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Mezcal Production in Mexico: Between Tradition and Commercial Exploitation

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Mezcal is a traditional iconic Mexican distilled beverage obtained from varied species of agaves. Regardless of the area of production, the process always consists of five stages: harvesting the agaves, cooking, crushing, fermentation, and distillation. It is produced in a large area of Mexican territory, a large part of which is protected by the Denomination of Origin mezcal (DOM). Over time, the word mezcal has evolved from a generic name to a more specific term used to describe the agave-distilled beverages produced in the territory protected by the DOM under the Mexican official standard NOM-070-SCFI-2016 which defined Mezcal as a "Mexican distilled alcoholic beverage, 100% from maguey or agave, obtained by distillation of fermented juices with spontaneous or cultivated microorganisms, extracted from mature heads of maguey or cooked agaves, harvested in the territory covered by the DOM." In the last 10 years, official production has increased, from <1 million liters in 2011 to almost 8 million liters. This substantial increase in production puts a lot of pressure on resources, in particular raw material, as part of the production is obtained from wild agave. On the other hand, it exposes tradition at risk by increasing production by modernizing production processes and sacrificing the artisanal aspect of this production. We consider appropriate to address the issue of sustainability in this context of great tradition and growing market demand. The article presents the relevant aspects of mezcal production, highlighting some particularities specific to certain production areas, it also addresses the problem of the official standard. A broad discussion is presented on the sustainability of artisanal processes, and the main points to be taken care of in this framework. Additionally, some elements considered as fundamental in the perspective of the design of a sustainable artisanal distillery are described. In summary, this article aims to review the current state of mezcal production, how sustainability may be addressed in a very artisanal process and what are the challenges of the production chain to satisfy an increase in demand without sacrificing the tradition and culture related to this iconic Mexican beverage.

Keywords: mezcal, agave, artisanal production process, sustainability, alcoholic beverage

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INTRODUCTION

Mexico is characterized as the country of agaves (also called magueyes), which grow in almost every state of the republic. In general, plants of the genus *Agave* are monocotyledonous, characterized by their rosette structure, long life span, with reproduction that can be sexual by seed (many of the species' flower only once in their life and then die) or propagate vegetatively by ground-level basal shoots or aerial bulbils (García-Mendoza et al., 2017). All *Agave* species are native from the American continent, and the central region of Mexico is considered the center of origin of this family (Eguiarte et al., 2000). These plants belong to the Mexican culture and have been used for multiple purposes since ancient times, like source of food, medicine, drink, construction material, living fences, fibers, vinegar, and ornaments, among others, and what remains mainly today, for the elaboration of beverages distilled or not (García-Mendoza, 1998; Delgado-Lemus, 2020). Agaves are notable for their high content of reserve sugars, fructans, which are highly branched polymers of fructose with a glucose molecule (Lopez et al., 2003).

The generic term for these distilled beverages obtained from agaves is mezcal, which derives from the Nahuatl mexcalli, from metl, maguey, and ixca, to cook or bake, i.e., cooked, or baked maguey (Blomberg, 2000; Bowen, 2015). In general, terms, mezcal can be defined as a distilled beverage obtained from the fermentation of the stems or the juices of the stems of different agave species, previously cooked and crushed or ground (NOM-070-SCFI, 2016). This definition includes all distilled beverages obtained from agaves, such as Tequila, Raicilla, Bacanora and mezcal itself (Álvarez-Ainza et al., 2017). A broad and entertaining description of the culture of mezcal can be found in Bullock's work (2017).

Over time, the word mezcal has evolved from a generic name to a more specific term used to describe the agave-distilled beverages produced in the territory protected by the Denomination of Origin mezcal (DOM) under the Mexican official standard NOM-070-SCFI-2016 (NOM) (https://mezcal.org/denominacion-de-origen-mezcal). Since its first publication in the Official Journal of the Federation (DOF) in 1994, as well as its subsequent amendments, mezcal is defined as a "Mexican distilled alcoholic beverage, 100% from maguey or agave, obtained by distillation of fermented juices with spontaneous or cultivated microorganisms, extracted from mature heads of maguey or cooked agaves, harvested in the territory covered by the DOM." **Figure 1** shows the DOM territory and its distribution in Mexico. For the first integrated states, the entire territory belongs to the DOM. In the later enlargements only certain municipalities of the new states were included in the DOM.

The same standard mentions that it is a liquid with aroma and flavor derived from the species of maguey or agave used, as well as from the elaboration process; diversifying its qualities by the type of soil, topography, climate, water, authorized producer, mezcal master, alcoholic graduation, microorganisms, among other factors that define the character and organoleptic sensations produced by each mezcal.

According to the specific process used for cooking the maguey or agave, crushing or grinding, fermentation and distillation, three categories of mezcal are obtained: mezcal; Artisanal mezcal and Ancestral mezcal (**Table 1**).

In addition to these three categories the NOM mentions six classes of mezcal: "Blanco" or "Joven" (colorless and translucent mezcal that is not subject to any further processing); "Madurado en Vidrio" (mezcal stabilized in glass containers for more than 12 months, underground or in a space with minimum variations in light, temperature and humidity); "Reposado" (mezcal that must remain between 2 and 12 months in wooden containers that guarantee its innocuousness, without restriction of size, shape, and volume capacity, in a space with minimum variations in light, temperature and humidity); "Añejo" (mezcal that must remain for more than 12 months in wooden containers that guarantee its innocuousness, with a capacity of <1,000 L, in a space with minimum variations in light, temperature and humidity); "Abocado con" (mezcal that must directly incorporate ingredients to add flavors, such as maguey worm, damiana, lemon, honey, orange, mango, among others) and finally "destilado con" (mezcal that must be distilled with ingredients to add flavors, such as turkey or chicken breast, rabbit, mole, plums, among others), in terms of the NOM.

Although the standard establishes a legal framework for the production of the beverage and provides a certain guarantee of quality for the consumer, both at national and international level, it is important to mention that several producers in the appellation of origin area do not certify under the NOM, partly because of the cost of this certification, partly because it is very complex to certify artisanal processes, and finally because the producer does not want to depend on a certifying body. Legally this prevents these producers from using the word mezcal on their labels (Gallardo-Valdez, 2016), in this case it is common to see mentioned for example the term "distilled agave beverage" or some already positioned brands do not mention anything specific. For this reason, it is difficult to have exact figures of the global annual mezcal production. **Figure 2** shows the production of certified mezcal between 2011 and 2020, which gives an idea of the production levels and the significant increase in production volumes since 2014. Oaxaca state is the principal mezcal producer, reflecting more than 90% of production in 2020 (COMERCAM, 2020). Based on personal communications we estimate that the real quantity of mezcal produced annually is twice the certified volume.

The past years also showed a significant increase in exports of both certified mezcal and certainly of non-certified products. In 2020, 66.6% of the certified mezcal was exported abroad, mainly to the United States (73.8%), followed by Spain, Canada, and Australia, among others. In total, mezcal has been exported to 72 countries, and since 2020, it is interesting to highlight some first sales in China (COMERCAM, 2020). In addition to this increase in exports, it is important to note that today there is a growing niche market for premium distilled agave beverages where consumers are looking for artisanal products with specific characteristics,

