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## ASSESSMENT OF SUSTAINABILITY IN ARTISANAL MEZCAL PRODUCTION IN SOUTHERN MEXICO: AN APPROACH BASED ON COMPOSITE INDICATORS

Xochitl Berenise Gonzales Torres<sup>1\*</sup>, Armando Luna Fuentes<sup>2</sup>, Marcos Pedro del Carmen  
Ramírez López<sup>3</sup>, Urbano Gustavo Curiel Avilés<sup>4</sup>, Eder Cristian Gopar López<sup>5</sup>, Isabel del  
Rayo Estrada Herrera<sup>6</sup>

<sup>1</sup>*Instituto Politécnico Nacional, Centro Interdisciplinario de Investigación para el Desarrollo Integral  
Regional unidad Oaxaca, México. ORCID iD: <https://orcid.org/0000-0001-9041-8870>,  
Email: [xbgt77@gmail.com](mailto:xbgt77@gmail.com)*

<sup>2</sup>*Instituto Politécnico Nacional, Centro Interdisciplinario de Investigación para el Desarrollo Integral  
Regional unidad Oaxaca, México. ORCID iD: <https://orcid.org/0000-0002-0625-9844>,  
Email: [armando.luna@live.com.mx](mailto:armando.luna@live.com.mx)*

<sup>3</sup>*Instituto Tecnológico de Oaxaca/ Tecnológico Nacional de México.  
ORCID iD: <https://orcid.org/0009-0003-8022-3924>, Email: [marcos.rl@itoaxaca.edu.mx](mailto:marcos.rl@itoaxaca.edu.mx)*

<sup>4</sup>*Universidad del Papaloapan. ORCID iD: <https://orcid.org/0000-0003-0015-8919>,  
Email: [gustavocurielaviles@gmail.com](mailto:gustavocurielaviles@gmail.com)*

<sup>5</sup>*Afiliación institucional: Doctorante del Tecnológico Nacional de México/Instituto Tecnológico de Oaxaca.  
ORCID iD: <https://orcid.org/0009-0009-1537-7103>, Email: [edercristiangopar@gmail.com](mailto:edercristiangopar@gmail.com)*

<sup>6</sup>*Investigadora Posdoctoral, Universidad Autónoma Metropolitana, Unidad Xochimilco.  
Email: <http://orcid.org/0000-0001-7625-2798>*

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Corresponding Author: Xochitl Berenise Gonzales Torres  
([xbgt77@gmail.com](mailto:xbgt77@gmail.com))

### ABSTRACT

*The objective of this study was to evaluate the sustainability of artisanal mezcal production in San Juan del Río, Oaxaca, considering the economic, social, and environmental dimensions in the face of increasing demand. The research sought to identify critical areas and propose strategies to strengthen responsible practices in the mezcal sector. The methodology was mixed, descriptive, and analytical, with a convenience sample of 29 producers. Information was collected through surveys, interviews, and direct observation. Seventeen indicators were constructed, grouped into three areas: economic (profits, market access, subsidies, certifications), social (employment, gender equity, community cohesion, job security, and intergenerational transmission of knowledge), and environmental (water use, biodiversity conservation, recycling, and biofertilizers). The results allowed us to identify three producer profiles: a) those with basic sustainable practices, focused on local markets; b) those with economic dynamism with access to diversified markets and certifications, albeit with environmental shortcomings; and c) those facing infrastructure limitations, low social cohesion, and a heavy dependence on intermediaries, which reduces their competitiveness. It is concluded that the sustainability of artisanal mezcal depends on balancing productive, social, and environmental factors, with promoting*

*strategies that integrate community management, responsible innovation, and organizational strengthening being a priority.*

**KEYWORDS:** Sustainability, Artisanal Production, Mezcal, Agave.

## 1. INTRODUCTION

The production of artisanal mezcal is an activity that combines cultural, economic, and environmental factors, representing an important source of income for rural communities. This beverage, which has a designation of origin due to its characteristics, has gained popularity in both national and international markets. On the other hand, the growth of the industry has brought problems related to sustainability, as increased demand has led to the overexploitation of natural resources such as water and soil, threatening wild agaves with extinction and affecting the biocultural heritage of mezcal-producing localities (Mercado, 2023).

In this sense, sustainability should not be evaluated solely from an economic or environmental perspective, but also from a social perspective, through three dimensions: environmental integrity, economic resilience, and social well-being, with the aim of finding areas that allow for more sustainable production. Artisanal mezcal production in Oaxaca is not just an economic activity, much less a passing fad; it is a living fabric where family memories, trades passed down in courtyards and palenques, and fragile ecosystems that sustain the agave and those who care for it rest on community practices, agricultural times, and territorial agreements that rarely fit on a spreadsheet. However, the boom in this drink, protected by its designation of origin, has reconfigured the market at an unprecedented speed, and today the national and international markets demand increasing volumes that, on the other hand, put pressure on access to water, accelerate monoculture, and push for the replacement of traditional techniques with more standardized processes, which are sometimes more efficient in industrial terms but not necessarily sustainable or fair for small producers. In 2024, for example, certified production reached 11.36 million liters (referring to 45% Alc. Vol.), and Oaxaca continued to account for the overwhelming majority of the national volume, a hegemonic position already visible the previous year with 90.51% of the total (COMERCAM, 2025; COMERCAM, 2024).

