019. G1 to G5 correspond to the groups according to the size of diameter.



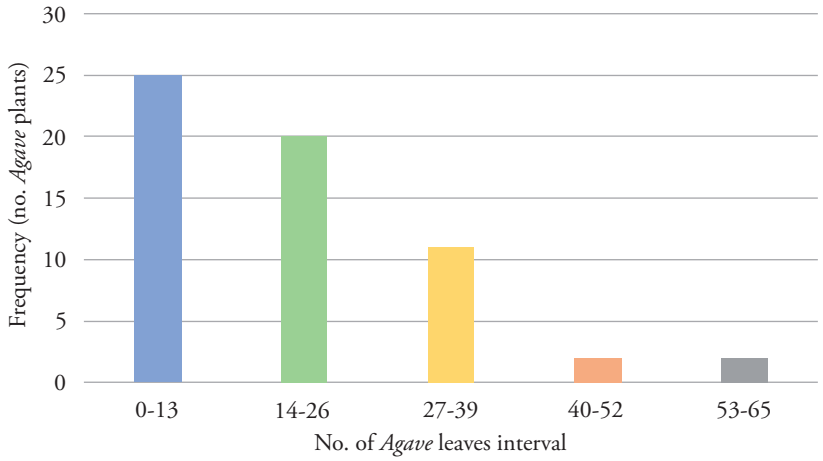

Source: Own elaboration.
**Figure 8**. Frequency of *Agave angustifolia* by category, considering the rosette diameter (cm), in the Paraje de los Ahogados sampling polygon, Sierra del Tentzo Natural Protected Area. July 25, 2019.

The frequency of *Agave angustifolia* by number of leaves was higher in ranges 0-13, 14-26, and 27-39, indicating very few well-developed individuals (Figure 9).

## Actions for sustainable use in the production of mezcal

### Establishment of nurseries and plantations

In accordance with dimensions of sustainability, the establishment of nurseries will allow addressing economic aspects, such as the generation of jobs and the creation of new sources




Source: Own elaboration.
**Figure 9**. Frequency of *Agave angustifolia* by category, considering the number of leaves, in the Paraje de los Ahogados, Sierra del Tentzo Protected Natural Area. July 25, 2019.

of income; environmental aspects, such as the conservation of *Agave*, preventing the extraction of wild specimens, as well as conserving associated species; and social aspects, such as the integration of the different actors involved in the *Agave*-mezcal production chain, creating alliances between actors and other production chains.

Based on the diagnosis made, and the study of wild *Agave* populations and a critical review of the literature (Illsley *et al*., 2005; Torres *et al*., 2013), it is proposed to establish a rustic nursery for *Agave* production. Minimum characteristics of this nursery are the use a 60% shade mesh, a fence to prevent the entry of livestock, and an area for seed germination and seedling acclimatization.

Initially, seeds must be collected from the wild. Later, they can be harvested within the same plantations. The seed harvest should be done during April and May, before fruits open to release the seed. It is suggested to collect fruits from lower branches first, while those from upper branches continue the ripening process. The seeds are obtained by opening the fruit with tweezers and separated by colours, black ones contain an embryo while the rest are empty. They are left to dry for a month before using them. The maximum storage time without germinating is a year and a half, to ensure their seed viability.

In San Diego La Mesa, there are 88 mezcal producers, each one producing an average of 800 liters per year. About 11.11 kg of *Agave* are required to make 1 liter of mezcal. It is estimated that each *Agave* pineapple weighs about 30 kg. Taking these data into account, it is possible to calculate the needs of producers as follows:

Annual production of mezcal=800 L/year/producer*88 producers=70,400 L/year
Kilos of *Agave* needed=70,400 L/year*11.11 kg *Agave*/L=782,144 kg of *Agave*/year
*Agave* plants needed=782,144 kg/year divided by 30 kg per pineapple=26,071 plants/year

The community needs at least 26,071 well developed *Agave* plants per year to cover the needs of raw material for the production of mezcal. As a unit, each producer needs 296 *Agave* plants to meet their annual production. If the average percentage of germination is about 50%, each producer must sow 592 seeds per year or, altogether, the nurseries established at the community must sow 52,142 seeds per year. This is only to meet the local demand for mezcal, however, the production of the plant may be greater to sell it to other communities or generate contracts with clients outside the municipality.