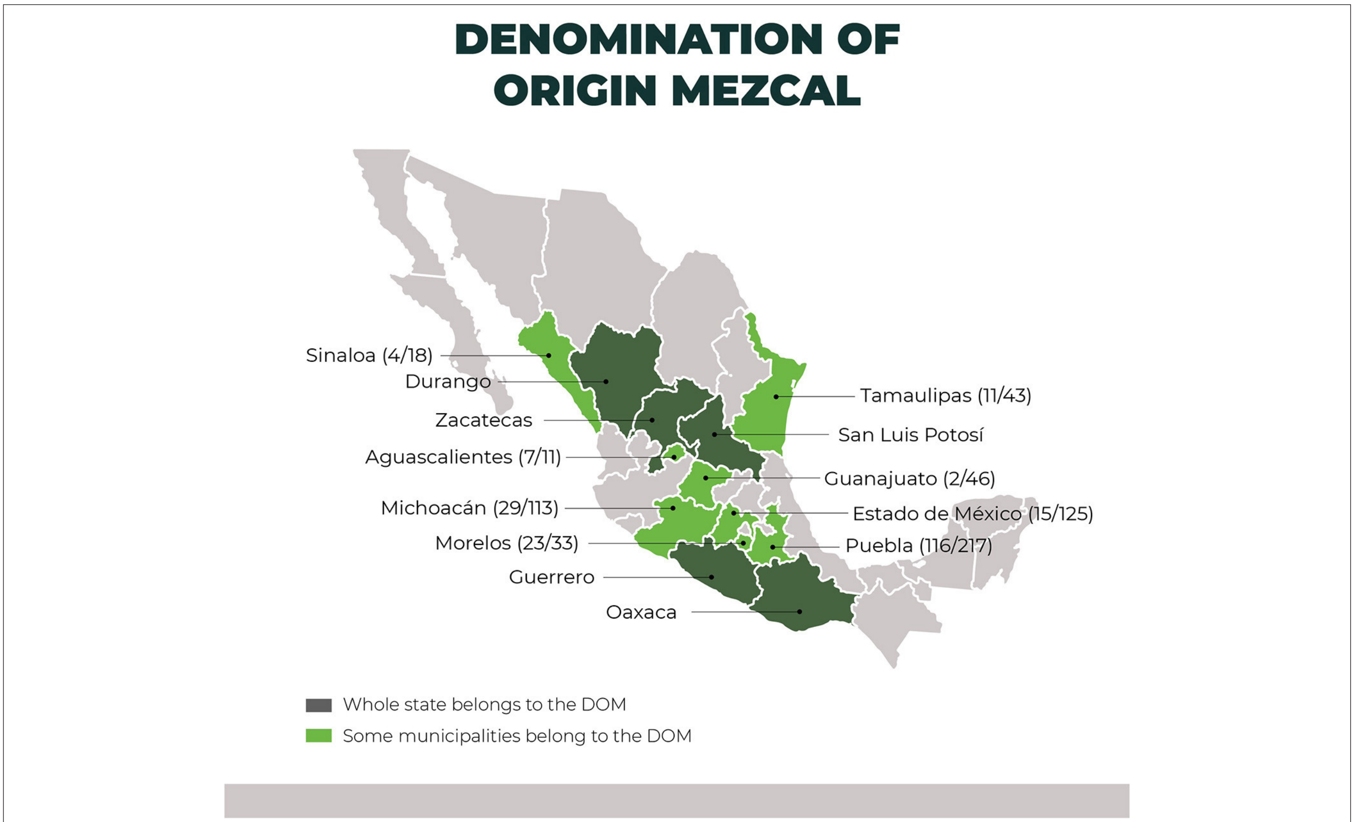

FIGURE 1 | DOM territory in Mexico. In the case of states that do not belong entirely, the number of municipalities included in the denomination/total number of municipalities in the state is mentioned.

TABLE 1 | Allowed process configurations of the different mezcal categories (NOM).

Categories of mescal	Mezcal	Artisanal mezcal	Ancestral mezcal
Main characteristics	(a) Cooking: pit, masonry, or autoclave ovens. (b) Milling: Chilean or Egyptian mill, grinder, mill train or diffuser. (c) Fermentation: wooden vats, masonry basins or stainless-steel tanks. (d) Distillation: stills, continuous distillers or copper or stainless-steel columns.	(a) Cooking: pit ovens or raised masonry ovens. (b) Grinding: with a mallet, Chilean or Egyptian mill, or grinder. (c) Fermentation: cavities in stone, soil or trunk, masonry basins, wooden or clay vessels, animal skins, which process may include the agave fibers (bagasse). (d) Distillation: with direct fire in copper pot stills or clay pots and, wooden, copper or stainless-steel pot stills; the process may include agave fibers (bagasse).	(a) Cooking: pit ovens. (b) Grinding: with a mallet, Chilean or Egyptian mill. (c) Fermentation: cavities in stone, soil or trunk, masonry basins, wooden or clay vessels, animal skins, which process may include the agave fibers (bagasse). (d) Distillation: with direct fire in clay or wooden pots; the process may include agave fibers (bagasse).

for example made of wild agaves, which puts an excessive pressure on the natural populations (Martínez Jiménez et al., 2019).

This article aims to review the current state of mezcal production in Mexico, how sustainability may be addressed in a very artisanal process and what are the challenges of the production chain to satisfy an increase in demand without sacrificing the tradition and culture related to this iconic Mexican beverage.

MATERIALS AND METHODS

The information analyzed was collected through a careful literature review in different databases.

Literature searches were conducted in Scopus, Google Scholar, and PubMed to detect the status of research on the sustainability of the mezcal production process. The search period was from 1990 to date. In addition, we collected information from technical reports, theses or books published mainly in Mexico and not available in the

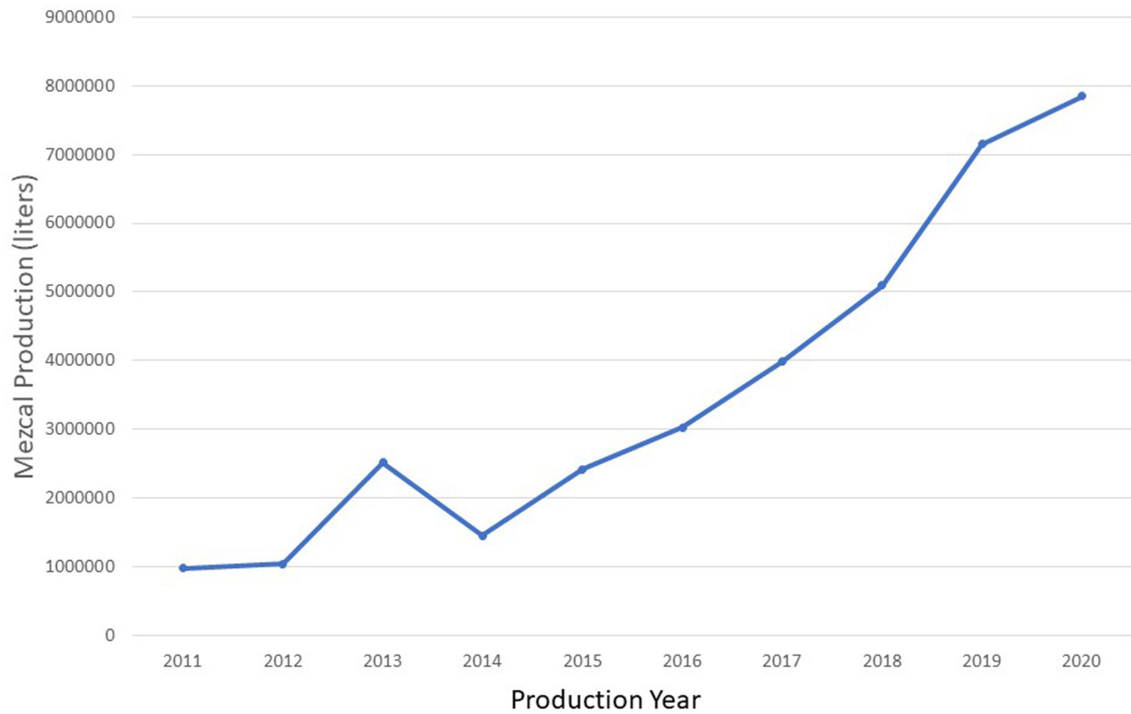

FIGURE 2 | Evolution of mezcal production between 2011 and 2020. Official production registered and certified by the mezcal regulatory council (COMERCAM, 2020).

databases. Several keywords or combinations of keywords were used for the search: [(1) mezcal, (2) mezcal and agave, (3) mezcal and sustainability, (4) mezcal and social, (5) sustainability and craft products, (6) sustainability and craft and product].

The database that yielded the most information was Scopus, with 208 published papers (search with the keyword mezcal). Many of them are directly related to the raw material, as the search combining the word mezcal with agave yielded 147 results. The combination of mezcal and sustainability allowed only nine papers to be found.