From this perspective, assessing sustainability cannot be reduced to an economic-environmental dichotomy, as it is ultimately a delicate balance between ecological integrity, economic resilience, and social well-being. It is precisely in this third component that Oaxaca exhibits historical vulnerabilities that condition the adoption of sustainable practices: in 2022, 58.4% of its population was living in poverty and 20.2% in extreme poverty,

ranking third nationally in both categories. These figures speak to persistent deficiencies in basic services and social security, especially in rural areas, where mezcal occurs as daily work and as material culture (CONEVAL, 2025; Government of Oaxaca, 2023).

The problem is evident in the palenque: for every liter of mezcal, between 7 and 11 liters of vinazas are generated with a high organic load, acidic pH, and high temperature. Improper disposal of this waste damages soils, waterways, and, ultimately, public health. At the same time, bagasse accumulates as a massive by-product that some families are already reusing, albeit still in an incipient manner, in blocks, compost, and agricultural substrates (Zelaya-Benavidez et al., 2021). In addition to this, the shift towards agave espadín monoculture—which accounted for around 86.31% of the raw material used in 2023—simplifies landscapes, reduces biodiversity, and can disrupt key ecological processes, such as pollination by nectarivorous bats when plants are harvested before flowering (Alducin-Martínez et al., 2022).

In this scenario, growing market demand coexists with inequalities that limit the ability of small producers to capture value and reinvest in more careful management practices, such as crop rotations, living fences, seed banks, water recirculation systems, and, on the other hand, with organizational arrangements that, although they exist, do not always manage to balance the asymmetries of information, credit, and price vis-à-vis intermediaries and marketers. Various state and sectoral assessments agree that the primary link assumes risks without proportionally recovering the benefits, especially where smallholdings and scattered production hinder economies of scale and socio-environmental traceability (Government of Oaxaca, 2017).

The objective of this study was to evaluate whether artisanal mezcal production in communities in Oaxaca is sustainable using indicators that reflect economic, social, and environmental dimensions.

## 2. THEORETICAL FRAMEWORK

In the community of San Juan del Rio, Oaxaca, the dynamics of mezcal production allow common challenges in resource management, such as water, to be addressed, which suggests that without collaboration between local actors, the viability and sustainability of production would be difficult. In this community, the bonds of trust and reciprocity between mezcal producers have allowed for greater cooperation in water management on collective

agricultural lands and the active participation of communities in resource management (Luna et al., 2024).

Sustainability seeks to balance current and future needs by using natural, social, and economic resources appropriately. This approach is also essential in the production of artisanal mezcal, where traditions are mixed with modernization in a context of increasing environmental and economic pressures, as Valenzuela-Zapata and Gaytán state in 2020.

### ***Artisanal Mezcal Production***

Mezcal is a distilled beverage that, in addition to its commercial value, represents a cultural and identity element for rural communities in Mexico (Bowen and Zapata, 2009). Its artisanal production involves traditional processes, such as cooking agave pineapples in earthen ovens, natural fermentation, and distillation in stills. These practices have been passed down from generation to generation, ensuring the preservation of ancestral knowledge (García et al., 2019). However, growing domestic and international demand has intensified the exploitation of natural resources and posed significant challenges to sustainability.

### ***Dimensions of Sustainability***

Sustainability in artisanal mezcal production can be assessed from three main dimensions: environmental, economic, and social. Each of these dimensions interacts and determines the overall level of sustainability of the system.

This analysis focuses on assessing the sustainability of artisanal mezcal production, addressing three fundamental dimensions: environmental, economic, and social. This research seeks to integrate both quantitative and qualitative indicators to generate a comprehensive overview of the state of sustainability in this sector. The application of analytical tools, such as cluster analysis and the composite index, has made it possible to identify key patterns, significant differences, and priority areas for intervention to improve producer performance.

### ***Environmental Dimension***

Mezcal production has a significant impact on the environment, particularly in terms of the use of wild agave, the generation of liquid waste (vinazas), and water consumption (Lian et al., 2021). The overexploitation of wild agave species reduces biodiversity and affects local ecosystems. In addition, untreated vinazas contaminate soils and water bodies, posing a critical challenge for producing

communities.

Strategies such as agave reforestation, the use of cultivated varieties, and the implementation of recycling technologies are essential to mitigate these impacts. Furthermore, the development of wastewater treatment systems can significantly reduce the environmental footprint of mezcal (Altieri, 1995).

### ***Economic Dimension***

Economic sustainability is linked to producers' ability to generate stable incomes and diversify their markets (Pretty, 2008). In the context of mezcal, small producers face barriers to accessing international markets and certifications, such as the Mezcal Denomination of Origin. These limitations restrict their ability to compete in a globalized market and make them dependent on intermediaries.

Strengthening economic resilience requires strategies that promote certification, associativity, and participation in government support programs. In addition, initiatives that promote mezcal tourism can diversify sources of income and increase the financial stability of producing communities (Bowen and Zapata, 2009).

### ***Social Dimension***

Social well-being in mezcal production is reflected in aspects such as gender equality, job security, and community participation (Chambers, 1994). Organizing into cooperatives has proven to be an effective strategy for strengthening the social fabric and improving working conditions in mezcal communities. However, challenges remain regarding the inclusion of women in leadership roles and the transmission of traditional knowledge to new generations. Promoting gender equality and the active participation of young people in the sector is essential to ensuring the social sustainability of mezcal (Chen, 2020). From this perspective, assessing sustainability in San Juan del Río requires operationalizing three dimensions—environmental integrity, economic resilience, and social well-being—without losing sight of their interdependence.