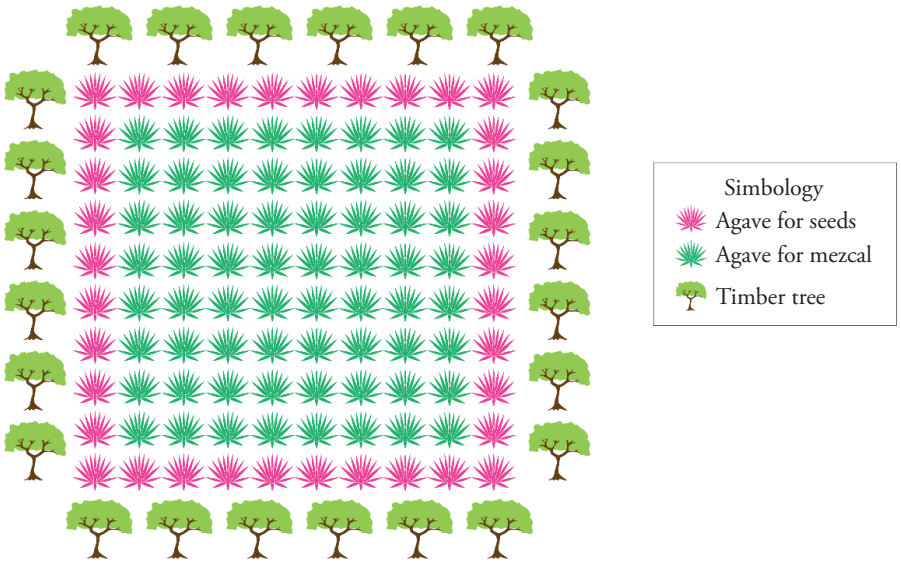
The fertilization of seedlings will begin in the nursery bags using organic fertilizers, such as manure, vermicompost, or the same bagasse (residue from the distillation of mezcal). In the nursery, it is suggested to fertilize with 0.5 kg of organic fertilizer per plant, every two months (Ayvar *et al*., 2017).

It is proposed to use at least 20% of cultivated *Agave* plants as seed suppliers. The most robust seedlings should be selected and separated to make special plantings of seedlings (Illsey, 2005). For crop establishment, it is recommended to plant at the beginning of the rainy season. Cultivation can be carried out in valleys or on slopes, following the contour lines when the slope is greater than 5% (Pérez Ramos *et al*., 2017). The space between

*Agave* plants should be 1 to 2 meters, and be fenced to prevent the entry of livestock for protecting the plants. It is recommended to fertilize the field before transplanting the *Agave* plants, using organic fertilizer integrated by removing the soil from the ground. There must be enough space to divide the land into 10 parts, where each part must contain the full annual production. This will ensure the necessary raw material for each year (296 *Agave* plants each year). Each plot must contain that amount of *Agave* plants needed, with a difference of one year in the planting date. In this way, after 10 years, the time necessary for complete development of the plant, the raw material is guaranteed for future generations. The necessary amount of *Agave* plants must be recalculated each year, based on the demand for mezcal. Once the quadrant has been harvested, the soil should be allowed rest for at least 1 year before planting again, promoting its natural regeneration. Likewise, crop rotation is suggested, as far as possible.

## Agroforestry system

The implementation of an Agroforestry System (AFS) in *Agave* plantations is viable for its conservation and use (Torres *et al.*, 2019), in which timber species that are usable for the same mezcal production process are involved, such as mesquite, juniper, and huizache. In Figure 10, the boundary or strip arrangement is proposed, which acts as a barrier/living fence. The rows next to the trees will be of *Agave* plants for seeds, with the aim of sheltering them by trees providing shade and protection from adverse weather, thus increasing chances of survival and ensuring sedes. Likewise, the shelter of trees will provide protection from the wind to the *Agave* inflorescences, preventing it from breaking during the reproductive stage.




Source: self elaboration.
**Figure 10**. Proposal for a *Agave*-mezquite-sabino agroforestry system. The separation between plants will be 1-2 m.

Accommodation in the boundary will also allow the exclusion of livestock in *Agave* plantations. The rows following plants for seeds will be of *Agave* plants for mezcal, which will be exposed to direct sunlight, so that they will generate more sugars and therefore optimal yields in distillation. The arrangement seen in Figure 10 represents a plot with 100 *Agave* plants, with a space of 1 to 2 meters in between. It is suggested that trees be intercropped in this way for the conservation of soil nutrients, for every 100 individuals planted, the timber can be used by pruning or cutting the entire specimen.

