

Production of *Agave* spp. and Mezcal

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ABSTRACT

Objective: To generate information on the production systems of *Agave* spp. and mezcal in the state of Oaxaca.

Design/methodology/approach: Surveys were conducted with *Agave* spp. and mezcal producers in the Central Valleys and Sierra Sur regions of Oaxaca, which are key areas for this activity. The municipalities with the largest cultivated areas and highest production levels were selected. The survey, consisting of 40 questions, covered producer information, production systems, product characteristics, and main challenges.

Results: Agave and mezcal producers in Oaxaca represent a wide range of ages, from young to older adults. The cultivated area varies considerably, with an average of 4.96 hectares per producer. Although at least seven *Agave* species are used, mezcal production is primarily concentrated on four: *A. angustifolia*, *A. potatorum*, *A. karwinskii*, and *A. americana* var. *oaxacensis*. Notably, more than 83% of mezcal is produced through artisanal methods, while the remainder is obtained using ancestral techniques.

Limitations of the study/implications: The findings underscore the need for improved planning of *Agave* cultivation, greater genetic diversification of plants, and strengthened phytosanitary control. Investment in infrastructure and capacity building is also necessary to enhance mezcal production while preserving its traditional identity.

Findings/conclusions: In the Central Valleys and Sierra Sur regions of Oaxaca, Agave and mezcal producers differ in age and educational background. Intensive and poorly planned cultivation practices generate economic uncertainty. Traditional mezcal production faces limitations related to infrastructure, pests, diseases, and loss of genetic diversity, all of which affect the sustainability of the production system.

Keywords: *A. americana* var. *oaxacensis*, ancestral, artisanal, genetic diversity, productivity.



INTRODUCTION

The genus *Agave* L., commonly known as maguey, belongs to the family Asparagaceae, subfamily Agavoideae (APG III, 2009; APG IV, 2016). It is native to the American continent, with a distribution range extending from the southern United States to Colombia and Venezuela (García-Mendoza, 2007). This genus comprises approximately 210 species, of which 159 are found in Mexico (García-Mendoza *et al.*, 2019). In Mexico, *Agave* species occur in more than 75% of the national territory, at elevations ranging from sea level to 3,400 m a.s.l., although they are most common between 1,000 and 2,000 m a.s.l. (García-Mendoza, 2007).

Mexico is recognized as the geographical center of origin and diversification of maguey plants, as these species were among the first to be utilized by Mesoamerican civilizations (García-Mendoza, 2007).

Since ancient times, *Agave* species have represented an invaluable resource and will continue to do so due to the wide range of benefits they offer and the diversity of products derived from them (Altieri and Nicholls, 2008). For these reasons, they are considered keystone species (Hernández-Hernández *et al.*, 2014), with both economic and cultural importance for past and present societies in Mexico (Arzaba-Villalba *et al.*, 2023).

Maguey exhibits a remarkable diversity of uses, including human and animal food, beverage production, medicinal applications, fuel, ornamental purposes, fiber extraction, fertilizers, and construction materials (García-Mendoza, 2007). It is also employed for soil stabilization, erosion prevention, and combating desertification (García-Moya *et al.*, 2011), and it has the capacity to adsorb lead (Romero-González *et al.*, 2007). From a chemical perspective, maguey is notable for the variety of compounds it contains, with saponins and sapogenins being particularly important (Jean-François *et al.*, 2024).

Agave species are of industrial importance, as they are used to produce distilled beverages such as mezcal (Zárate-Martínez *et al.*, 2024), although they are more widely known for tequila production (Jean-François *et al.*, 2024). In the state of Oaxaca, Mexico, at least ten *Agave* species are used for mezcal production (García-Mendoza, 2018). Mezcal is a traditional beverage obtained from the sugars contained in the *Agave* stem, known as the “piña,” which is harvested when the plant reaches its maximum weight and size (Torres *et al.*, 2013). The organoleptic characteristics of mezcal are primarily determined by the *Agave* species, the production process, and the region of origin (Hernández, 2017).

The main *Agave* species used for mezcal production include: *Agave angustifolia* Haw. (cultivated), *Agave rhodacantha* Trel. (semi-cultivated), *Agave potatorum* Zucc. (semi-cultivated), *Agave seemanniana* Jacobi (wild), *Agave marmorata* Roezl (wild), *Agave karwinskii* Zucc. (wild), *Agave americana* L. var. *americana* (semi-cultivated), and *Agave americana* L. var. *oaxacensis* Gentry (wild) (García-Mendoza, 2010).

Oaxaca hosts the greatest diversity of *Agave* species in Mexico, with 38 species, 13 of which are endemic (García-Mendoza, 2018). These species occur under different management conditions: some are cultivated, others semi-cultivated, and others remain in the wild (García-Mendoza, 2010). Despite the biological, cultural, and economic importance of *Agave* in the region, there are currently no studies detailing the area dedicated to the production of each species. The Agricultural and Fisheries Information Service (SIAP,

for its acronym in Spanish) reported that in 2024, 11,774 ha in Oaxaca were allocated to *Agave* production, without specifying the species (SIAP, 2024). Meanwhile, the Mexican Mezcal Regulatory Council (COMERCAM) reported that in 2024, mezcal with 45% Alc. Vol. reached a production volume of 10,305,729 L, of which 97.01% corresponded to the artisanal category and 85.25% was produced using maguey espadín (*Agave angustifolia*) (COMERCAM, 2025). It is important to note that the data provided by COMERCAM do not include producers not affiliated with the organization.