Composite indicators are powerful tools for synthesizing multiple dimensions of a complex phenomenon, facilitating comparisons between producers, and identifying priority areas for improvement (Lindén, 2018). However, their construction involves crucial normative and technical decisions such as the selection of variables, normalization with direction criteria ("benefit" vs. "cost"), the design of justified weightings, and the

choice of aggregation rules consistent with the desired level of compensability, which must always be transparent and subject to rigorous uncertainty and sensitivity analysis, thus avoiding the production of "cardboard rankings" or spurious conclusions (Nardo, 2008; Saisana et al., 2007).

### 3. METHODOLOGY

The study was conducted in San Juan del Río, Oaxaca, due to its importance in the agave-mezcal system of Oaxaca. San Juan del Río is located in the Central Valleys region, 94.73 km from the capital city. It belongs to the district of Tlacolula and occupies

0.07% of the state's surface area. This town borders the municipalities of San Pedro and San Pablo Ayutla, belonging to the Mixe district, Santo Domingo Albarradas and Santo Domingo Tepuxtepec to the north, San Lorenzo Albarradas and San Pedro Quiatoni to the south, San Lorenzo Albarradas to the west, and San Pedro Quiatoni to the east. The predominant climate in the municipality is semi-dry, very warm and warm (67.86%), followed by semi-warm subhumid with rainfall in summer (31.97%), and, to a lesser extent, semi-dry semi-warm (0.1%) and temperate subhumid with rainfall in summer (0.07%).

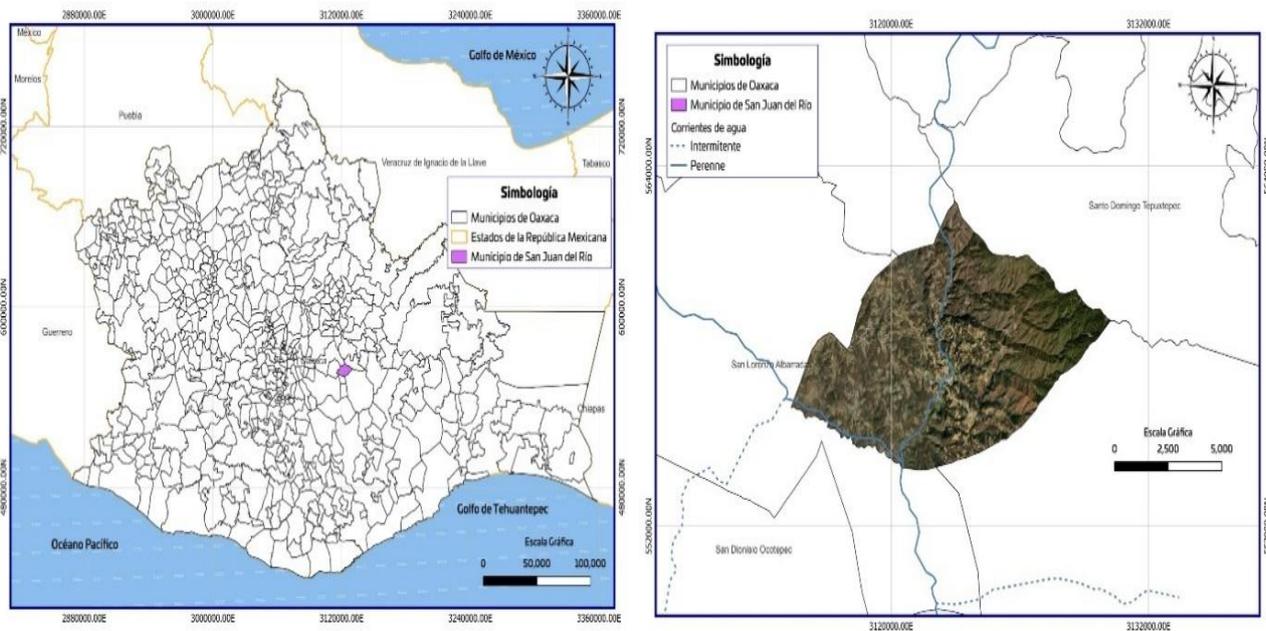


Figure 2: Micro and macro location of the study area.

Source: Own elaboration, QGis

The average annual rainfall is 600-900 mm, with June, July, August, September, and October being the rainiest months of the year. The electronic data collected shows the following soil composition: Extrusive igneous rock: Acidic tuff (98.11%) Limestone sedimentary rock - 1.89% Main metals - Gold and silver.

According to INEGI, 2020, the existing population is 1,372, with 443 occupied dwellings, an average level of schooling of 6.9, and an indigenous language population of 1,115. The bodies of water in the municipality come from the Rio Grande, which originates in the lands of San Pablo and San Pedro Ayutla, crosses the town, and flows into the Rio Nejapa, as well as the Rio San Juan, Rio Trapiche, and Rio Salado.

Its flora is varied, as it has extensive areas of forest and chaparral in the hills surrounding the villages.

Nanche and oak trees predominate, as well as evergreen plants that prevent water or moisture loss during the winter. There is an abundance of maguey plants for producing mezcal and pitayos from which prickly pears are harvested. The trees and plants that can be cultivated are avocados, guavas, chicozapote, mangoes, mamey, and corn. Lilies and bougainvillea flowers are abundant, and there are some plants with medicinal purposes, such as rue, basil, horsetail, chamomile, and cacahuatón.

The vegetation that predominates in the municipal area is a result of the physical characteristics of the soil, but currently, the negative effects of rapid climate change and the decrease in the soil's resilience to resist these changes have a greater impact.

A mixed descriptive-analytical design with concurrent integration of evidence was adopted.