The analysis of the information found shows that the available data is very scarce, and few papers address the issue of sustainability of mezcal production as such.

MARKETING AND REGULATIONS

A decade ago, the mezcal production in most factories was a family business owning small and mid-sized enterprises. Their annual production was low because it did not represent the main economic activity. Moreover, mezcal production depended on factors such as the distance for agave harvesting, access to the factory, services such as water and electricity, number of families involved in the process, and the size of the factory. During a long time, the mezcal factories have managed to stay in the market operating under subsistence conditions, so most do not earn enough income to grow (Illsley Granich et al., 2009). They survived even in environments of economic, social and political crisis, trying to maintain their cultural identity (Vázquez Elorza et al., 2017).

In recent years, there has been an increase in the production and sale of mezcal, both in national and international markets, which has caused an excessive use of natural resources. The incorporation of national and international investors, politicians, entrepreneurs, professionals, distribution intermediaries, marketers, among others, have made their appearance interested in participating in the mezcal market, causing an increase not only in the production of mezcal, but also in the number of brands (Hernández López, 2020).

The participation of so many actors has caused that the producer is kept at a lower social and economic level, with low prices for their products, while the marketers increase the prices of the products, achieving high profits that do normally not benefit the economy of the producers (Gómez Jarquín et al., 2014). Despite this, some factories have managed not only to maintain their cultural identity, but also to grow, to produce high-quality products, to locate them in the best markets, and to achieve a better quality of life (Hernández López, 2020). Likewise, they are working to maintain the biodiversity of its natural environment, looking for the sustainability of their processes. They have had to propagate and replant agaves and timber trees to guarantee the quality and quantity of their raw materials, as well as to reduce and treat their waste to reduce the environmental impact.

It is possible to distinguish between mezcal producers: those that have certified mezcal brands and meet the requirements of NOM (Gómez Jarquín et al., 2014; Hernández López, 2020) and those who fail to certify their products. Some producers cannot certify because of the cost of the certification process or because their products fail to comply with the provisions of the NOM.

In recent years, the DOM has incorporated other producing regions since its first version did not consider all the territories in Mexico where mezcal is produced (Gallardo-Valdez, 2016). Currently, the authorized areas include the entire states of Oaxaca, Zacatecas, Durango, Guerrero and San Luis Potosi and some municipalities of Michoacán, Tamaulipas, Guanajuato, Puebla, Morelos, Estado de Mexico and, very recently, Sinaloa. This continuous extension of the DOM has become controversial, especially in the original production states (NOM-070-SCFI, 2016). With the focus on the sustainability of production, an important question is how much does the DOM support small mezcal producers? Does this appellation really promote regional development and protect ancestral knowledge? The marketing of mezcal requires compliance with NOM standards. It is frequently seen as complex and even unattainable by a sector of producers. So, many of them decide to continue producing a spirit without certification, which is not necessarily of low quality, to sell it in their communities and maintain a tradition inherited from previous generations (Bullock, 2017).

However, not only by producing the distillate in the DOM territory, it can be called mezcal, but it is essential that it complies with the official Mexican standard of mezcal, which indicates the specifications that must be accomplished to grant the authorization for the packaging and sale of this spirit.

It is mandatory that each bottle describes the agave species used, the percentage of each species (in case of mixtures), the type of mezcal, the category of mezcal, the alcoholic content, the production region, among other concepts (NOM). **Table 2** lists the chemical parameters and their minimum and maximum permitted levels.

Among the compounds regulated by the standard, one of the most problematic is methanol, as it often does not comply with the standard (especially in the more artisanal processes) and creates a problem for the producer. This compound is found frequently in fruit-based drinks where pectin is hydrolyzed prior to or during fermentation by pectin methyl esterases (PME), which release the methoxy groups generating methanol (Bindler et al., 1988; Pineau et al., 2021). To reduce the production of methanol, processes such as the removal of the peel or skin of fruits (Hodson et al., 2017), use of very ripe fruit, heating and/or pasteurization to deactivate the PME enzyme (Hang and Woodams, 2010; Miljić et al., 2016), chemical pasteurization using dimethyl dicarbonate (Blumenthal et al., 2021) and even PME enzyme inhibitors such as the use of epigallocatechin gallate (EGCG) (Saelee et al., 2020) have been used.

Although the agaves used for mezcal production are not fruits, they contain pectin which affects the production of methanol. In the case of mezcal, there is no evidence that the activity of pectin methyl esterases (PME) is the main responsible for the methanol production, because, during the process, there is a cooking stage prior to fermentation, which may imply the thermal deactivation of the agave endogenous PME enzyme (Arellano et al., 2012). However, since the temperature is high for prolonged periods of time, the demethylation of the pectin is generated during this stage (Solís-García et al., 2017). There is evidence that during fermentation it is possible to observe an increase in methanol concentration (Vera Guzmán et al., 2009; Kirchmayr et al., 2017), however this variation can be attributed to a lack of homogenization of the must, due to the presence of bagasse (Solís-García et al., 2017). There is no evidence that methanol is produced during the distillation of mezcal, however, during the first distillation it is a widespread practice that agave bagasse is added to the distillation tank, with a high probability of generating methanol if pectins are still present. Distillation is also a stage in which various cuts of the distillate are made to separate the desired components from the unwanted ones, involving a separation of the streams that contain a higher concentration of methanol.

Finally, as in fruit distillates, the concentration of methanol in mezcal depends on the agave species (Vera Guzmán et al., 2009), the degree of maturity (Aguirre et al., 2001), thus as, the place where the agaves grow (Pinal et al., 2009; González Seguí et al., 2020). However, a main source of variation is distillation because the equipment used in the mezcal production processes is rustic or rudimentary; the heat is provided by wood combustion. Most of the stills do not have internal temperature measurement either in the pot, hat (chapeau) or even at the outlet of the condensates. Therefore, it is common to observe temperature variations during distillation, which implies that the volatile compounds are not separated based on their different physicochemical characteristics, causing that the methanol limits are not accomplished (Prado-Ramírez, 2014).

Methanol, as already mentioned, is a restricted compound in different beverages around the world. **Table 3** shows the maximum permitted levels as well as the raw material used. Methanol concentration in mezcal is not as high as compared to other distilled beverages, however, for many producers it is difficult to obtain their beverages below 300 mg/100 mL of anhydrous alcohol, mainly due to the distillation processes and equipment they use.

González Seguí et al. (2020) present an important discussion on the methanol concentration limit in the standard, based on a careful review of the origin of these limit values. The authors highlight that methanol concentration limits are set by the economy of each country for technological, but not toxicological, reasons. It is clear that mezcals exceed in some cases the amount of methanol set by the NOM, however, the values recorded are below European (European Commission, 2019), North American (Bindler et al., 1988), and World Health Organization standards (World Health Organization, 2014), where there is a history of higher tolerance to methanol than in current Mexican standards. Thus, the authors propose a thorough revision of these values, based on the particularities of the elaboration processes and not by taking data from other beverages. This would undoubtedly support the small producers who certify their products and could help to increase the volume of certified mezcal even more.

The NOM also regulates other compounds such as higher alcohols, furfural, aldehydes, lead, and arsenic. However,

TABLE 2 | Chemical compounds regulated by the NOM and their minimum and maximum permitted levels.

Parameters	Units	Low	High	Mandatory analytical technique
Alcohol Volume at 20°C	% ABV	35	55	NMX-V-013-NORMEX-2013
Dry extract	g/L of mezcal	0	10	NMX-V-017-NORMEX-2014
Higher alcohols	mg/100 mL of anhydrous alcohol	100	500	NMX-V-013-NORMEX-2013
Methanol	mg/100 mL of anhydrous alcohol	30	300	NMX-V-013-NORMEX-2013
Furfural	mg/100 mL of anhydrous alcohol	0	5	NMX-V-013-NORMEX-2013
Aldehydes	mg/100 mL of anhydrous alcohol	0	40	NMX-V-013-NORMEX-2013
Lead (Pb)	mg/L of mezcal	–	0.5	NMX-050-NORMEX-2010
Arsenic (As)	mg/L of mezcal	–	0.5	NMX-050-NORMEX-2010

TABLE 3 | Legal limits for methanol contents (in grams per liter of 100% vol. alcohol) in different spirits.