The study hypothesized that there are no significant differences in management, use, or cultivated area among the different *Agave* species in Oaxaca. Accordingly, the objective of this study was to generate information on the production systems of *Agave* and mezcal in Oaxaca.

MATERIALS AND METHODS

Study Area

The study was conducted in the state of Oaxaca, Mexico, one of the regions with the highest diversity of *Agave* species in the country. The research focused on two key regions: the Central Valleys and the Sierra Sur, due to their importance in *Agave* and mezcal production.

Identification of Representative Municipalities

In 2022, surveys were conducted with *Agave* and mezcal producers in Oaxaca. Municipalities were selected based on those with the largest areas allocated to *Agave* cultivation, according to SIAP (2021), and those with the highest mezcal production, according to Martínez (2017) (Table 1).

Table 1. Municipalities with the highest *Agave* and mezcal production in the state of Oaxaca, Mexico.

Region	District	Municipality	Surveys Conducted
Valles Centrales	Tlacolula	San Pedro Quiatoni	10
Valles Centrales	Tlacolula	Tlacolula de Matamoros	9
Valles Centrales	Tlacolula	San Donisio Ocotepc	4
Valles Centrales	Tlacolula	San Lorenzo Albarradas	4
Valles Centrales	Tlacolula	Santiago Matatlán	4
Valles Centrales	Tlacolula	San Juan Guelavia	2
Valles Centrales	Ejutla	San Agustín Amatengo	5
Valles Centrales	Ejutla	Heroica Ciudad de Ejutla de Crespo	4
Valles Centrales	Ejutla	La Compañía	3
Valles Centrales	Ocotlán de Morelos	San Baltazar Chichicápam	3
Sierra Sur	Miahuatlán	San Luis Amatlán	10
Sierra Sur	Miahuatlán	San Francisco Logueche	2
Sierra Sur	Miahuatlán	Sitio de Xitlapehua	1
Sierra Sur	Yautepec	Nejapa de Madero	9
Sierra Sur	Sola de Vega	Villa Sola de Vega	3

Sampling

In each municipality, the sample size was determined using the methodologies proposed by Aguilar-Barojas (2005) and Rojas (2013), applying Equation 1. As a result, a sample of 73 producers was obtained, and surveys were administered across 15 different municipalities.

$$n = \frac{\frac{Z^2 p_n q}{d^2}}{1 + \frac{Z^2 p_n q}{Nd^2}}$$

Where: Z =Confidence level (95%); d =Precision level (10%); p_n =Proportion of the population belonging to the group of interest (0.8); $q=(1-p_n)=0.2$; N =Population size; n =Sample size.

Structure and Content of the Survey Administered to Agave and Mezcal Producers

The survey administered to *Agave* and mezcal producers consisted of 40 questions, organized into four sections: (a) general information of the producer, (b) description of production systems, (c) product characteristics, and (d) main issues in production systems. The questions included in each section were as follows:

- a) **General information of the producer:** age, education level, and family members.
- b) **Description of production systems:** land area (ha), number of plants per producer, planting density (plants ha⁻¹), and number of species in production.
- c) **Product characteristics:** *Agave* weight (kg), *Agave* age (years), sugar content (°Brix), number of plants per producer, sale price of *Agave* in 2021 (MXN \$ kg⁻¹), mezcal presentation, whether the mezcal is certified, annual mezcal production volume, sale price of mezcal in 2021 (MXN \$ L⁻¹), and market.
- d) **Main issues in production systems:** problems in *Agave* production and problems in mezcal production.

Data Analysis

A database was created using Excel[®] version 16. For the statistical analysis, a descriptive analysis was conducted, and the following were calculated: a) Measures of central tendency: mean (the average value of a set of numerical data), median (the middle value of an ordered dataset from smallest to largest), and mode (the value that occurs most frequently within a dataset). b) Measures of dispersion: range (the difference between the largest and smallest values), variance, standard deviation (SD), and coefficient of variation (CV).

Variance was calculated using Equation 2.

$$S^2 = \frac{\sum (x_i - \bar{x})^2}{n - 1}$$

Where: S^2 =variance; \sum =summation; x_i =value of the i -th observation of variable x ; \bar{x} =mean value of variable x ; n =sample size.

The standard deviation (SD) was determined using Equation 3.

$$S = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n - 1}}$$

Where: S =SD.

The coefficient of variation (CV) was calculated using Equation 4.

$$CV = \frac{S}{\bar{x}} * 100$$

Where: S =SD; \bar{x} =mean value of variable x .

RESULTS AND DISCUSSION

General Information of Producers

The measures of central tendency for the general information of *Agave* and mezcal producers indicate that the mean age of the producers was 48.3 years, the median was 48 years, and the mode was 50 years. Regarding education, the mean was 9.11 years, corresponding to the completion of secondary school. The mean family size was 3.98 members, with a mode of 5 members (Table 2).

The measures of dispersion for the general information of producers indicate that the age range was 53 years, with a standard deviation (SD) of 12.15 years and a coefficient of variation (CV) of 25.16%. Regarding education, the range was 24 years with a CV of 52.51%. The family size ranged by 6 members, with a CV of 37.95% (Table 2).