**Table 1: Methodology.**

Phase	Description	Instruments/Techniques	Expected results
1. Design and eligibility criteria	A mixed descriptive-analytical approach was adopted with concurrent integration of evidence. The selection included only mezcal producers with at least one completed production cycle, an active distillery in the municipality, and informed consent; industrial or semi-industrial units were excluded.	Definition of inclusion/exclusion criteria; application of informed consent; anonymous coding.	Refined universe of 34 eligible cases; final sample of 29 units.
2. Information collection	Information was collected in the field between April and June 2024, a period of high production activity, to ensure ecological validity.	- Structured survey (14 sociodemographic items, agronomic practices, marketing, and support). -Semi-structured thematic interviews: sustainability, knowledge transfer, market barriers, etc.). - Direct observation in 11 palenques (cooking, fermentation, and distillation).	Mixed base with quantitative data and contextualized qualitative narratives.
3. Qualitative coding	Testimonies and observations were systematized to extract analytical categories.	Open and axial coding in Python, consolidating a matrix of categories/subcategories linked to each area of the index.	Qualitative matrix structured by dimensions (economic, social, environmental).
4. Construction of indicators	Fourteen indicators were defined, organized into three areas: economic, social, and environmental.	Min-max normalization (0-1); equal weighting per indicator; construction of indices by dimension and overall.	Partial and global indices comparable between units.
5. Statistical analysis	Multivariate techniques were applied to identify sustainability typologies.	- Ward's hierarchical clustering with Euclidean distance ( <i>scikit-learn</i> ). - Determination of the k=3 r by elbow criterion and silhouette index.	Identification of three clusters; significant differences by indicator cluster; global silhouette and by cluster.
6. Visualization and communication	Results were synthesized in accessible graphs for community feedback and academic analysis.	Matplotlib was used to generate dendrograms, indicator radars, and comparative indices.	Clear and reproducible visual representations.
7. Ethics and data protection	The ethical process was treated as a living dimension, not as an administrative formality.	Informed consent form, clarification of doubts, delivery of copies; anonymization through codes; encrypted storage and restricted access.	Voluntary participation, confidentiality protection, return of results to the community.

Source: Own elaboration, 2025

The quantitative aspect was constructed based on 14 indicators organized into three areas: economic (profitability, access to contracts/markets, subsidies, certifications), social (employment, family participation, intergenerational transmission of knowledge, job security, community organization/cohesion), and environmental (use of biofertilizers, water consumption, biodiversity conservation, recycling/waste reuse, energy sources). The qualitative aspect involved semi-structured interviews and direct observation to reconstruct narratives, practices, and productive contexts; in this way, numerical patterns could be interpreted in light of contextual descriptions.

Eligibility was a substantial part of the design: only mezcal producers with at least one completed production cycle, an active distillery within the municipality, and informed consent were included; industrial or semi-industrial units and individuals who declined to participate were excluded. This screening reduced the operational universe; from a

broad but informal local group, and after verifying activity conditions, 34 eligible cases were accessed. Snowball sampling allowed us to reach family networks and cooperatives with low visibility. In addition, safeguards were established to limit referrals per participant and the minimum balance of certified/non-certified participants to reduce homophily bias. The final sample consisted of 29 units.

Fieldwork was carried out between April and June 2024, a period of high productive activity which, in fact, increases the ecological validity of the records. A structured survey was administered (14 items on sociodemographic data, agronomic practices, marketing, and support), guided interviews were conducted on twelve thematic areas (sustainability, knowledge transfer, market barriers, among others), and direct observation was carried out in eleven palenques during full days of cooking, fermentation, and distillation. The testimonies were coded in Python using an open-axial procedure until a matrix of categories and subcategories linked to each area of

the IMSM was consolidated.

The base of 29 cases and 14 indicators was normalized to 0–1 using min-max; equal weights were assigned per indicator (parsimony criterion) and indices were constructed per dimension (average of its indicators) and an overall index (average of the three dimensions). The typology was estimated by hierarchical clustering (Euclidean distance, Ward's method);  $k=3$ .

The formula applied for the development of each index was:

Economic index (row  $i$ ):

$$I_i^{\text{econ}} = (1/4) \cdot \sum_{j \in \text{ECO}} x_{i,j}$$

Social index (row  $i$ ):

$$I_i^{\text{soc}} = (1/5) \cdot \sum_{j \in \text{SOC}} x_{i,j}$$

Environmental index (row  $i$ ):

$$I_i^{\text{env}} = (1/5) \cdot \sum_{j \in \text{ENV}} x_{i,j}$$

Composite index (row  $i$ ):

$$I_i^{\text{comp}} = (I_i^{\text{econ}} + I_i^{\text{soc}} + I_i^{\text{amb}}) / 3$$

Normalization (min-max) and benefit/cost orientation

For each indicator  $j$ , if starting from raw data  $X_{i,j}$ , it is normalized to [0,1] with min-max:

$$x'_{i,j} = (X_{i,j} - \min(X_{\cdot,j})) / (\max(X_{\cdot,j}) - \min(X_{\cdot,j}))$$

Sets of indicators by dimension

ECO = { profitability; access to contracts/markets; subsidies; certifications }

SOC = { employment; family participation; intergenerational transfer of knowledge; job security; community organization/cohesion }

AMB = { beneficial water use; biodiversity conservation; waste recycling/reuse; use of biofertilizers; energy sources }

The quantitative analysis was performed in Python 3.x within Jupyter Notebook, which allowed the process to be documented and reproducibility to be ensured. First, the database was cleaned and normalized (14 indicators on a scale of 0–1), and then the indices were constructed by dimension (economic, social, and environmental) and a global

index was calculated as the average of the three. Using the scikit-learn package, a Ward hierarchical clustering with Euclidean distance was applied; the number of groups was defined as  $k=3$ , combining the elbow and silhouette criteria. Finally, matplotlib was used to generate the dendrogram and indicator radar, ensuring that the representation was clear and useful for community feedback.