Country or organization	Maximum limit of methanol (mg/100 mL anhydrous alcohol)	Spirit beverage applied
European Union (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019R0787&rid=6)	200	Wine spirit, brandy or Weinbrand
	1,000	Grape marc spirit or grape marc
	1,500	Fruit marc spirit
	1,000	Fruit spirits
	1,200	Fruits spirits produced from the following fruits: apricots (*Prunus armeniaca* L.), apple (*Malus domestica* Borkh.), plum (*Prunus domestica* L.), quetsch (*Prunus domestica* L.), peach [*Prunus persica* (L.) Batsch], mirabelle (*Prunus domestica* L. subsp. syriaca (Borkh.) Janch. ex Mansf.), pear (*Pyrus communis* L.), except for Williams pears (*Pyrus communis* L. cv "Williams"), raspberry (*Rubus idaeus* L.), blackberry (Rubus sect. Rubus)
	1,350	Fruit spirits produced from the following fruits: quince (*Cydonia oblonga* Mill.), blackcurrant (*Ribes nigrum* L.), juniper berry (*Juniperus communis* L. or *Juniperus oxicedrus* L.), Williams pear (*Pyrus communis* L. cv "Williams"), redcurrant (*Ribes rubrum* L.), elderberry (*Sambucus nigra* L.), rosehip (*Rosa canina* L.), sorb apple (*Sorbus domestica* L.), rowanberry (*Sorbus aucuparia* L.), wild service tree [*Sorbus torminalis* (L.) Crantz]
	1,000	Cider spirit, perry spirit and cider and perry spirit
	Not mentioned	Honey spirits, Hefebrand or lees spirit, Beer spirit, Topinambur or Jerusalem artichoke spirit
	10	Vodka
	Not mentioned	Spirit (supplemented by the name of the fruit, berries, or nuts) obtained by maceration and distillation
	Not mentioned	Geist (supplemented by the name of the fruit or the raw materials used)
	Not mentioned	Gentian, Juniper-flavored spirit drink, Gin, Distilled gin
	5	London gin
	Not mentioned	Others
United States (https://www.fda.gov/regulatory-information/search-fda-guidance-documents/cpg-sec-510200-brandy-containing-methyl-alcohol-food-additive)	350	Domestic brandies
	1,000	Foreign brandies
México (NOM-006-SCFI-2016; NOM-070-SCFI- 2016; NOM-142-SSA-1995)	300	Tequila, mezcal and other agave distilled beverages

these compounds generally comply with the marked levels if potable water and good manufacturing practices are used, so an extensive mention of these quality attributes is not necessary.

MEZCAL PRODUCTION AREAS AND PRACTICES

The production steps carried out during the production of mezcal show a high diversity of the agave species, operational conditions, production practices and the equipment used. In **Figure 3**, the principal steps of the process are presented with some particularities of each area of production. In the context of sustainability, several factors influence efficiency, the agave handling, and the conditions of every factory. Since the majority of mezcal producers are not measuring any process parameters and mostly do not record any data, it is difficult to know the average efficiency, for example, sugar hydrolysis during cooking or the conversion efficiency of sugars during the fermentation stage. In fact, the great diversity of *Agave* species and process conditions confers the products clear sensorial differences between Mexican states, regions, and factories (Arellano et al., 2012).

Agave Species and Harvest

Different agave species are used for mezcal production depending on the production region (**Table 4**). For example, mezcal production in Oaxaca (highest production volumes) uses mainly cultivated *A. angustifolia*, but several wild species are also used. *Agave cupreata*, *A. angustifolia*, and *A. inaequidens* are commonly used in Guerrero and Michoacán. The principal species used in Zacatecas and San Luis Potosí is *A. salmiana* meanwhile in Durango *A. duranguensis* (Bowen, 2015; Álvarez-Ainza et al., 2017; Bullock, 2017).

As a substantial number of the agave plants are recollected from the environment rather than being cultivated in fields, it is difficult to know when the plants reach their highest sugar content. Factors such as location, topology, climate, and soil composition may contribute to differences in size, weight, and composition (Vera-Guzmán et al., 2018). Most mezcal producers have learnt empirically which plants to harvest, and which leave to grow on. For some agave species, a widely used practice is waiting for the scape (quiote) to grow, cut it off and wait between 6 and 12 months to harvest the plants, since this moment implicates the highest sugar content (Aguirre et al., 2001). Since the agave plants need several years to grow and mature, depending on the agave species between 5 and 15 years (García-Mendoza et al., 2017), it is necessary to manage the proportion of plants to harvest and those to left on the "field/mountain." An

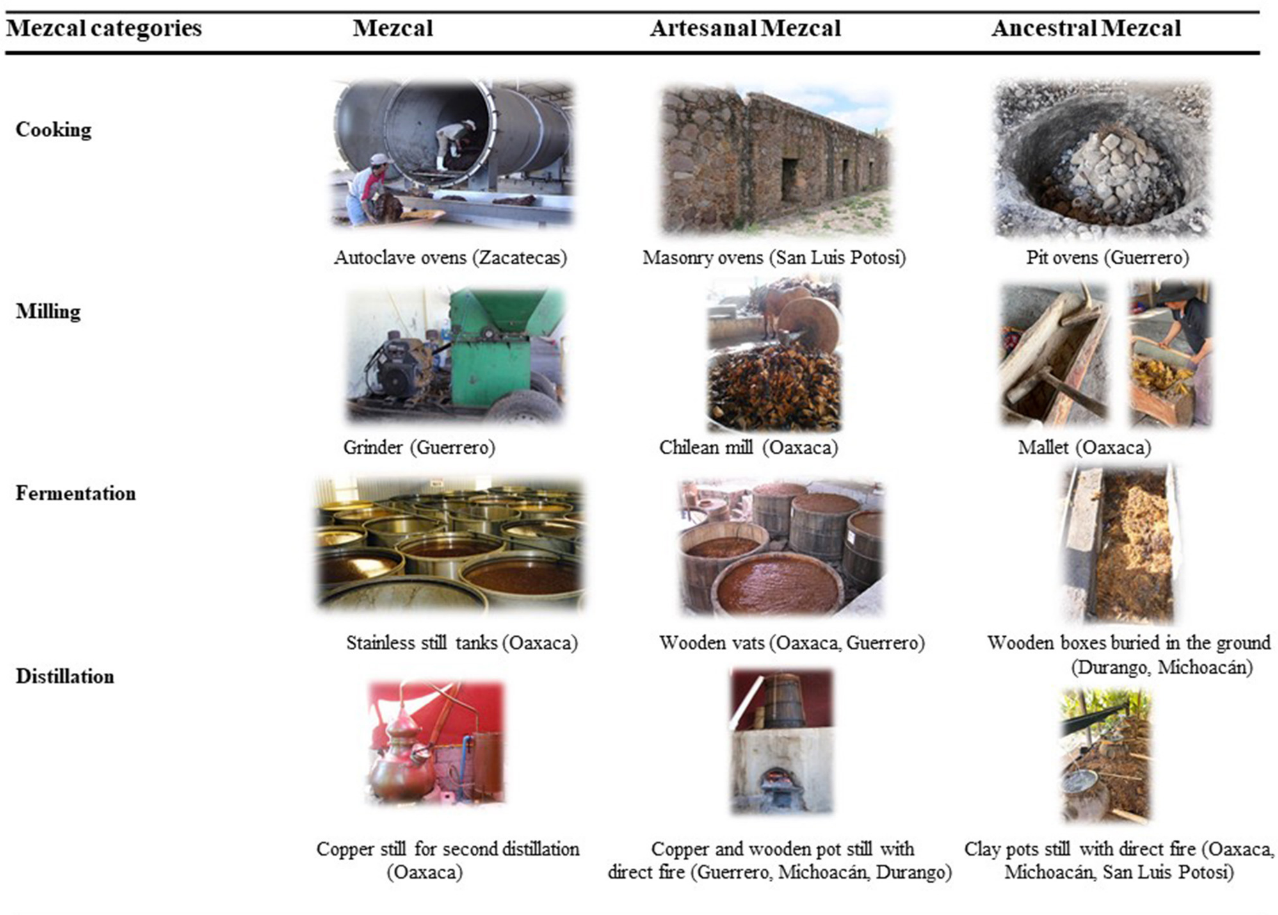

FIGURE 3 | Illustration of the principal steps of the Mezcal production. At each stage, an example of the equipment used for each type of mezcal is presented. The main geographical areas where they are used are mentioned too.