Agave and mezcal producers belong to different age groups, ranging from young adults (18-44 years), through middle-aged adults (45-59 years), to older adults (60-74 years). The average age of the producers interviewed in this study aligns with the findings of Cuevas *et*

Table 2. Measures of central tendency and dispersion for the general information of producers.

Variable	Mean	Median	Mode	Range	SD	CV
Age (years)	48.3	48	50	53	12.15	25.16
Education (years)	9.11	9	9	24	4.78	52.51
Family members	3.98	4	5	6	1.51	37.95

SD=Standard deviation; CV=Coefficient of variation.

al. (2019), who surveyed three different groups of *Agave* producers in Oaxaca and reported mean ages of 47.7, 51.1, and 60.7 years. Similarly, Reyes-Terrazas *et al.* (2023) conducted a study in Cuautlacingo, Otumba, State of Mexico, where they interviewed nopal producers and found mean ages of 41 and 50 years for two groups of producers. These results reflect consistency in the ages of agricultural producers across the country. This is further supported by the coefficient of variation for age (25.16%), indicating high homogeneity among *Agave* and mezcal producers.

Regarding education, the mean, median, and mode indicate that the producers have completed secondary school; however, the CV of 52.51% indicates a high level of heterogeneity.

Authors such as Antonio and Ramírez (2008) interviewed small *Agave* producers in the state of Oaxaca and reported a mean education level of 5.2 years (incomplete primary education), which is 3.8 years lower than that reported in this study. The age and educational level of producers are key factors that influence their cultivation methods and their capacity to adopt new technologies (Borja-Bravo *et al.*, 2016). A higher level of education facilitates access to updated information and the incorporation of technological innovations into production practices (Chilonda and Van Huylenbroeck, 2001).

Academic training influences not only the efficiency of production processes but also the willingness of producers to adopt new techniques and tools that contribute to improving the quality and sustainability of production. Characterizing producers and their educational level allows for a better understanding of production systems and is key for designing policies and strategies that promote the improvement and adaptation of their practices in response to sectoral challenges (Cuevas *et al.*, 2019).

The average number of family members refers to those who directly participate in activities related to *Agave* and mezcal production. In this study, this average was lower than that reported by Hernández *et al.* (2022), who found an average of five members. This factor is crucial, as family labor is primarily responsible for productive tasks. Antonio *et al.* (2015) noted that most *Agave* producers in the region do not hire external labor, relying instead on family workforce. Analyzing this indicator is essential for understanding labor dynamics within production units and for designing strategies to optimize the use of family resources in *Agave* and mezcal production.

Description of Production Systems

The area dedicated to *Agave* production varies among producers, with a mean of 4.96 ha, a median of 3.0 ha, and a mode of 3.0 ha. Planting density depends on factors such as the species cultivated, land slope, and crop management practices; however, in this study, the mean density was 1,744.52 plants ha⁻¹, the median was 1,225 plants ha⁻¹, and the mode was 1,000 plants ha⁻¹. Producers reported having plants of different ages, and considering all age classes, the mean number of plants per producer was 6,977.78, with a mode of 2,000 plants. The number of *Agave* species managed by producers varied, with a mean of 2.69 species, although the mode was only one species (Table 3).

According to the measures of dispersion, the range of area dedicated to *Agave* production was 19 ha, with a CV of 93.96%, indicating high variability. The range of planting density

was 3,666 plants ha⁻¹, with a CV of 67.99%, reflecting heterogeneity in these data. The range of plants per producer was 37,000, with a CV of 128.89%, indicating high variability in the number of plants per producer. Regarding the number of species, the range was 4 species, with a CV of 60.45%, indicating heterogeneity in these data. This is further evidenced by the mode, median, and mean, which were 1, 2, and 2.69 species, respectively (Table 3).

Production systems in the state of Oaxaca are heterogeneous. The maguey-mezcal production system in Oaxaca identified four types of *Agave* producers in 2013: (a) subsistence producers, with up to 3 ha under cultivation; (b) small-scale producers, cultivating between 3 and 6 ha; (c) medium-scale producers, with 6 to 22 ha under cultivation; and (d) large-scale producers, managing more than 22 ha (Hernández *et al.*, 2022). Years later, Martínez (2017) reported the percentages of each producer category: subsistence producers accounted for 68.2%, small-scale producers for 19.7%, medium-scale producers for 10.8%, and large-scale producers for 1.4%. In this study, 70.37% of *Agave* producers manage 3 ha or less, which aligns with Martínez (2017) and confirms that the majority of *Agave* producers are subsistence farmers. However, it is important to note the ongoing need to increase the area dedicated to *Agave* production (Zárate-Martínez and Rodríguez-Hernández, 2022) due to growing demand for raw material.

Planting density in *Agave* production is highly variable and depends on factors such as the species cultivated, the type of system (monoculture or polyculture), the use of machinery, land slope, and the intended purpose of the production. In Oaxaca, up to 94.3% of producers practice intercropping, combining *Agave* with maize and beans (Cuevas *et al.*, 2019). Cruz *et al.* (2013) reported that the planting density of *A. angustifolia* ranges from 1,500 to 2,200 plants ha⁻¹, which is consistent with the mean of 1,744.52 plants ha⁻¹ found in this study. However, given that the range was 3,666 plants ha⁻¹, the high heterogeneity of *Agave* production systems in Oaxaca can be inferred.