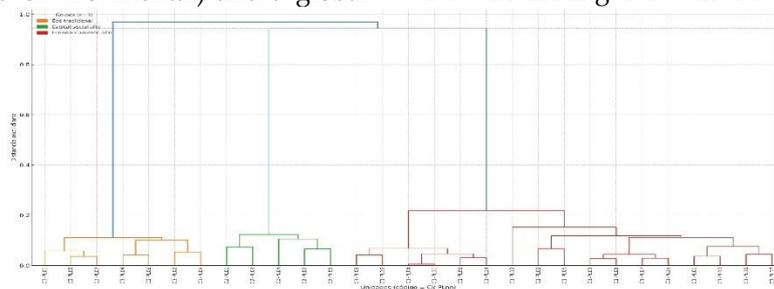
The relationship with the participants was as important as the instruments themselves, so the ethical process was treated as a living dimension of the study and not as a formality. All participants received an informed consent form explaining the objectives, procedures, and voluntary nature of their participation, as well as their right to withdraw without consequence. In addition, any questions were answered at the time, before signing, and a copy was provided for their records. From this perspective, anonymization was a fundamental step: cases were coded with alphanumeric identifiers and the database was stored in an encrypted repository with restricted access. Furthermore, no sensitive personal data or financial information that could allow indirect identification was collected.

#### 4. RESULTS

Artisanal mezcal production is not only a central economic activity for many rural communities, but also deeply rooted in the cultural traditions of these regions. However, producers face growing challenges related to competition in globalized markets, environmental pressure, and the need for social cohesion. In this context, sustainability analysis is crucial to identifying strategies that balance economic demands with the preservation of natural resources and community well-being.

##### Cluster Analysis: Identification of Patterns

The cluster analysis conducted in this study revealed the existence of three main groups of producers, each with distinctive characteristics in terms of performance in the dimensions evaluated. The most relevant findings for each cluster are described below:



**Graph 1: Hierarchical clustering dendrogram (Ward's method, Euclidean distance).**

Note. The labels on the X-axis follow the format Ck-PLnn: C = cluster assigned after the cut ( $k=3$ ); PL = plantation code; nn = sequential number. The height of the junctions represents the Euclidean fusion distance.

Source: own elaboration with Python, 2024.

**Cluster 1: Average Performance** This group includes producers with intermediate levels of sustainability in the three dimensions analyzed. Although they show progress in adopting sustainable practices, they face significant limitations in terms of infrastructure and access to technology. The lack of community support networks also limits their ability to implement innovations or access external financial resources.

In addition, these producers tend to operate in local markets, which restricts their ability to generate diversified income. Despite these barriers, cluster 1 stands out for its willingness to collaborate in collective initiatives, suggesting potential for improving sustainability through training and organizational strengthening programs.

**Cluster 2: High Economic Performance** This group is distinguished by its success in the economic dimension, reflected in broader access to diversified markets and quality certifications, such as the Mezcal Designation of Origin. These producers have managed to improve their profitability through the implementation of effective business practices and the incorporation of innovative elements into their production processes. However, they lag significantly in the environmental dimension, especially in the management of waste such as vinasses.

The disconnect between successful economic practices and environmental sustainability suggests that current financial incentives are not designed to simultaneously promote economic growth and environmental conservation. This underscores the need for public policies that promote a comprehensive approach to sustainability.

**Cluster 3: Low Performance** This cluster groups together producers who face multiple barriers, including a lack of financial resources, inadequate infrastructure, and low levels of social cohesion. These factors limit their ability to adopt sustainable practices or compete in broader markets. In many cases, these barriers are exacerbated by the migration of young people to urban areas, which affects the ability to regenerate the workforce and pass on traditional knowledge.

This group faces a high risk of economic and social exclusion, reinforcing the importance of implementing strategies specifically tailored to their needs. This includes providing accessible financing, training in clean technologies, and strengthening local cooperation networks.

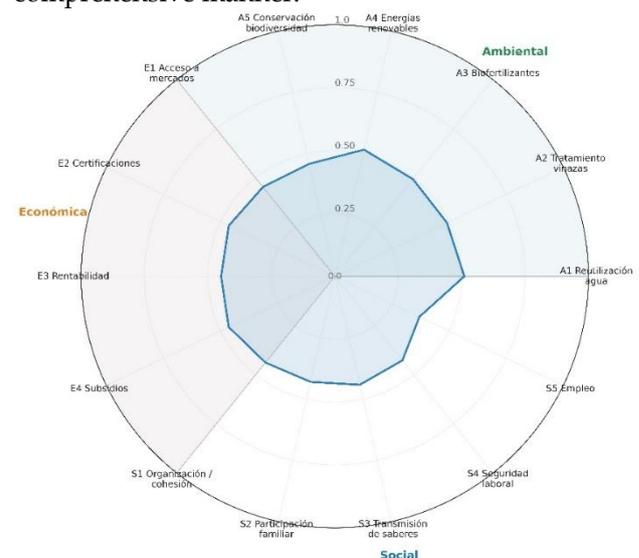
The composite index calculation provides a comprehensive measure of sustainability, based on standardized indicators that assess producers'

performance in environmental, economic, and social dimensions. The results reveal an overall average of 0.46, indicating a moderate level of sustainability in the sample analyzed. However, variations between dimensions and clusters highlight specific areas that require priority attention.