TABLE 4 | Agave species exploited in different production regions considered in the NOM.

State	Agave	References
Aguascalientes (seven municipalities)	*A. angustifolia* (C) *A. salmiana* (C)	Gallardo-Valdez and Solís-Medina, 2019
Durango	*A. durangensis* (C, W) *A. angustifolia* (W)	García-Mendoza, 2012; Bowen, 2015; Loera-Gallegos et al., 2018
Estado de México (15 municipalities)	*A. angustifolia* (C, W)	Sánchez-Jiménez et al., 2020
Guanajuato (two municipalities)	*A. salmiana* (W)	Molina-Guerrero et al., 2007
Guerrero	*A. cupreata* (W) *A. angustifolia* (C, W)	García-Mendoza, 2012; Kirchmayr et al., 2014; Bowen, 2015
Michoacán (29 municipalities)	*A. cupreata* (C) *A. inaequidens* (W) *A. tequilana* (C) *A. sahuayensis* (W)	García-Mendoza, 2012; Bowen, 2015; Cházaro-Basáñez et al., 2020; Delgado-Lemus, 2020
Oaxaca	*A. angustifolia* (C) *A. rhodacantha* (W) *A. potatorum* (C, W) *A. seemanniana* (W) *A. marmorata* (W) *A. karwinskii* (W) *A. americana* (W)	García-Mendoza, 2012; Bowen, 2015; Martínez Jiménez et al., 2019
Puebla (117 municipalities)	*A. potatorum* (C, W) *A. marmorata* (W) *A. angustifolia* (C, W) *A. salmiana* (C, W)	García-Mendoza, 2012; Bowen, 2015
Sinaloa (four municipalities)	*A. angustifolia* (C, W) *A. tequilana* (C)	Núñez-Hernández, 2011; Bowen, 2015; Salazar-Leyva et al., 2016
San Luis Potosí	*A. salmiana* (W)	García-Mendoza, 2012; Bowen, 2015
Tamaulipas (11 municipalities)	*A. americana* (W) *A. santicarolis* (W)	García-Mendoza, 2012; Zúñiga-Estrada et al., 2018
Zacatecas	*A. salmiana* (W) *A. durangensis* (W) *A. tequilana* (C) *A. guadalajarana* (W)	García-Mendoza, 2012; Bowen, 2015; Torres-García et al., 2019

C, cultivated; W, wild.

interesting way to manage agave is reported by Illsey et al. (2018) in the state of Guerrero, where the community implemented a controlled forest management of the agaves. In **Table 4**, some data of maturation age and mezcal production yields are mentioned, demonstrating the great differences between regions and agave species used.

In some mezcal factories, the distance to mature agave is long, also the time it takes to harvest enough plants and carry them to the factory are high, representing additional factors for sustainability since it requires longer transport distance probably inducing stress in harvested plants, which may increase the degree of methoxylation of pectins. This information, however, has been obtained from producer interviews and it is necessary to conduct additional work to obtain scientific data (**Table 5**).

TABLE 5 | Comparison of maturity age, production yields of different *Agave* species in different production areas.

Agave species	Maturity age (years)	Yield (agave kg/L of mezcal production at 55% ABV)	References
Agave angustifolia	6–10	8–14	Martínez Jiménez et al., 2019
Agave karwinskii	10–14	11–19	Martínez Jiménez et al., 2019
Agave americana	8–12	8–16	Martínez Jiménez et al., 2019
Agave potatorum	7–13	14–20	Martínez Jiménez et al., 2019
Agave tequilana	5–9	9–13	Interview with producers
Agave salmiana	7–10	25–35	Interview with producers
Agave guadalajarana	10–15	20–30	Interview with producers
Agave cupreata	7–12	12–17	Interview with producers
Agave sahuayensis	7–12	11–18	Interview with producers
Agave inaequidens	7–14	20–30	Interview with producers
Agave durangensis	6–10	12–18	Interview with producers

Agave tequilana plantations typically have between 2,500 and 5,000 agaves per hectare. Therefore, considering an average weight of 40 kg per agave head, between 100 and 200 tons can be produced per hectare (INEGI, 1997). However, this is not the case in mezcal production, where there is no massive cultivation. Therefore, it is recommended to carry out reforestation of wild agave and cultivation of the most used agaves to guarantee the production of the necessary material year after year, considering the time required to reach maturity.

Cooking

Compared to the tequila industry, where the agave stems are steam cooked (Cedeño, 1995), with or without applying pressure, or the fructans are acid hydrolyzed after their extraction from the plants, the application of heat is not well-standardized in most mezcal factories (Solís-García et al., 2017). The most common and traditional way to cook agave stems is under ground, in conical pit ovens lined with stone and heated by burning vast amounts of wood. The amount of firewood used is an average of a 1:1 ratio with the amount of agave that will be cooked, this is one ton of firewood per ton of agave. The type of stones used to line the oven and to separate the embers from the agave stems and the type of wood, the log size (size of the pieces) and for example the water content (green wood or dried/stored wood) are factors that determine the temperature and the time the agave stems need to be left to cook in the oven (Álvarez-Ainza et al., 2017). Although temperature and cooking time are the main factors that define the efficiency of fructan hydrolysis, some other factors can be logically inferred from the way the cooking is performed. The placement of bigger agave stems near to the heat source and smaller pieces on top of them surely contributes to a homogenous hydrolyses of the fructan polymers. In some factories, a bucket of water is added through an orifice in the center, once the oven is tapped with jute sacks and soil, which favors a more homogeneous distribution of the heat inside the oven (Duran-Garcia et al., 2007). During the cooking stage, Maillard and oxidation reactions take place increasing the concentration of furfural, hydroxymethylfurfural and others compounds which may lead to fermentation inhibition, increasing fermentation time (Soto-García et al., 2009).

It is also necessary to carry out the transfer of the necessary firewood. Therefore, producers prefer to have large cooking ovens, to carry out the least number of cooking. The use of this type of oven does not allow the collection of sweet honeys that are exuded during cooking, which are lost in the bottom of the oven. Losses in general during this stage oscillate around 10%. Therefore, it would be advisable to design cooking equipment that, without losing its traditional vision, can recover sweet honeys and prevent the agave from overheating. A hybrid system between surface oven and masonry oven would be recommended, for example, connecting the still with just water to the oven to add vapor, maintain the temperature, humidity and collect the sweet honey in the bottom, could increase the efficiency process.

Grinding, Crushing, or Juice Extraction

To make the hydrolyzed sugars inside the cooked agave stems available for microorganisms during fermentation, they need to be grinded or crushed, or as in the tequila industry (Cedeño, 1995), the cooked agave is milled and washed out with warm/hot water. Then, the agave juice is obtained and subsequently fermented. In most cases of mezcal production, the crushed plant material is simply placed into fermentation vats and water is added. Regarding efficiency, the different equipment that can be used makes it difficult to compare this step between mezcal production regions. The most traditional way to achieve this is by cutting and crushing (with human force) the agave pieces with wooden mallets or by passing over a big millstone with animal force (Chilean mill) (Duran-Garcia et al., 2007). Each grinding equipment generates a different performance, while the wooden mallets generate between 100 and 150 kg/h, the blade mill and Chilean mill can grind up to 1,000 kg/h (Kirchmayr et al., 2014). Another difference between the equipment is the amount of large fragments of agave, the use of mallets to beat the agave is the system that does not completely crumble the agave, followed by the Chilean mill and finally the blade mill. Generating large fragments decreases fermentation performance, so guaranteeing homogeneous grinding with a high degree of defibration leads to better results (Duran-Garcia et al., 2007). It is even reported that including a motor in the milling pan can increase the milling performance by 20% (Caballero Caballero et al., 2013). There is no data on how many sugars are lost during bad grinding, however, they could range between 5 and 10%, according to the evaluation of the sugar content in the agave heads and the initial sugar content in the fermentation. Today, motored machinery adopted from other agricultural activities may achieve the goal in much less time, however, alters the image of an ancestral production process.