In the municipality of Villa Sola de Vega, Oaxaca, 60% of producers collect, propagate, or plant more than one *Agave* species (Ríos-Colín *et al.*, 2022); in other words, most producers manage more than one species. This aligns with the findings of this study, in which the mean number of species per producer was 2.69, with a range of 4 species. However, Hernández *et al.* (2022) concluded that most *Agave* producers in Oaxaca cultivate only a single species. This was common prior to the mezcal boom; subsequently, some producers sought to diversify and cultivate more than one *Agave* species. The producers interviewed in this study utilize at least seven *Agave* species (Table 4).

Table 3. Measures of central tendency and dispersion for the characteristics of *Agave* production systems.

Variable	Mean	Median	Mode	Range	SD	CV
Size of land (ha)	4.96	3	3	19	4.66	93.96
Density (plants ha ⁻¹)	1,744.52	1,225	1,000	3,666	1,186.12	67.99
Plants per producer	6,977.78	3,000	2,000	37,000	8,993.95	128.89
Number of species	2.69	2	1	4	1.62	60.45

SD=Standard deviation; CV=Coefficient of variation.

Hernández *et al.* (2022) identified the main *Agave* species cultivated in Oaxaca as *Agave angustifolia*, *A. rhodacantha*, *A. potatorum*, *A. karwinskii*, *A. marmorata*, and *A. convallis*, which aligns with the results of this study. Among these, *A. angustifolia* is the most preferred by producers due to its agronomic advantages. According to Cuevas *et al.* (2019), this species has a short growth cycle, produces large piñas, and generates a high number of pups or hijuelos. The producers interviewed highlighted that the size of the piñas allows for higher yields and, consequently, greater income.

Few producers utilize *A. lyobaa* due to its restricted distribution of less than 10,000 km², classifying it as a microendemic species. In addition, its medium size, with stems approximately 80 cm in height (García-Mendoza *et al.*, 2019), limits its use. In Oaxaca, small *Agave* producers have experienced changes in their cultivation and marketing practices driven by the increased consumption of mezcal (González *et al.*, 2023).

In 2019, production was expanding, with the reactivation of land and adaptation of traditional techniques to meet growing demand. However, the current scenario shows an oversupply of *Agave* relative to demand, which could create imbalances in the *Agave*-mezcal production chain.

Product Characteristics

When comparing the weight of the piñas of *A. americana* var. *oaxacensis*, *A. angustifolia*, *A. karwinskii*, and *A. potatorum*, it was observed that *A. americana* var. *oaxacensis* had the heaviest piñas, with a mean weight of 130 kg. This was followed by *A. angustifolia* at 83.75 kg, while *A. potatorum* had the lightest piñas, with a mean weight of 44.17 kg (Table 5).

Agave angustifolia is harvested at an average age of 7.19 years, when it reaches a sugar content of 33.09 °Brix, and in 2021 its price was MXN \$9.37 kg⁻¹. For *A. karwinskii*, producers harvest at 8.63 years, with an average sugar content of 22.67 °Brix. *A. potatorum* is harvested at 8.33 years, reaching 25 °Brix. Finally, *A. americana* var. *oaxacensis* is harvested at 8.8 years, although producers did not report sugar content data.

Agave angustifolia is the most widely cultivated species in the state of Oaxaca, as all surveyed producers grow it, with a mean of 28,855 plants per producer. This is followed by *A. potatorum*, with a mean of 10,683 plants, and *A. americana* var. *oaxacensis*, cultivated by 18.6% of producers, with a mean of 6,400 plants. Finally, *A. karwinskii* has a mean of 4,875 plants per producer.

Table 4. Main *Agave* species utilized by producers.

Species	%	Species	%
<i>A. angustifolia</i>	100	<i>A. karwinskii</i>	35.6
		<i>A. potatorum</i>	23.7
		<i>A. americana</i> var. <i>oaxacensis</i>	18.6
		<i>A. rhodacantha</i>	11.9
		<i>A. marmorata</i>	6.8
		<i>A. lyobaa</i>	3.4

According to the coefficients of variation, the variables evaluated for different *Agave* species show varying levels of dispersion. For *A. angustifolia*, the CV for piña weight was 29.68, for harvest age 19.50, for sugar content 16.36, and for sale price 16.92, indicating relative homogeneity of the data and representative means. In *A. karwinskii*, piña weight and harvest age had CVs of 28.59 and 26.91, respectively, also suggesting that the means are representative. Sugar content showed lower variability (CV=10.83) with a range of 5 °Brix.

In contrast, for *A. potatorum*, both sugar content (CV=34.64) and harvest age (CV=36.13) show high dispersion, indicating heterogeneous data and a non-representative mean. Finally, *A. americana* var. *oaxacensis* exhibited a CV of 24.77 for harvest age, suggesting homogeneity and a reliable mean (Table 5).

A. angustifolia exhibits notable morphological diversity, evidenced by the wide variation in piña weight. According to Cruz *et al.* (2013), piñas can weigh between 31 and 133 kg, with a mean of 80.87 kg and an average total reducing sugar (TRS) content of $21.16\% \pm 3.15$. Despite this variability, producers do not consider it problematic, as they prioritize piñas with high sugar content, typically those older than six years. For mezcal production, piñas with sugar concentrations above 35 °Brix are preferred, ensuring the

Table 5. Measures of central tendency and dispersion for the characteristics of *Agave* piñas marketed.