**Environmental Dimension:** The average score of 0.49 reflects significant deficiencies in biodiversity conservation and waste management. Dependence on non-renewable natural resources, such as wild agaves, and the lack of adequate infrastructure for waste treatment represent significant challenges and . However, some producers have begun to implement sustainable practices, such as bagasse recycling, demonstrating the potential to improve this indicator through access to clean technologies.

**Economic Dimension:** With an average score of 0.46, producers who participate in international markets and have certifications achieve greater profitability in this dimension, which strengthens their economic sustainability. However, this advantage is not distributed equitably, as many small producers remain excluded from these benefits due to structural barriers, such as lack of access to financing and training.

**Social Dimension:** The average score of 0.42 indicates an intermediate level of social sustainability. Although community cohesion and traditional practices, such as tequio, have strengthened the social fabric in some cases, gender equity and youth inclusion remain areas for improvement. These gaps limit the potential impact of collective initiatives and reduce the capacity of communities to address challenges in a comprehensive manner.



**Figure 2: Indicators (0-1) by dimension.**

Source: Own elaboration, 2025

Below are specific interpretations related to the possible responses and results obtained. Low-performing clusters (Cluster 1) likely correspond to producers who do not reuse water or do so in minimal percentages, and who also do not treat vinasses. Leaders (Cluster 2) report reusing more than 50% of water and treating liquid waste in greater proportions. These practices contribute to the high sustainability score reflected in the composite index.

The frequency of soil quality analysis and the proportion of land dedicated to reforestation significantly influence the main components. Producers in Cluster 2 could perform more frequent analyses (annually or more than once a year) and have more than 30% of their land dedicated to reforestation, contributing to their outstanding position.

The use of alternative energies (biogas, solar) is a differentiating practice among the leaders, while clusters with intermediate or low performance mainly use non-certified wood, affecting their environmental performance. Producers in Cluster 2 have a high proportion of production destined for international markets (more than 50%), which coincides with high values in PC1. Their access to markets allows them to obtain higher incomes and diversify their customer base.

Designations of origin and quality standards are more common among leading producers, who report more than 50% certification. In addition, they have a strong presence at trade fairs and on social media, strategies that explain their better performance. Producers in the intermediate and high clusters have received funding from government or private programs, while those in Cluster 0 lack this type of support.

Low-performing clusters may have limitations in employee training and provide fewer days off. Leaders stand out by offering frequent training and better working conditions. High values in PC2 reflect gender inclusion policies and greater participation in community activities (such as tequios), characteristics that are more common in Cluster 2. These elements contribute to strengthening social cohesion and improving quality of life.

Leading producers tend to be active members of local associations or cooperatives, which not only encourages the exchange of best practices but also strengthens their position in the market. The results show that high-performance clusters combine sustainable practices, market access, and social commitment. This reinforces the importance of considering these dimensions in an integrated

manner to drive the development of the mezcal industry.

The environmental dimension of artisanal mezcal production reflects both significant challenges and promising advances. The low average on indicators such as biodiversity conservation (0.56) highlights the need to reduce dependence on wild agave. This finding coincides with Alducin-Martínez et al. (2022), who warn of the risk of extinction associated with its intensive use and the lack of comprehensive studies, reinforcing the strategy of prioritizing cultivated varieties and promoting reforestation.

On the other hand, recycling initiatives, such as the use of bagasse to manufacture construction materials, present a replicable model that not only minimizes waste but also generates economic and social benefits. However, the lack of adequate infrastructure for the treatment of waste, such as vinasses, limits the scope of these practices. The adoption of technologies such as biodigesters could be a viable solution, as suggested by Altieri (1995) and other agroecological approaches.

The average profitability indicator of 0.75 in the economic dimension shows that artisanal mezcal production can be an important economic driver. However, dependence on intermediaries and lack of access to diversified markets are factors that limit its potential. Low participation in certifications, such as the Mezcal Denomination of Origin, limits the competitive t of producers in international markets, a barrier also identified by Bowen and Zapata (2009).

Mezcal-related tourism represents an important opportunity to diversify income. Data suggest that producers who integrate tourism activities into their operations achieve higher incomes and greater financial stability. However, the lack of training and government support in this area represents an obstacle to expanding these opportunities. In the social dimension, the results highlight a mix of strengths and limitations. Although cooperatives and collective activities have strengthened the social fabric, gender inequality remains a concern. The average score of 0.45 for gender equality highlights the need to implement programs that promote the active participation of women and young people in leadership roles, a strategy that has proven effective in other rural sectors (Chen, 2020). The transmission of traditional knowledge also faces challenges due to youth migration. Creating economic and educational incentives for young people to remain involved in mezcal production is crucial to preserving this ancestral tradition.

**Table 1: Producer Profiles.**

Cluster	n	Environmental index	Economic index	Social index	Composite index
"Economically high"	17	0.50	0.47	0.32	0.43
"High social capital"	5	0.27	0.54	0.56	0.46
"Eco-traditional"	7	0.64	0.37	0.57	0.53

Source: Own elaboration, 2025

Table 1 shows three profiles of artisanal mezcal producers identified through cluster analysis, each with a different performance in the environmental, economic, and social dimensions, as well as in the composite sustainability index.

"Economically high" cluster (n=17): This cluster has moderate values in the environmental (0.50) and economic (0.47) indices, but lower values in the social index (0.32), indicating that, although they achieve a certain degree of economic stability and apply basic environmental practices, there is a marked weakness in community cohesion, gender equality, and social participation. Its composite index (0.43) reflects a medium-low level of overall sustainability.