In addition to the above, although it is not a milling problem, the time that cooked agave is stored in some production areas is long, which causes the growth of desired and undesired microorganisms on the agaves surface, consuming sugars without ethanol production. This factor has not been evaluated either, but it can cause losses of up to more than 20% when the milling stage start 2 weeks after agave cooking (data obtained by interview with producers). It is recommended that the cooked agaves are not stored for more than 1 week, for that it is preferable to determine the size of the cooking oven should be no greater than the amount of agave that can be processed in a week.

Fermentation

The fermentation is a crucial step during mezcal production where a complex and variable microbiota intervenes (Kirchmayr et al., 2017). Since the fermentation is carried out with cooked agave parts and fibers it can be considered a semi solid-submerged fermentation process. It is not possible to directly calculate the yields or the sugar conversion efficiencies by measuring the sugar and ethanol content at the start and the end of the fermentation, respectively, since the sugars contained in the agave pieces and fibers slowly dissolve into the must (Soto-García et al., 2009). Usually, the producers calculate the amount of agave used to produce one liter of mezcal. Depending on the agave species and its maturity, up to 25% of its weight correspond to sugars (fructans before and fructose/glucose after cooking) (García-Mendoza et al., 2017) and it would theoretically be possible to obtain 1 liter of Mezcal (50% ABV) with 4 kg of agave. The reality, however, is far away from that. The efficiencies are normally between 10 and 20 kg agave for 1 liter of mezcal but sometimes may raise up to 25–35 kg of agave (**Table 4**).

The fermentation vessels are frequently packed first with the cooked agave pieces and fibers and afterwards just enough water is added to cover the fibers. In many regions, the plant material is compacted before water addition, which limits even more the possibility that the sugars diffuse into the liquid phase. Besides the known impact of high initial sugar content on the performance of the yeasts in a broad range of other alcoholic fermentations, it is noteworthy that several other compounds derived from the raw material (e.g., saponins) or generated during the cooking step (e.g., HMF, furfural) are reported growth inhibitors for the microorganisms (Soto-García et al., 2009).

Most fermentations are carried out as spontaneous processes, allowing the growth of the native microbiota. Yeast species as *Pichia kluyveri, Kluyveromyces marxianus, Candida ethanolica, Saccharomyces cerevisiae, Torulaspora delbrueckii*, *Hanseniaspora guillermondii* and others has been found during the fermentation; also, several bacteria as *Lactobacillus* spp., *Acetobacter* spp., *Weissella* spp. *Leuconostoc* spp., this diversity explains variations in volatile compound profiles of each batch (Verdugo-Valdez et al., 2011; Páez-Lerma et al., 2013; Kirchmayr et al., 2014; Kirchmayr et al., 2017).

During mezcal fermentation stage commercial yeasts are normally not used. The cooked agave contains yeast inhibitors such as HMF, furfural, and saponins, and commercial yeasts cannot growth (Garcia-Soto et al., 2011; Alcázar et al., 2017). The wild yeast is adapted producing better fermentation behaviors. However, biodiversity must be conserved to warrant the native properties on each mezcal region process and avoid commercial yeasts.

Finally, the fermentations are frequently slow because the temperature is not controlled, the initial sugars generally are high (more than 150 g/L) and the initial yeast populations are low. Those factors trigger low ethanol production at the end of fermentation (25–50 g/L) (Vera Guzmán, 2012), This problem could be avoided if the mezcal producer increased the yeast at the beginning using an inoculum (with endogenous yeast) prepared before the fermentation. This activity let begin with higher yeast and low bacteria, increasing not only ethanol production, also, decreased the fermentation time and the quality could be homogenous (Nuñez-Guerrero et al., 2016).

Distillation

In the production of mezcal, two distillation steps are carried out. Only a few more technified factories achieve the desired alcohol content in one step by using distillation columns or through a special still design. The first step is carried out commonly by verting both the agave must and fibers into the still, obtaining an ∼5-fold increase in alcohol content in the distillate regarding the alcohol content in the must (between 20 and 30% ABV). The second step is achieved by distilling the obtained liquid again achieving a 2–3-fold increase in alcohol concentration (between 50 and 60% ABV). The still pots are frequently heated with wood where the amount and type of wood again defines the velocity of the temperature increase. To obtain a product which fulfills the specifications of the NOM standard the heads and tails are cut off during second distillation.

Distillation is the stage with greatest losses during the mezcal production process (15%), because some equipment used does not have a hermetic seal, which has repercussions in leaks during the process. In addition, the condensate does not have the correct temperature either in many mezcal factories the hot mezcal is recovered causing losses of aromas and ethanol (>40°C). Finally, the process is carried out using firewood, there is no sensible control of the heat, causing variations in the separation of the compounds due to changes in temperature. As two distillations are carried out, normally, the same equipment is used, so the losses are accumulated. To improve this stage of the process, producers must add thermometers in the still head, in the cooling water for condensation and in the condensate, finally, based on the temperatures, design a distillation strategy that allows maintaining controlled distillation conditions. In addition, adapt systems that prevent leaks, although this part is a bit more complex, due to the diversity of equipment used to carry out this stage of the mezcal production process.

Technical Recommendations

The easiest way to control and assure the process efficiently is by measuring parameters such as temperature, sugar concentration, and alcohol content and by weighting the raw material before and after cooking as well as the volume of water added to the fermentation vessel. The temperature inside the pot, the distillation flow and the temperature of the distillate also are important parameters to determine. A continuous record of the different parameters recommended to measure during each step of the mezcal production process contributes to observing and understanding how these impact on the efficiency of the process and on the quality of the final product. Since the production process are highly diverse between states, regions and factories and may be affected also by the different seasons during the year, specific production schemes should be established which allow mezcal producers to obtain their products with constant efficiency and expected quality.

In **Table 6**, the main problems encountered in the different process steps during mezcal production and the parameters that should be determined are shown.

SUSTAINABILITY ASPECT IN ARTISANAL PRODUCTION

The United Nations recently defined the Sustainable Development Goals (SDGs), also known as the Global Goals (United Nations, 2021). The United Nations adopted them in 2015 as a universal call to action to end poverty, protect the planet, and ensure that by 2030 all people enjoy peace and prosperity. The United Nations also "recognize that action in one area will affect outcomes in others, and that development must balance social, economic and environmental sustainability." Following the above, the European Union views sustainable development as meeting current needs without compromising the ability of future generations to meet their own needs (European Union, 2021). The United States Environmental Protection Agency considers that sustainability means that humans and their environment can harmony produce what present and future generations need (United States Environmental Protection Agency, 2021). All definitions coincide in the necessity of interaction of economic, social, and environmental aspects that reinforce them. Thus, sustainability is a concept inherent in the modern world that must be applied to the productive chains that are economic entities, but with social and environmental dimensions that must be harmonious with each other. It has been mentioned the capacity of the origin denominations to produce positive impacts in the economic, social, and environmental dimensions (Pérez-Akaki et al., 2021).