Variable	Mean	Median	Mode	Range	SD	CV
<i>A. angustifolia</i>						
Weight (kg)	83.75	80	60	90	24.85	29.68
Age (years)	7.19	7	7	6	1.40	19.50
Sugar content (°Brix)	33.09	35	35	17	5.41	16.36
Plants per producer	28855	11000	3000	198000	41124.17	142.52
Price 2021 (\$ kg ⁻¹)	9.37	9	10	8	1.58	16.92
<i>A. karwinskii</i>						
Weight (kg)	75.63	80	80	75	21.62	28.59
Age (years)	8.63	9.50	6	6	2.33	26.97
Sugar content (°Brix)	26.67	25	25	5	2.89	10.83
Plants per producer	4875	4000	2000	8000	3399.05	69.72
<i>A. potatorum</i>						
Weight (kg)	44.17	35	35	70	27.46	62.18
Age (years)	8.33	7.5	12	7	3.01	36.13
Sugar content (°Brix)	25	30	30	15	8.66	34.64
Plants per producer	10683	5750	3000	39400	14804.11	138.57
<i>A. americana</i> var. <i>oaxacensis</i>						
Weight (kg)	130	100	100	230	73.45	56.50
Age (years)	8.8	8	8	2	2.18	24.77
Sugar content (°Brix)	S/D	S/D	S/D	S/I	S/I	S/I
Plants per producer	6400	2000	2000	19000	10311.86	161.12

SD=Standard deviation; CV=Coefficient of variation.

desired quality and product profile. *A. angustifolia* is the most commonly commercialized species for this purpose.

Agave prices are highly variable, primarily due to a lack of planning in its production. Producers often establish their plantations based on market prices, creating cycles of oversupply and scarcity. For example, the average price of *Agave* decreased from MXN \$9.37 kg⁻¹ in 2021 to only MXN \$3.00 kg⁻¹ in 2024. This price volatility is particularly significant, as producers must wait up to six years to recover their investment and achieve profits.

To reduce the risk associated with purchasing raw material, local buyers often personally select the piñas, ensuring they meet the required maturity and quality standards. According to Vega and Pérez (2017), this practice is key to guaranteeing a high-quality final product and fair compensation for producers. In this context, market dynamics and personalized purchasing highlight the need for strategic planning in both production and marketing of *Agave*. The ability to adapt to market fluctuations and secure high-quality raw material is fundamental for the sustainability and profitability of the sector.

Cruz *et al.* (2013) reported that the piñas of *A. karwinskii* weighed between 8 and 57 kg, values lower than those obtained in this study, where the mean weight was 75.63 kg. Various authors have highlighted the cultural and ecological importance of this species, as well as its notable morphological diversity, reflected in the complex traditional nomenclature used to describe its variants (Vázquez-Pérez *et al.*, 2020). According to Martínez-Jiménez *et al.* (2019), *A. karwinskii* piñas reach weights between 35.39 and 57 kg over approximately 12 years, with total reducing sugar (TRS) concentrations ranging from 19.20% to 27.29%.

A. potatorum is highly valued by the mezcal industry due to its high sugar content, being even more profitable than *A. angustifolia* (Hernández *et al.*, 2022). Although it is a small wild species, with piñas of approximately 9.27 kg that reach maturity in 6.33 years and have a TRS content of 20.10% (Martínez-Ramírez *et al.*, 2013), the data from this study differ from these reports, as producers indicated a higher mean weight of 44.17 kg and maturity reached at 8.33 years.

Regarding *A. americana* var. *americana*, Lira *et al.* (2009) reported piñas weighing 49.67 kg, reaching maturity at 5 years, with a TRS content of 25.87%. However, in this study, a much higher mean weight of 130 kg was observed. Additionally, Guerrero *et al.* (2023) documented an anomaly in this species, consisting of a double floral stalk, possibly caused by an autosomal mutation or apical damage from insects or pathogens. This condition was not observed among the producers interviewed.

In Oaxaca, mezcal is produced from *A. marmorata*; however, none of the producers interviewed in this study reported using this species, possibly due to its long life cycle. Jiménez-Valdés *et al.* (2010) noted that *A. marmorata* is common in small-scale rural economies because of its large size and the possibility of obtaining up to 5 L of mezcal per plant. Nevertheless, its maturation can take up to 35 years, making it a highly long-lived species (Nogales, 2017). This information could not be confirmed in the present study.

Agave production is carried out primarily using traditional methods and knowledge transmitted across generations (González *et al.*, 2023). The recent increase in demand has raised prices, attracting new actors, particularly young people interested in cultivation as

an economic opportunity. According to González *et al.* (2023), this interest aims not only to capitalize on the market but also to prevent potential shortages. However, an oversupply of *Agave* is currently observed, creating imbalances in production systems and challenging the resilience of producers, defined as their capacity to adapt to change without losing their structure or identity (Cinner and Barnes, 2019).