Several authors suggest incorporating annual crops between the rows of *Agave* plants, allowing even more diversity in the plantation, helping soil conservation, and reducing the existence of pests and diseases (Zizumbo-Villarreal *et al*., 2009; Bautista and Smit, 2012; Ayvar *et al*., 2017; Herrera-Pérez *et al*., 2017). These authors suggest cultivating maize, beans, peanuts, or chickpeas during the first three years of establishing the *Agave* plantation. Fertilization should be done annually, incorporating organic fertilizer into the land, such as sheep, cattle or goat manure, vermicompost or bagasse compost, it is estimated that between 1.5 and 4 kg per plant are needed (Ayvar *et al*., 2017; Pérez Ramos *et al*., 2017).

Regarding phytosanitary control the "picudo" (*Agave* weevil; *Scyphophocus intersticialis*), and the "gallina ciega" (white grub; *Phyllophaga* spp.), they can be prevented and reduced by having crops with a wide diversity of agricultural and forest species (Zizumbo-Villarreal *et al*., 2009; Bautista and Smit, 2012). Other preventive measures are: 1) Plow the land prior to planting, to expose those pests that are in the soil, such as the "mayates" (May bettles; *Rhynchophorous* spp.) and other larvae; 2) Manual weed control; 3) Removal of sick or infested leaves, or completely eliminate and remove the sick or infested *Agave* plant from the property. As a biological control, it has been found that the fungus *Beauveria bassiana* can be applied to the plant leaves, causing the mortality of the weevil and other pests, when used in solutions with concentrations of $2.1 \times 10^{10}$ spores/ml (Ayvar *et al*., 2017). Although pesticides and herbicides are commonly used, it is suggested to avoid the use of agrochemicals and to emphasize preventive actions and manual control.

**Sustainable extractive practices in the wild**

*Agave* production will be obtained 7 to 10 years after planting, due to its biological cycle. During this period, the mezcal community will continue extracting wild specimens to cover the demand. This is why it is important to propose guidelines for sustainable extractive practices to allow the conservation of biodiversity in the area. The following practices to promote *Agave* conservation are proposed: 1) To extract only mature *Agave* plants. The youngest individuals must remain intact to allow their natural development; 2) To leave at least 20% of the plants in the mature stage, so that they reach a reproductive process to promote regeneration by seed. In practice, this means leaving intact 1 *Agave* for every 4 plants cut. Plants to be preserved must be marked in a visible way, showing other mezcal masters, called "jimadores", that they are *Agave* plants for seed and must not be harvested; 3) When only leaves are used, a maximum of 50% can be cut from

mature individuals; and 4) It is recommended to transplant plantlets for favoring the development of new *Agave* individuals in the same harvesting areas (Secretaria de Medio Ambiente y Recursos Naturales, 2012).

**Restoring wild populations**

Based on the peasant management manual for wild mezcal *Agave* plants (Illsley *et al*., 2005), the manual for germination and management of forest species (Rodríguez *et al*., 2002), and research studies by Torres (2009, 2013), we propose a strategy for restoring wild *Agave* populations in the Sierra del Tentzo State Reserve, selecting a site within the core zone of the reserve. The selected area must be fenced to prevent the entry of livestock, to delimit the reforestation área, and therefore to prohibit *Agave* extraction. Four actions will be carried out within this site:

1) Dispersal of seeds from this or other sites in the reserve, in order to promote natural *Agave* populations. It is recommended to disperse seeds harvested the same year during rainy months.
2) The restoring of wild *Agave* populations by seedlings from community nurseries. They should be older than 2 years, and be planted under the shade of protective tres for increasing chances of survival. The number of *Agave* plants to be planted in the reforestation areas will depend on the amount extracted annually. In this case, it is proposed that 20 *Agave* plants be planted for each harvested individual, and the recommendation is to plant at the beginning of the rainy season.
3) Pertinent practices for fire prevention.
4) Elaboration of annual inventories to know the initial state of the site and its progress. Regarding this last point, it is essential to establish a commission for quantifying and carrying out an annual census of mature *Agave* plants, as well as supervising the reforested sites. Mezcal masters from different factories must be organized for this, in synergy with municipal authorities. There is a possibility of creating community guidelines to impose sanctions and to influence the proper management of natural resources.