"High social capital" cluster (n=5): Excels in the social (0.56) and economic (0.54) indices, although it has the lowest environmental score (0.27). This suggests that its strengths lie in community organization, cooperation, and social networks, combined with relatively stable incomes, but with clear shortcomings in environmental management (e.g., waste management or biodiversity conservation). Its composite index (0.46) is

intermediate, driven by the social dimension.

"Eco-traditional" cluster (n=7): This cluster has the highest environmental index (0.64) and good social performance (0.57), although its economic index is the lowest of all (0.37). This describes producers with conservation practices, efficient use of resources, and a strong attachment to traditional knowledge, but with limitations in generating sustained income or accessing competitive markets. Its composite index (0.53) is the highest, due to the weight of the environmental and social dimensions.

**Table 2: Cluster with water recirculation processes and certified production.**

Cluster	Recirculation ≥ 90%	Certified production n ≥ 0.5
"Economically high"	60	88
"High social capital"	60	40
"Eco-traditional"	100	43

Source: Own elaboration, 2025

Overall, the data indicate that no single group stands out simultaneously in all three dimensions; rather, each cluster has specific strengths and weaknesses. This raises the need for differentiated strategies: for the "economically high," reinforce the social aspect; for the "high social capital," improve environmental management; and for the "eco-traditional," strengthen the economic component without sacrificing their achievements in environmental sustainability and community cohesion.

**Table 3: Analysis of empirical evidence from interviews.**

Analytical category	Dominant traditional sub-theme	Descriptive evidence (synthesis of narratives and observation)	Freq.
Sustainability	Traditional water management	Shallow wells (8-15 m, bucket + windlass).	15 / 29
	Recirculation system	Closed circuit that cools the distillate and returns the water to the tank; reduces consumption by ~90% compared to the open method.	29 / 29
	Local organic fuel	Oak wood ( <i>Quercus</i> spp.) mixed with dry bagasse; conical earthen kilns.	22 / 29
	In situ conservation of agaves	Manual harvesting of shoots and communal replanting; ban on illegal extraction.	18 / 29
Transmission of knowledge	Reuse of bagasse	60% of producers use it as fertilizer or to make adobe bricks.	20 / 29
	Oral family learning	Children learn from the selection of shoots	29 / 29
	Traditional gender roles	Women supervise grinding/fermentation; men carry firewood and distill.	19 / 29
Market barriers and opportunities	Rituals and festive calendar	Intensive production before festivals; blessing of the oven with mezcal.	15 / 29
	NOM-070 certification status	70% (≈20) certified; 30% (≈9) not certified due to costs and paperwork.	20
	Intermediation and price	Intermediaries offer 25-35% less than direct sales; certified products achieve better margins at trade fairs.	18 / 29
	Artisanal labeling	Lack of packaging and health registration restricts access to gourmet stores; reused glass bottles are used.	16 / 29
	Seasonal shortage of firewood	Competition for oak during the dry season; some palenques reduce batches to maintain traditional cooking methods.	12 / 29

Source: Own elaboration, 2025

## 1. Sustainability

The practices observed show a strong presence of traditional elements combined with specific innovations: The use of shallow wells with manual extraction (15/29) indicates continuity in low-impact methods, although with limitations in supplying increasing volumes.

The water recirculation system (29/29) is the most widespread innovation, reducing water consumption by up to 90% compared to the open method, which marks a significant environmental advance. Oak wood combined with dry bagasse (22/29) and conical earth ovens reflect the persistence of techniques adapted to the environment, although pressure on oak trees poses a risk of overexploitation. The in situ conservation of agaves (18/29) through suckers and communal replanting points to participatory land management, reinforced by the community's veto on illegal extraction. The reuse of bagasse (20/29), either as fertilizer or for adobe bricks, represents a circular economy model with environmental and construction benefits.

## 2. Transmission of knowledge

The cultural dimension is a central pillar of the production system: Oral family learning (26/29) ensures that knowledge about agave management, from the selection of suckers, remains within the domestic sphere. Traditional gender roles (19/29) reveal a relatively rigid division of tasks: women are responsible for grinding and fermentation, while men are in charge of firewood and distillation. The rituals associated with the festive calendar (15/29) connect production with key community events, including the blessing of the oven, which strengthens the link between cultural identity and the production process.

## 3. Market barriers and opportunities

Marketing is conditioned by structural and regulatory factors: NOM-070 certification status shows that 70% of producers are certified ( $\approx 20$ ), which improves their margins, while the remaining 30% ( $\approx 9$ ) are left out due to costs and paperwork. Intermediation (18/29) reduces direct income by between 25% and 35%, particularly affecting those who are not certified, although those who are certified achieve better prices at fairs. Artisanal labeling, limited by a lack of packaging and health registration (16/29), restricts access to high-value niches, forcing the use of reused packaging. Seasonal shortages of firewood (12/29) during the dry season generate competition for oak and force some

palenques to reduce production in order to preserve the traditional artisanal method.

## 5. DISCUSSION

The findings of this research show that sustainability in artisanal mezcal production cannot be reduced to a single value or an arithmetic sum of indicators. Rather, it is a field of tensions where economic, social, and environmental factors converge, operating in an interdependent and often contradictory manner. The identification of three clusters with different profiles reinforces the idea that sustainability is relational and situated, rather than a static or uniform state. This reading coincides with the warning that composite indicators, although useful for comparison, must be interpreted in dialogue with the territorial conditions and methodological assumptions that underpin them (Paruolo, Saisanab, and Saltelli, 2013; Saisana, Saltelli, and Tarantola, 2005).