In the Miahuatlán district of Oaxaca, *Agave* production is closely linked to mezcal production (Cuevas *et al.*, 2019). Although this relationship has been common throughout the state, in recent years external buyers outside the *Agave*-mezcal chain have emerged, encouraging the entry of new producers and the expansion of cultivated areas. This dynamic has created an imbalance between supply and demand, resulting in overproduction, price drops, and social conflicts, including job losses. The rapid expansion of the mezcal market, both nationally and internationally, has put pressure on the adaptive capacity of the production system and small-scale producers. González *et al.* (2023) also emphasize that these changes pose a significant challenge to the resilience of the *Agave* sector in Oaxaca.

Throughout Oaxaca, there has been a notable increase in the area dedicated to *Agave* cultivation, with plantations now visible even in non-traditional zones, such as along road margins. According to SIAP data (2024), between 2018 and 2023, the cultivated area increased by 44.88%, from 8,100 to 11,736 ha. During the same period, production rose by 162%, from 97,777 to 256,549 t. This growth suggests improvements in production systems, reflected in more efficient land use, higher planting densities, better yields, and increased investment.

The limited financial capacity of producers hinders the expansion and intensification of cultivation to meet growing demand (González *et al.*, 2023). Nevertheless, over the past five years, the average yield has increased by 12.88% (COMERCAM, 2024), and more plantations than necessary to meet market demand have been established. Toledo *et al.* (2020) caution about the uncertainty in the adaptive capacity of the *Agave*-mezcal value chain in Oaxaca and the risk of raw material shortages, which could negatively affect mezcal producers. Currently, the first effects of oversupply are already being observed; however, producers are learning to interpret market signals and rely on their experience, allowing them to anticipate changes and adapt to the new context (Young *et al.*, 2006).

Eighty-four percent of producers sell their mezcal in bulk, 10% in bottles, and 6% offer both options depending on customer demand. Regarding certification under NOM-070-SCFI-2016 (2017), 68% indicated that their mezcal is not certified, as their market is local and customers value flavor over certification; only 32% of producers hold certification. Currently, five recognized certification bodies operate in the mezcal sector: the Asociación de Maguey y Mezcal Artesanal A.C. (AMMA), the Centro de Innovación y Desarrollo Agroalimentario de Michoacán A.C. (CIDAM), Certificación Mexicana S.C. (CMX), the Consejo Mexicano Regulador de la Calidad del Mezcal A.C. (COMERCAM), and Verificación y Certificación PAMFA A.C. (PAMFA). Historically, COMERCAM was the sole certifying body, playing a key role in standardizing and regulating the sector. The emergence of new certifiers has diversified and enhanced the process, providing more specialized and comprehensive evaluations that help ensure the authenticity and quality of mezcal.

Most producers sell their mezcal in bulk and are not motivated to obtain certification, as they do not perceive clear benefits. Furthermore, older producers often reject the idea of engaging with external organizations for certification. Certification faces several challenges, as it is viewed more as an expense than an investment, increasing production costs. Toledo *et al.* (2020) note that producers perceive COMERCAM more as a revenue-collecting entity than as an agent that promotes development, supervises compliance with NOM-070-SCFI-2016, or contributes to value creation.

Mezcal is primarily produced from four species: *A. angustifolia*, *A. potatorum*, *A. karwinskii*, and *A. americana* var. *oaxacensis* (Table 6). More than 83% is produced using artisanal methods, while the remainder is made using ancestral techniques. The average annual production per producer is 2,359 L for *A. angustifolia*, 537 L for *A. potatorum*, 456 L for *A. karwinskii*, and 322 L for *A. americana* var. *oaxacensis*. Mezcal from *A. potatorum* commands the highest price, with an average of MXN \$248 L⁻¹, followed by *A. karwinskii* at MXN \$241 L⁻¹, while the most affordable is from *A. angustifolia* at MXN \$214 L⁻¹.

Measures of dispersion reveal high variability in annual mezcal production among producers. The production ranges by species were as follows: *A. angustifolia* (29,940 L), *A. potatorum* (1,900 L), *A. karwinskii* (4,940 L), and *A. americana* var. *oaxacensis* (950 L) (Table 7), with CVs of 253.27%, 112.92%, 219.01%, and 205.55%, respectively, indicating the high variability in mezcal production capacity among the producers surveyed.

Mezcal production in Oaxaca involves at least eight species and seventeen varieties of *Agave*, both wild and cultivated (Cuevas *et al.*, 2019). However, *A. angustifolia* accounts for the majority of production, despite not being endemic to the region (Vega and Pérez, 2017). Beyond its economic value, *Agave* and mezcal production represents a practice deeply rooted in cultural identity, passed down from generation to generation (Antonio and Terán, 2008).

In 2023, 86.31% of mezcal produced in Mexico was made from *A. angustifolia*, followed by *A. potatorum* at 2.42%, data that align with the results of this study (COMERCAM, 2024). Mezcal from *A. potatorum* is highly valued by consumers, and its price can be up to 300% higher than that of other species (Martínez-Ramírez *et al.*, 2013). The flavor of mezcal varies depending on the species used, due to differences in volatile aromatic compounds (Vera-Guzmán *et al.*, 2010).

Most of the producers interviewed indicated that mezcal is primarily marketed at the local and regional levels, together accounting for 66.7% of sales (40% local and 26.7%

Table 6. Measures of central tendency for mezcal production and sale prices.