Community agreements will be necessary for the distribution of benefits, since *Agave* plants in this area are of common use. In this context, it is suggested to establish a number of plants proportional to the participation and the contribution made by each mezcal master, either in time (daily wage), in cash or in kind. In general, a review of community agreements should be made to regulate access, use, and management of *Agave* plants and other regional natural resources. *Agave* plants can even be used to reforest and help soil retention, water infiltration, and erosion reduction, when planted on contour lines, in areas devoid of vegetation or for aquifer recharge, in the form of embankments or terraces, or as living barriers around other crops, promoting the conservation of other resources.

## By-product management

Bagasse is one of the main residues from mezcal production, being the remaining fibers of the distilled must, composed mainly of lignocellulose. In the case of factories from San Diego La Mesa, they generate about 400 kg of bagasse for each ton of *Agave*, a value similar to that reported in the literature (Ordaz *et al*., 2019). That is, for every liter of mezcal, 4.4 kg of bagasse are produced. Taking into account that, on average, each mezcal master produces 800 liters per year, each mezcal producer generates 35,200 kg of bagasse annually. There are various applications considering the large amount produced, thus four strategies are proposed for the use of bagasse: composting, eco-bricks, substrate for cultivation, and firewood alternative.

## Bagasse for compost

A common use of bagasse in the mezcal industry is composting (Hernández, 2014; Gurrola *et al*., 2016; Ordaz *et al*., 2019). This practice is carried out by mezcal producers, who stack the bagasse beside the factory, where it is decomposed for two years and later used to fertilize plantations. Due to the fact that composting is recurrent, the following suggestions are made to optimize its efficiency: 1) A black plastic or some other insulating material should be placed as a base, to prevent leaching and draining to the ground causing erosion; 2) The compost must also be covered by a black plastic, to maintain the humidity of bagasse and to increase its temperature by solar exposure, accelerating decomposition; 3) Turning the compost constantly to obtain a homogeneous decomposition; 4) To incorporate cattle manure to enrich nutrients in the compost; 5) To screen the final compost for a better incorporation into the soil; and 6) To elaborate biodigester bales.

## Bagasse for eco-bricks

Dehydrated bagasse as raw material is used for the production of bricks for construction (Hernández, 2014; Estrada and Rodríguez, 2016; Ruiz *et al*., 2019), which can be used in the production of warehouses, houses, or extensions of the factory. Research works show that the incorporation of bagasse in the manufacture of masonry or adobe bricks is feasible and even adds properties to constructions, such as lightness of materials, resistance to compression without affectations in the setting time. According to Ruiz *et al*. (2019), who carried out experiments with bagasse from *A. angustifolia*, a species of interest in the case of San Diego La Mesa Tochimiltzingo, it has been established that the concentration of bagasse should be 18% with respect to the weight of the adobe. The bagasse must be dehydrated and chopped in pieces of about 0.5 cm, the size of the bricks can be defined as needed, as long as the proportions of the mixture are equivalent. This strategy allows the use of waste from mezcal factories, turning bagasse into a by-product that can be used as raw material for the production of construction materials.

## Bagasse as a substrate

Research works have shown that maguey bagasse can be used as a substrate for the mushroom production (Guzmán-Dávalos *et al*., 1987; Baena *et al*. 2005; Chairez-Aquino *et al*., 2015), tomato (Ordaz *et al*., 2019), and *Agave* in the nursery (Crespo *et al*., 2013). The cultivation of mushrooms has been shown to be feasible for both *Agave* bagasse and sugarcane bagasse, which have similar characteristics in terms of their lignocellulosic character. The most studied species are those commercially called oyster mushrooms (*Pleurotus* spp.), which grow on *Agave* bagasse producing enzymes that degrade cellulose, lignin and hemicellulose. Regarding tomato cultivation (*Solanum lycopersicum*), it is proposed to use bagasse as an organic substrate for soiless cultivation. In the case of *Agave* cultivation, coconut powder and bagasse derived from composting are used, in a proportion of 30% to 50%, for seedlings from 16 months of age (Martínez-Gutiérrez *et al*., 2013). There is also a high probability of functionality using the bagasse as a substrate to germinate *Agave* sedes. This could result in economic savings considering the production of *Agave* plants for mezcal in the nursery. Another study carried out on tequila *Agave* bagasse showed the viability of bagasse as a substrate for broccoli cultivation, because it is biostable (Rodríguez *et al*., 2005).