An excellent review about the characteristics and multiple uses of agaves was recently published (Pérez-Zavala et al., 2020). Nevertheless, alcoholic beverages production is only a part of the agave producing chain, including food, fiber, and fodder, among other uses. Mezcal is a spirit experiencing a strong growing demand with production from 980,000 L to 7.85 million liters between 2011 and 2020 (Martínez et al., 2019; Pérez-Zavala et al., 2020). It also leads to a growing need for raw material and overexploitation since natural population's extraction is often practiced without programs to ensure avoiding the risk of species extinction. Certain efforts are in progress to culture some agave species but unfortunately using a model of substitution natural forest areas by vegetative propagation using a few clones. It leads to an impoverishment of the genetic diversity of agave populations (Delgado-Lemus et al., 2014b). Nevertheless, despite the risk of adopting unsustainable practices to meet the growing

TABLE 6 | Common problems encountered and recommended parameters to determine during mezcal production process.

Process step	Harvest	Cooking	Crushing/grinding	Fermentation	Distillation	Product handling
Natural resources	Agave	Wood		Water	Wood, cooling water	
Common problems	Harvest of not-mature agave, long distance to factory, long storage time until cooking	Sugar loss (agave carbonization), inhibitor production	Sugar unavailability (undergrinding), storage time of cooked agave	Residual sugars (slugish fermentations), acidification	Overheating, Product contamination (oxidized stills)	Product contamination (inapropriate product storage)
					Ethanol and VOC loss (inefficient condensation), lack of fractioning schemes	
Recomended parameters to determine	Sugar content (refractometer)	Temperature, weight (wood, crude agave)	Weight (cooked agave)	Weight (agave), Volume (water), sugar content (densimeter), temperature (water for prep and during fermentation)	Volume, alcohol content, temperature (still, condensator, cooling water)	Alcohol content, temperature
Waste/by-products	Agave leaves	Ashes, burned agave stems			Bagasse, stillage/vinasse	

market demand, mezcal is a DOM that still has time to plan a growth that will result in sustainable production.

Mezcal production begins with selecting appropriate wild, semi-cultivated, or cultivated agave plants (Maciel Martínez et al., 2020). Agaves are considered non-timber forest products, which are species of slow growth and maturation. Whether wild or cultured, agave plants must grow for at least 8 years to be suitable for mezcal production (Martínez et al., 2019). The exploitation of more than 50 agave species allows producing mezcal in the Mexican regions included in the DOM (Pérez-Zavala et al., 2020; Tetreault et al., 2021). Several agave species allow satisfying primary and secondary human needs been the central element in the economy of the communities that are maguey managers (Delgado-Lemus et al., 2014b; Torres et al., 2015a,b). Nevertheless, agave species used to produce mezcal are widely exploited in the regions considered into the DOM due to the growing demand for mezcal by the global markets. Consequently, it determines the establishment of monocultures for the most exploited species, generating many biological, environmental, and sociocultural losses (Torres-García et al., 2019). Poorly planned exploitation does not include actions that ensure the recovering of wild populations, putting them at risk of deforestation (Delgado-Lemus et al., 2014b; Félix-Valdez et al., 2016). The agave used for mezcal production needs to cut inflorescences early, interrupting the sexual reproduction cycle (Félix-Valdez et al., 2016). Plantations of agave species should follow adequate management to preserve genetic diversity (Delgado-Lemus et al., 2014b). Previously, it had been mentioned important aspects to adequate agave plantation management such as (Torres et al., 2015):

- Protection of young escapees by avoiding domestic animals,
- To allow that at least 30% of adult wild and cultured plants produce seeds for reforestation and genetic diversity assuring,
- Consider the impact of seasonal changes on natural and cultured populations,
- To introduce at least 20% of one- and 2-year-old cultured agave plants, and
- To consider both professional ecological research and local knowledge to develop effective management programs.

Increase in mezcal production has strongly pressed wild populations of *Agave potatorum* at a producing zone in Puebla-Oaxaca (Delgado-Lemus et al., 2014a). Considering this finding, Félix-Valdez et al. (2016) studied the effect of extraction of those wild populations on their genetic variability. They concluded that there is an evident environmental degradation, but population variability could not be seriously compromised. Nonetheless, strategies to reintroduce plants must be urgently implemented because of high structuring among populations and high dependence on pollinators. It is particularly important in areas of low plant density (1,000 m^2 with <6 reproductive individuals) to assure the pollinator's arrival. An additional recommendation is to design management plans without mixing seeds from different populations because adaptation to different environments may vary.

Mezcal production in Zacatecas was described focusing in to analyze the agro-industrial chain as well as to propose a tactical supply chain planning model (López Nava et al., 2014). Some of their findings are the following. Agave producers and some mezcal makers have poor socioeconomical conditions. There is deficient integration among agave producers and mezcal producers, which generates significant bottlenecks along the producing chain, causing that only 33% of the mezcal production capacity is used. Mezcal producers must upgrade the management of their factories, focusing on the marketing, sales, and outbound logistics activities which were the most susceptible to improvement. These authors recommended developing a marketing plan to enhance mezcal consumer appreciation and to implement a coordinated and collaborative process between micro, small, and medium-sized companies in the sector to strengthen the production chain.

Mezcal production from *Agave cupreata* was analyzed to determine the environmental impact and energy demand (Maciel Martínez et al., 2020). Those authors established that an industrialized process generates more CO_2 emissions than process carried out by hand, while processes using cultured agave also generates more CO_2 emissions than that using wild agave. They also determined an energy demand of 218.4 MJ per liter of mezcal which is equivalent to the energy obtained from the combustion of 6.16 L of gasoline.

Pérez-Zavala et al. (2020) pointed out that natural cross-pollination allows to maintain genetic diversity to agave species, while asexual reproduction by offshoots generates low genetic variability respect to mother plants. Then, wild plants extraction diminishes agave reproductive and demographic performance (Félix-Valdez et al., 2016).

It has been highlighted the efforts to culture non-timber forest products of high market demand such as agave. All efforts for culture non-timber forest products have the objective to diminish the pressures on wild populations. Nevertheless, it needs to use additional land as well as other resources not always available for rural communities, which can lead to a debt trap for those people. Additionally, these land-use changes can produce environmental problems such as deforestation, diminishing genetic diversity, and ecosystem degradation (Krishnakumar et al., 2012).

Sustainable practices in the mezcal production chain have focused mainly on raw material production (Maciel Martínez et al., 2020). In fact, it has been argued that mezcal culture would be protected preserving plants but also farming and production recipes passed from generation to generation (Bullock, 2017). Nevertheless, converting agave heads into mezcal needs to be improved to maximize the use of fermentable sugars. Moreover, the economy of the whole producing chain could be enhanced by working on the energy efficiency of the process and using subproducts such as agave leaves, vinasses, and bagasse. It would allow obtaining other valuable products and reduce the environmental impact of the mezcal production chain.

Mezcal production chain could be the point of support to create a sustainable economy based on the integral use of agave, extending the benefits so that they range from farmers to investors, preserving the environment and the lifestyle of the communities. Pérez-Zavala et al. (2020) pointed out that ubiquity of agaves in Mexico should be exploited to identify agave species probably unnoticed to promote investments that enhancing the life conditions, particularly for the Mexican population living in low socioeconomic communities.

Mezcal has had short chain involvement (proximity among producers and consumers) and small scales, but it could be changed by the recent accelerated growth of the product (Pérez-Akaki et al., 2021). This expansion of production and commercialization attracts the interest of international investors who simply add products to their products portfolios. Nevertheless, it could be unincentivized by Mexican normativity that recognizes mezcal's artisanal and ancestral categories (NOM-070-SCFI, 2016).

Bowen and Zapata (2009) argued that DOMs must have a legal framework that warrants sustainable production practices to really contribute to perdurable rural development and environmental preservation. Benefits to farmers have been limited although the growth in exportation of mezcal (Pérez-Akaki, 2016).

Strategies to reach sustainable production of mezcal should consider close interaction among the participants of the mezcal production chain (agave producers, distillery operators, bottlers, and sellers). It may ensure fair distribution of profits for all of them and should attract consumers for a high-quality product. Consumer's attraction actions can include alliances with:

- Organizations of restaurants and bars owners to promote mezcals from diverse origin (region and/or agave species).
- Research centers to study biology, physiology, and ecology of agave, to optimize their production processes and help to highlight the distinctive characteristics of each mezcal, as well as to help planning sustainable production.
- Government instances to fund programs and projects for wild populations preservation, assuring genetic diversity, and sustainable cultivation of agave. Mexican government should review and actualize the legislation concerning mezcal production to include a sustainability perspective.