Species	Type of mezcal: arte-sanal/ancestral (%)	Production (L/year)	Price 2021 (\$/L)
<i>A. angustifolia</i>	96.5 / 3.5	2,359 / 500 / 500	21.21 / 200 / 200
<i>A. potatorum</i>	89 / 11	537 / 350 / 300	248.49 / 250 / 250
<i>A. karwinskii</i>	100 / 0	456 / 200 / 100	239.62 / 250 / 200
<i>A. americana</i> var. <i>oaxacensis</i>	83 / 17	322 / 200 / 250	216.04 / 200 / 200

Mean / Median / Mode.

Table 7. Measures of dispersion for mezcal production and sale prices.

Species	Mezcal: artesanal/ ancestral (%)	Variable	Range	Variance	SD	CV
<i>A. angustifolia</i>	96.5 / 3.5	Producción*	29,940	35,706,266	5,975	253.3
		Precio ⁺	200	1,949.54	44.15	482.9
<i>A. potatorum</i>	89 / 11	Producción	1,900	368,392.86	606.95	112.9
		Precio	200	2,007.30	44.8	554.6
<i>A. karwinskii</i>	100 / 0	Producción	4,940	999,107.33	999.55	219
		Precio	180	2,205.62	46.96	510.2
<i>A. americana</i> var. <i>oaxacensis</i>	83 / 17	Producción	950	438,054.44	661.86	205.6
		Precio	170	892.13	29.86	723.3

*=L year-1, ⁺= $\$ L^{-1}$, SD=Standard deviation, CV=Coefficient of variation.

regional). Only 16.7% is sold nationally, and a small proportion is exported. Regarding Agave, 90% is destined for the local market and 10% for the regional market. *Agave* buyers are mainly from the region and primarily act as intermediaries to distribute it to other states in the country. In Oaxaca, the *Agave*-mezcal value chain is key due to its impact on employment generation. In 2023, national mezcal production reached 12.2 million liters, of which 90.5% (11.07 million liters) was produced in Oaxaca. Of this amount, 8.32 million liters were bottled, and approximately 5.75 million liters were destined for export (COMERCAM, 2024).

Main problems in production systems

Thirty-nine point six percent of the producers interviewed reported that the primary issue in *Agave* production is pest control, particularly the agave weevil (*Scyphophorus acupunctatus* Gyllenhal). Most producers combat this pest primarily using fipronil. In second place, 38.4% identified diseases as a significant concern (Figure 1). *S. acupunctatus* is considered the most severe and important pest affecting commercial *Agave* species (Arista-Carmona *et al.*, 2023), as it substantially limits production (González *et al.*, 2007).

Agave distilled product production in Mexico has grown exponentially in recent years (Arellano-Plaza *et al.*, 2022), creating pressure on wild populations, loss of natural vegetation, and intensification of agricultural management (Lira *et al.*, 2022). Among the producers interviewed, intensive production and asexual reproduction through pups or hijuelos are commonly used to shorten the cultivation cycle. However, clonal propagation carries risks such as the accumulation of deleterious mutations, loss of genetic diversity, and an increased pathogen load (Lian *et al.*, 2019).

Although some studies have identified a certain degree of genetic variability in asexual reproduction (García-Mendoza, 2007), *Agave* species generally combine sexual and asexual reproduction, a strategy that favors their survival in harsh environments (Arizaga and Ezcurra, 2002). Genetic diversity is fundamental for biodiversity at all levels (Frankham *et al.*, 2010), and in agaves, hybridization, polyploidy, and vegetative reproduction are key evolutionary mechanisms (García-Mendoza, 2007). However, the

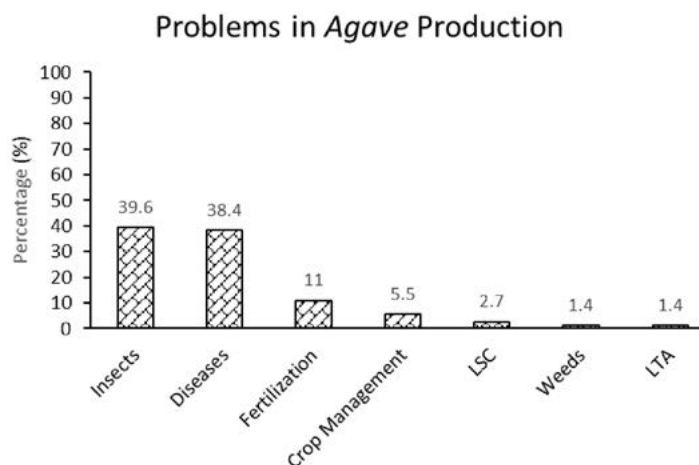


Figure 1. Main problems affecting Agave production. LSC: Low Sugar Content; FdAT LTA: Lack of Technical Assistance.

producers interviewed reported that they do not use seeds to establish new plantations, relying solely on pups or hijuelos from their existing crops.

The mode of reproduction in *Agave*, whether sexual or asexual, directly influences its genetic diversity. In the case of *A. angustifolia*, a key species in mezcal production in Oaxaca, understanding its genetic variation and population structure is essential for its conservation, sustainable management, and assessment of the impact of domestication (Klimova *et al.*, 2023). However, due to high demand, many plants do not reach the flowering stage, thereby limiting sexual reproduction. *A. angustifolia* is a diploid, self-incompatible species capable of both sexual and asexual reproduction and is pollinated by bats (*Leptonycteris*), birds, and bees (Rivera-Lugo *et al.*, 2018; Molina-Freaner and Eguiarte, 2003). However, the producers interviewed indicated that asexual reproduction via pups or hijuelos is the only method employed, suggesting low genetic and morphological diversity. This reduction is common in domesticated species, where artificial selection and genetic drift decrease variability (Doebley *et al.*, 2006; Khoury *et al.*, 2021).