In economic terms, NOM-070 certification and intermediation appear to be structural pillars. From the perspective of global value chain governance (Gereffi, Humphrey, and Sturgeon, 2005), certification operates as a coordination mechanism that defines who has access to differential prices and specialized markets. However, as the literature on geographical indications warns, these labels can function as tools for cultural valorization and, at the same time, as devices of exclusion when costs and procedures exceed local capacities (Bowen and Valenzuela-Zapata, 2009). The fact that 70% of the units studied are certified, while the remaining 30% are excluded for economic and administrative reasons, reflects this tension between inclusion and exclusion. In fact, certified producers have access to better margins, but the intermediation that affects 18 of 29 units immediately erodes between 25% and 35% of direct income, showing that added value is not always captured in the territory.

On a social level, the strength of the cluster with high social capital shows that community cohesion, intergenerational transmission of knowledge, and solidarity networks are not a "cultural bonus" but authentic mechanisms of sustainability. The theory of common goods has emphasized how shared rules and trust strengthen collective resource management (Ostrom, 1990), while ethnobotanical studies confirm that agroforestry systems with agaves sustain biodiversity and resilience (Torres-García, Rendón-Sandoval, Blancas, Casas, and Moreno-Calles, 2019; Eguiarte, Souza, and Scheinvar, 2021). In our case, these practices act as a buffer against market pressure and environmental

crises, validating the premise that sustainability is not only technological, but also relational and cultural (Acosta, 2013).

The environmental dimension, for its part, reveals the dependence on biomass for cooking and the problematic management of vinasses and bagasse. Life cycle assessments show that these by-products concentrate the main environmental impacts of artisanal mezcal (Ruiz-Camou, Núñez, and Musule, 2023). In response to this, the technical literature proposes transition routes based on situated innovation, such as anaerobic digestion and co-digestion with cattle manure, capable of reducing pollutant loads and generating biogas in rural contexts (Robles-González, Galíndez-Mayer, Rinderknecht-Seijas, and Poggi-Varaldo, 2012; Zelaya-Benavidez *et al.*, 2022). From the perspective of socio-technical transitions, such innovations function as "niches" that gradually become embedded in the productive regime, combining traditional knowledge and modular technologies (Geels, 2002).

In methodological terms, the construction of the index using min-max normalization and equal weights favors parsimony, but also assumes substitutability between dimensions. Two theoretical debates resonate here: on the one hand, the capabilities approach reminds us that development is not reduced to aggregate goods, but depends on the expansion of real freedoms (Sen, 1999); on the other, sensitivity analyses and transparency in the construction of indicators are considered basic conditions for avoiding simplistic interpretations (Paruolo *et al.*, 2013; Saisana *et al.*, 2005). This implies that a robust index is not just a comparative figure, but a decision space with explicit rules about what can compensate for what, and to what extent.

In short, the theoretical discussion suggests that the sustainability of artisanal mezcal is best understood as a multidimensional and situated process, marked by tensions between regulation and tradition, market and community, technology and culture. Rather than seeking homogenization, the challenge is to recognize that each cluster represents a different trajectory of sustainability and therefore requires differentiated strategies. In this way, the analysis of composite indicators not only illuminates the internal inequalities of the sector, but also provides elements for thinking about the governance of common goods, socio-technical transition, and the role of social capital in the cultural and environmental reproduction of mezcal-producing territories.

## 6. CONCLUSIONS

Artisanal mezcal production in Oaxaca is a fundamental pillar for rural communities, not only from an economic perspective, but also from a cultural and environmental one. This study has identified key issues that require attention and strategies that can strengthen the sustainability of this activity. Business cooperation networks and traditional practices, such as *tequio*, have proven to be effective tools for addressing contemporary challenges. However, limitations remain that must be addressed through coordinated efforts and public policies.

In the environmental dimension, the implementation of clean technologies and waste recycling stand out as important advances. However, dependence on non-renewable natural resources, such as wild agaves, underscores the need to adopt more aggressive conservation strategies. The creation of community nurseries and reforestation training could be key initiatives to ensure the sustainability of local ecosystems.

From an economic perspective, the results reflect that cooperation networks have enabled producers to reduce costs and access broader markets. However, the lack of adequate infrastructure and limited access to financing represent significant barriers. Promoting rural tourism as an additional source of income could diversify the local economy and increase the financial resilience of producers.

In social terms, community cohesion has been a determining factor in the success of collective initiatives. *Tequio*, as an ancestral practice, not only strengthens social ties but also ensures the equitable distribution of resources and benefits. However, the low participation of women and young people in leadership roles represents a limitation that must be addressed through specific programs that promote gender equality and inclusion.

Analysis of the three dimensions suggests that the overall sustainability of mezcal production requires an integrated approach. Cooperatives and producer networks are essential for articulating solutions that balance economic demands with environmental conservation and social well-being. These organizations have the potential to act as intermediaries between producers and government institutions, facilitating access to necessary resources and support.

In conclusion, artisanal mezcal production has great potential to become a model of sustainable development for rural communities in Oaxaca. This potential can only be fully realized if strategies are implemented that integrate economic, social, and environmental dimensions, thus ensuring the long-

term viability of this activity. Public policies and support programs must be aligned with these needs, promoting equitable development that preserves the cultural values and natural resources of the

producing communities. The combination of innovation, cooperation, and the fusion of traditional practices may be the key to ensuring a sustainable future for the mezcal industry and its communities.

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