Finally, it is mandatory to create geographic information system maps of wild and cultivated agave plantations and the location of distilleries, allowing everyone in the production chain to receive a fair profit and monitor levels of harvesting of wild agave. These maps will help to plan sustainable levels of extraction of wild agave populations. It must be understood that these are very current ideas, which means changing the way people do things. Mezcal chain producers face some constraints in reaching sustainable production, such as high fees and bureaucracy to certify the product, mainly small producers. They also face high cost of inputs, low efficiency of production processes, and poor linkage with researchers to help overcome such limitations. Pérez-Akaki et al. (2021) also highlighted the public institutions' responsibility to support and guide the development of productive chains to reach more equitable benefits for all participants.

Another proposal is that of Vázquez Elorza et al. (2020), who propose the establishment of technological route maps. This strategy seeks to improve the functionality of production chains, based on recognizing what is needed to develop better products for the market. Through workshops with agave and mezcal producers in Oaxaca and Aguascalientes, it was detected that changes in the markets force companies to innovate and look for alternative routes. However, in these workshops it was clearly detected that the lack of organization for the use of limited resources constitutes a very urgent problem to be solved, in addition to all the above-mentioned.

ADDITIONAL SUSTAINABILITY ASPECTS REGARDING MEZCAL FACTORIES

Despite the highly diverse practices and production processes that are carried out in the different mezcal production regions, exist some common features that all mezcal factories should consider. Those aspects include location, conception, construction, and area distribution of a mezcal factory.

Regarding the location, the mezcal production process requires high quantities of three natural resources: agave, firewood, and water. So then, it seems logical that any factory should be conceived and built a short distance to them. Unfortunately, due to historical reasons, e.g., the prohibition period during the 20th century, many factories are found in remote places, frequently in the mountains, where these resources are not always abundant. Remarkably, the water supply is limited in many factories, and the provision with this resource is accomplished with tank trucks, increasing fuel costs.

Since the four stages of mezcal production are sequential and lineal, an adequate space distribution is needed to enhance process efficiency and productivity. It is logical that the grinding area, for example, would be between the cooking and fermentation areas. As enormous amounts of material must be moved manually between areas, they should be adjacent. Ideally, they should be conceived in different heights/levels, with the cooking area at the highest point and the distillation and storage area at the lowest. Although, as mentioned, several factors regarding the storage of raw, cooked, and crushed agave may affect process efficiency, the space for each stage and the capacities of the machinery and equipment should be considered before constructing a mezcal factory. The load capacity of the pit oven, for example, should consider the time needed for processing the cooked agave. At the same time, the size of the still should contemplate the capacity of fermentation vessels.

Historical reasons forced mezcal production into secrecy, explaining why mezcal factories in the past had to be austere regarding equipment or construction. Still, nowadays, several aspects concerning good manufacturing practices should be implemented while preserving traditional processes. Some examples are the following:

1. Concrete floors and walls which separate the production areas from the surrounding environment would improve the cleanliness and the impact of weathering. The wood fire used to heat the stills during the distillation process generates smoke which directly affects the workers' health.
2. Installing chimneys is mandatory to assure the correct extraction of the smoke improving the worker's safety.
3. The utilization of by-products such as agave leaves, vinasses, and bagasse must be considered to conceive a new distillery.

Some calculations can be made to help establish a sustainable mezcal production plant that schedules a desired annual production. Consider a factory with the annual goal of producing 14,000 liters of mezcal at 55% ABV, a typical production in the mezcal industry. Considering a yield of 10 kg of agave per liter of mezcal, that factory will require ∼144 tons of agave. Since agave pineapples weigh 35 kg, around 4,100 agave plants will be harvested to achieve the production goal. Sustainable exploitation demands replanting at least that number of agave plants. Nonetheless, some plants would have a disease problem or damage by animals. It means that maintaining the wild or cultivated population will require planting 4,500 agave plants a year, considering around 10% of damaged plants.

Care about the factory operation; it must be considered that mezcal is usually produced for 9 months during the year because production is suspended during the rainy season. Then, near to 1,560 liters must be produced each month. It implies that the weekly agave processing must be close to 4,000 kg. Fermentation performs near 30–32°C, and warm water will require to start the fermentation in some cold areas from November to February. Inoculum is not usually employed to start fermentations.

Nevertheless, it has been proposed to add an inoculum based on selected wild yeasts. It should be prepared 1 day before starting the fermentation using agave juice and aeration in an appropriate volume (Kirchmayr et al., 2017). Regarding distillation, it is recommended to perform it by controlling the pot, the distillate, and the condensation water temperatures. An introductory remark about increasing the process yield is the need to recover sweet honey during cooking.

Producers want to preserve their traditional artisan processes but reach higher process yields. This change could take a few years, but it is likely never to happen. The producing areas are mainly located in highly marginalized municipalities that frequently do not have access to electricity, potable water, and access roads. Therefore, agave producers, mezcal producers, sellers, and governments must actively work to reach a better product quality and a higher price for the mezcal. This collaboration also would preserve agave species as well as the traditional knowledge and lifestyle of the producers.

Tequila was converted from a regional beverage to a distilled spirit with global success. However, it brought over-farming and technician processes needed to increase production and to satisfy the market demand. As a result, today's tequila has little in common with the traditional drink from a 100 years ago, while people of the producing communities have not received the benefits of the so-called tequila boom (Bowen, 2015). Bullock (2017) pointed out that it forgot the aim of a denomination of origin concerning protecting the product, but mainly the culture and people around the production process. This author questions whether it can be done better when taking mezcal to the global marketplace.

CONCLUDING REMARKS

This article presents elements of the current situation of mezcal, the production chain, as well as the need for sustainable development, considering that it is a traditional and artisanal process in a context of a substantial increase in demand. In this sense, the problems that this entails were mentioned, such as: the cultivation of agave, which in many production areas is wild and there is no established procedure for its cultivation or management to guarantee its commercial exploitation. The different agave species that can be used in mezcal production were also mentioned, which not only has an impact on the sensory properties of the product, but also on production yields and composition, including compounds such as methanol, furfural, and higher alcohols.

The review of the regulations that apply to mezcal suggests that a thorough and well-supported review of the parameters of the standard is urgently needed, particularly in the authorized levels of methanol, because wild agaves may contain methanol precursors in higher and variable concentrations between species, impacting on compliance with the physicochemical parameters of the official Mexican standard. Compliance with the current parameters sometimes becomes complex and can limit domestic marketing and definitely the export of the product.

Current artisanal and ancestral mezcal production processes require enormous quantities of agave to produce small volumes, due to losses at each stage of the production process. In the case of the use of wild agaves, as they are overexploited, their availability has gradually diminished in some regions, a situation that could, in a brief time, have an impact on mezcal production capacity. Currently, there is a fear that the adoption of technology will eliminate the characteristic of being a traditional and artisanal product, with its own regional characteristics. It is necessary and urgent to carry out studies to evaluate the impact of technological adoption to guarantee the homogeneous quality of the products obtained, which would make it possible to preserve and promote the recognition of mezcal and even the availability of agave in the required quantities. The article provides elements that demonstrate that it is possible to implement different technologies to avoid losses and standardize the process. These elements also contribute to a more sustainable process.

In general, strategies to achieve sustainability in the mezcal production chain must involve all actors in the chain, including consumers, so that they understand the consequences of consuming mezcal made from wild agave that does not come from a controlled and sustainable extraction process.

This work demonstrates that it is possible to move the mezcal production process toward a more sustainable process, without affecting its artisanal image, taking care of the cultural part of the process by applying appropriate technologies.

AUTHOR CONTRIBUTIONS

MK, NS-C, and AM contributed to conception of the review. MK, NS-C, MA-P, JP-L, and AM wrote sections of the manuscript. AM prepared the final version. All authors contributed to manuscript revision. All authors contributed to the article and approved the submitted verion.

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