In this context, it is necessary to implement conservation and genetic improvement strategies. Some producers reported the extraction and theft of wild *Agave*, which exacerbates the loss of diversity. This situation is particularly critical for species such as *A. potatorum*, which reproduces only by seed and whose flowering is often interrupted before completion, with no conservation measures in place (Ríos-Colín *et al.*, 2022). Genetic diversity, in both wild and cultivated species, is essential for the future of cultivation, adaptation to climate change, and pest management (Allendorf *et al.*, 2022; Swarup *et al.*, 2021).

The development of a sustainable mezcal industry requires the active participation of local communities, informed management based on data from both wild and cultivated *Agave*, and, eventually, the implementation of environmental regulations (Klimova *et al.*, 2023). Currently, the absence of a sustainable management plan places several *Agave* species at risk (Zárate-Martínez *et al.*, 2024). To conserve genetic resources, it is essential

to promote both *in situ* and *ex situ* preservation and to encourage the use of germplasm collections (seeds or nurseries), taking into account local cultural, ecological, and climatic factors. The use of a limited genetic pool increases the vulnerability of cultivation to diseases, pests, and climate change (Klimova *et al.*, 2023).

The growing demand for *Agave* has led producers to expand cultivation areas, integrate into other stages of the agave-mezcal value chain, form new organizations, adopt modern communication methods, and enter into lease agreements for communal lands (González *et al.*, 2023). As early as 2015, it was reported that several wild species, such as tepeztate (*A. marmorata*), arroqueño (*A. americana* var. *oaxacensis*), coyote, and sierrudo (*A. americana*), were at risk due to overexploitation (Ríos-Colín *et al.*, 2022). A total of 67.6% of producers indicated that the main limitation in mezcal production is the lack of infrastructure, while 29.4% identified low production capacity, primarily attributed to difficulties in adapting to climatic conditions. These factors are closely related, as insufficient infrastructure is often the direct cause of limited production capacity (Figure 2).

Mezcal production is experiencing an unprecedented boom, driven primarily by the growth of the international market, with a sustained increase of nearly 40% (Zárate-Martínez and Rodríguez-Hernández, 2022). However, producers acknowledge that their infrastructure is insufficient to meet current demand. This rapid growth has generated significant environmental consequences, including the overexploitation of wild Agave, a reduction in the genetic diversity of cultivated species (Klimova *et al.*, 2023), and increasing ecological pressure on ecosystems (Zárate-Martínez *et al.*, 2024). Additionally, the production process requires large amounts of firewood, contributing to deforestation (Valiente-Banuet, 2023).

The industry also faces technical challenges, such as inefficient cooking, incomplete fermentation, limited control during distillation, and high generation of agroindustrial residues (Acosta-García *et al.*, 2023). Nevertheless, traditional agricultural systems have demonstrated a high capacity for resilience in the face of disturbances, suggesting that producers can adapt, innovate, and improve their socioeconomic conditions without losing their identity or ancestral practices (Barrientos-Rivera *et al.*, 2020).

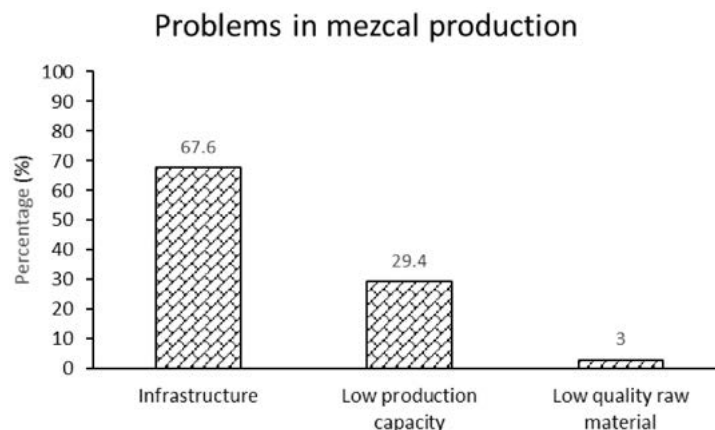


Figure 2. Main issues affecting mezcal production.

CONCLUSIONS

In the Central Valleys and Southern Sierra regions of Oaxaca, agave and mezcal producers exhibit a wide range of ages and educational levels. Agave production is carried out intensively, predominantly as monoculture, and without strategic planning, primarily responding to market fluctuations. This lack of foresight generates uncertainty regarding selling prices and affects the economic stability of producers.

Mezcal production in the region is largely carried out using traditional methods oriented toward the national market. These practices, transmitted from generation to generation, contribute to the authenticity and quality of the product, although they also face limitations due to increasing demand and insufficient infrastructure. Among the main challenges in agave production are pest and insect management, the spread of diseases, and the loss of genetic diversity associated with the extensive use of asexual reproduction and the expansion of monocultures. These factors reduce the resilience of the crop under adverse environmental conditions.

Regarding mezcal production, the main challenge is the limited production capacity of many producers, who are not always able to meet market demands in terms of volume and continuity.

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