## Bagasse and *Agave* leaves as firewood alternatives

In the baking or cooking stage of one ton of maguey, 185 kg of green firewood and 85 kg of dry firewood are required to distill that amount of *Agave*. Calculations to estimate the necessary amount of green and dry firewood, annually, in the case of the Tepenahuazo factory indicated that, to meet the demand for mezcal, 23,020 kg of green firewood and 10,577 kg of dry firewood are needed. Mezcal producers from San Diego La Mesa Tochimiltzingo only take advantage of the *Agave* pineapple, so leaves are left in the plantations. In some factories, called "palenques", from Oaxaca and Puebla, *Agave* leaves are used as a complement to firewood in the baking process. It is then suggested that factories studied implement the practice of collecting and using leaves for baking *Agave* pineapples. In this way, a residue from the removal of leaves of wild *Agave* (jimado) is converted into raw material for the production of mezcal, reducing the amount of green firewood needed and therefore reducing deforestation.

It is suggested to use dehydrated bagasse as fuel in the baking and distilling processes of *Agave*, since it has been shown that this residue has a combustion heat value of 9.55 MJ/kg, which can replace the palm used to light the oven and the dry wood used for distillation (Chávez-Guerrero and Hinojosa, 2010). As a future project, the possibility of producing bioethanol from *Agave* leaves may be explored (Corbin *et al*., 2015).

## Management of vinasses

Vinasses are one of the most important residues in the production of mezcal, for every liter of mezcal produced, 14.9 liters of vinasses are obtained (Ordaz *et al*., 2019). Due to their

physicochemical characteristics, vinasses are very aggressive for the environment, mainly soils and water bodies, since they have a low pH, high acidity, require a high chemical demand for oxygen, and have a high concentration of organic matter solids, which can cause eutrophication (Robles-González *et al*., 2012; Morán-Salazar *et al*., 2016; Ordaz *et al*., 2019).

There are biological and chemical treatments, such as anaerobic digestion, ozonation, and aerobic procedures including the use of bacteria, such as *Pseudomonas*, and some fungi (Robles-González *et al*., 2012). However, they are treatments that require the use of complex and expensive equipment, such as reactors, fluidized beds, digesters, filters and stills, being a non-viable technologies in the case of San Diego La Mesa Tochimiltzingo. The neutralization of vinasses using lime has been reported to be used later in the irrigation of fields (Hernández, 2014). It is recommended that irrigation be carried out in areas located more than 50 meters away from protected reserves, outside groundwater supply areas, more than 15 meters away from the edges of communication routes, and at a distance of 1000 meters from urban centers (CONADESUCA and SAGARPA, 2016). The use of neutralized vinasses for irrigation also serves as a fertilizer, due to its high concentrations of carbon, nitrogen, potassium and phosphorus (Ordaz *et al*., 2019).

Disposing vinasses in this way reduces the risk of soil erosion, eutrophication of water bodies, and promotes an increase in plant cover (Robles-González *et al*., 2012). The adoption of compost using vinasses and solid organic matter is a low-cost technology, suitable for rural regions, which is proposed as the main strategy for the case of San Diego La Mesa Tochimiltzingo. Another use of bagasse and vinasses is the production of biogas (Gómez *et al*., 2014), although this requires a more elaborated technology and investment.

**Rain collector in factory**

For each ton of *Agave* used for fermentation, 300 liters of well water are used, whereas in the distillation stage 9,000 liters of cooling water are used for the condensation of the liquor, of which 100 liters are lost by evaporation for each ton of distilled *Agave*. That is, each ton of *Agave* will require 400 liters of water in the transformation process. Therefore, to make 1 liter of mezcal, 11.11 kg of *Agave* are used, so the total kilograms of *Agave* used annually can be calculated, and the relationship is made with the liters of water needed per ton. According to these calculations for the specific case of the Tepenahuazo factory, 49,773 liters of water/year are needed coming from wells near the factory. The use of rainwater as a sustainable strategy is accordingly justified. This factory has an area of 1,000 $m^2$. It is suggested to install a rain collector for using the collected water in the mezcal manufacturing process. To calculate the volume of water that can be collected annually, the formula proposed in the Rainwater Harvesting Manual for Urban Centers (Adler *et al*., 2008) was used:

$$\text{Water volume} = (0.80)\ (\text{effective collecting area})\ (\text{amount of annual rainfall})$$

An annual rainfall range of 800 mm is reported for San Diego La Mesa Tochimiltzingo (INEGI, 2009), equivalent to 800 liters per year per square meter. Considering that half of 1,000 $m^2$ is roofed, excluding the baking area, and using the runoff coefficient of 0.8, the annual volume of water to be collected was calculated in 320,000 liters/year. By having a rain collector of these dimensions, there would be an extra 84.4% of water available, which can be used for toilets or irrigation of nurseries and plantations. In rainwater harvesting systems, the largest investment is the storage container, so it is suggested to build a 50,000 liter capacity tank.

**Certification by the Mezcal Regulatory Council**

A certification from the Mezcal Regulatory Council (MRC) allows producers to call their product "mezcal", by complying with all requirements for the denomination of origin and the authentication studies. If they are not certified, the product can only be called "*Agave* distillate". When producers comply with the certification, they are granted seals and permits that guarantee authenticity of their product. This facilitates the entry to formal markets, such as restaurants, bars, liquor stores, supermarkets, among others, as well as the sale of the product in bulk to marketers. Being part of the MRC also has the advantage of appearing in the lists of authenticated mezcals. Barraza-Soto *et al*. (2014) indicated that the association and certification of mezcal contributes to minimizing intermediarism and increasing economic income.

**Agrotourism and rural tourism**

The municipality of San Diego La Mesa Tochimiltzingo is located 19 km, approximately 35 minutes by car, from the municipality of Atlixco, which is a Magical Town and a tourist center with high regional demand mainly. This represents an advantage for mezcal masters, as they have an enormous opportunity to market their products in this local touristic area. Currently, the community has a tour created in 2019, which consists of visiting nurseries, and mezcal factories in the municipality, including tastings of mezcal and food. Tours do not include transportation to San Diego La Mesa Tochimiltzingo. One solution is to create alliances with tourist service providers in Atlixco, who will be able to provide tourists with transportation to San Diego La Mesa Tochimiltzingo, as well as to increase the dissemination of tours, by including them in the catalogue of tourist agencies. As part of the promotion strategy, it is suggested that the municipality seeks the support of the Ministry of Culture and the Ministry of Rural Development, which usually promote this type of initiatives, as they have done with the "Festival of Mezcal Producers", which takes place every year in November. For the direct marketing of mezcal, alliances can be made with restaurants and bars in the city of Atlixco that seek to offer their customers regional, artisanal, and cultural experiences. Sales contracts can be created, avoiding intermediaries as much as possible, so that the majority of the profits can go to the mezcal masters.

In summary, the proposed strategies are focused on a sustainable perspective that starts involving the community and mezcal producers in the efficient management of resources,

in such a way that they obtain an economic benefit without extracting extensively. It is noted that the implementation of these alternatives may require institutional support or support from companies related to the sector.

## CONCLUSIONS

For mezcal masters of San Diego La Mesa Tochimiltzingo, the main problem is the lack of *Agave* plants for the production of mezcal, due to the excessive use of wild extraction techniques, along with little training for planting and the lack of reforestation techniques. The need to increase the number of *Agave* plantations was demonstrated to guarantee the raw material and meet the demand for distillate, as well as reducing the harvest of wild specimens, contributing to their conservation. Regarding management practices, it was found that 94% of mezcal masters extract wild *Agave* and carry out inflorescences removal, interrupting the natural propagation of the plant. The rest have started planting during the last 5 years, but they have a lack of training in *Agave* planting and care. Regarding the population structure and the state of conservation of the wild *Agave*, the groups of plants are made up of different sizes, a sign of a healthy ecosystem. There was evidence of extraction of 9 *Agave* plants in the entire quadrant, which represented a loss of at least 18,000 seeds. The calculated population density was 460 individuals/ha, which is relatively low, since there are regions where densities of 1,080 to 1,340 individuals/ha have been recorded. This indicates overexploitation even in conservation areas. No individuals of *A. potatorum* were found, showing the overexploitation of the resource and thus reinforces the need of a strategy for the conservation of *Agave* in the region. The implementation of strategies proposed for each of the links in the *Agave*-mezcal chain will allow to move towards a process of sustainable elaboration of mezcal, through its entire value chain, from the cultivation of *Agave* to the commercialization of the distillate. The organization of mezcal producers and mezcal masters, the integration of relevant actors, as well as the analysis of ecological, economic and social viability of the production-consumption system in each region are of great importance.

**Acknowledgements**

This research was possible thanks to the support of the Center for Research in Native Plants (CIPNA)-UPAEP, the Municipal Presidency of San Diego La Mesa Tochimiltzingo and the Mezcal Masters of Tepenahuazo.

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