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Pulque: Beverage Transcending Historical Boundaries

Diana Rodríguez-Vera [1,*], Roberto Rivera Pérez [2], Ivonne Maciel Arciniega-Martínez [3], Marvin A. Soriano-Ursúa [4], Aldo Arturo Reséndiz-Albor [5], Fernanda Magdaleno-Durán [6], Jazmín García-Machorro [7] and José A. Morales-González [7,*]

1 Sección de Estudios de Posgrado e Investigación, Escuela Superior de Medicina del Instituto Politécnico Nacional, Plan de San Luis y Diaz Mirón s/n, Mexico City 11340, Mexico
2 Sociología, Universidad Autónoma Metropolitana Azcapotzalco, Mexico City 02128, Mexico; rrp@azc.uam.mx
3 Laboratorio de Inmunonutrición, Escuela Superior de Medicina del Instituto Politécnico Nacional, Plan de San Luis y Diaz Mirón s/n, Mexico City 11340, Mexico; iarciniega@ipn.mx
4 Academia de Fisiología, Escuela Superior de Medicina del Instituto Politécnico Nacional, Plan de San Luis y Diaz Mirón s/n, Mexico City 11340, Mexico; msoriano@ipn.mx
5 Laboratorio de Inmunomucosas, Escuela Superior de Medicina del Instituto Politécnico Nacional, Plan de San Luis y Diaz Mirón s/n, Mexico City 11340, Mexico; aresendiza@ipn.mx
6 Clínica de Nutrición Especializada Béke, Texcoco 56130, Mexico; nutfernandabeke@gmail.com
7 Laboratorio de Medicina de Conservación, Escuela Superior de Medicina del Instituto Politécnico Nacional, Plan de San Luis y Diaz Mirón s/n, Mexico City 11340, Mexico; jazzgama81@gmail.com
* Correspondence: drodriguezv1904@alumno.ipn.mx (D.R.-V.); jmorales101@yahoo.com.mx (J.A.M.-G.)

Abstract

Pulque, an available traditional Mexican fermented beverage, has deep ethnographic and cultural significance. It was originally consumed by pre-Columbian civilizations, including the *Teotihuacanos*, *Mexicas*, *Otomies*, *Zapotecas*, *Mixtecas*, and *Maya*. It was revered as a sacred drink with both ceremonial and medicinal uses, often reserved for elites and priests. Its production is based on the ancestral extraction and fermentation of *aguamiel*, a sweet sap obtained from agave plants. While advances in food technology have occurred, traditional techniques for obtaining and fermenting *aguamiel* remain prevalent, especially in rural communities, reflecting the resilience of indigenous knowledge systems. Recent interest in *pulque* has focused on its nutritional content and potential health benefits when consumed in moderation, though risks related to excessive intake remain a concern. Moreover, cultural initiatives aim to revitalize indigenous heritage through gastronomic promotion, tourism routes, and festive traditions. This study explores *pulque's* production processes, its cultural symbolism, and its evolving role within Mexican society, suggesting that its survival reflects both continuity and adaptation in the face of modernity. This paper is also presented as a narrative integrative review to explore the biocultural significance of *pulque* across the anthropological, historical, biochemical, and public-health domains.

Keywords: biocultural heritage; functional beverage; *agave* fermentation; tradition; cultural symbolism

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1. Introduction

Traditional fermented beverages have garnered increasing attention in recent decades due to their complex sociocultural significance, nutritional potential, and microbial diversity (Steinkraus 2004; Tamang et al. 2016). Among them, *pulque*—a pre-Hispanic fermented drink derived from the sap of certain *Agave* species—stands out for its long-standing role in the ceremonial, ritual, and dietary practices of Mesoamerican civilizations (Bruman 2000). While widely recognized as a cultural symbol, *pulque* also possesses functional nutritional

attributes that have sustained indigenous populations in central Mexico, particularly in contexts of dietary scarcity (Dale et al. 2023; MacNeish 1964).

Pulque (also known as *neutle*, *tlachicotón*, *cara blanca*, *tlapehue*, *vino blanco*, and *iztacochtli*) stands as the principal traditional fermented beverage within the studied region (Gabriela Daniela Álvarez-Ríos et al. 2022). The objective of this article is to examine *pulque* through an interdisciplinary lens that bridges ethnographic inquiry and a concise historical review. This exercise in interdisciplinary analysis does not delve into exhaustive depth within each field, but rather aims to articulate a cross-sectional synthesis.

Our approach considers *pulque* as a contemporary phenomenon that endures into the present as a historical echo—a living reflection of the past. Beyond its cultural and symbolic significance, the study also explores its nutritional properties and potential implications for public health. This analysis engages in a horizontal dialogue between disciplines, privileging methodological and epistemological plurality to explore *pulque* not only as a beverage but as a nexus of tradition, identity, and health knowledge systems.

Accordingly, we synthesize anthropological, historical, and microbiological evidence to reposition *pulque* as a culturally significant fermented beverage with potential probiotic benefits. This paper is structured as follows: Sections 1 and 2 contextualize *pulque* within pre-contact Mesoamerica; Section 3 examines ethnographic records; Section 4 describes traditional Mesoamerica and traditional fermentation methods; Sections 5 and 6 review *pulque's* nutritional and functional properties; and Sections 7 and 8 discuss contemporary public-health and probiotic implications.

Pulque has historically contributed to the daily energy intake and micronutrient supply among rural communities, with studies documenting its content of vitamin C, B-complex vitamins, amino acids, and minerals like calcium and iron (Escalante et al. 2004). In addition to its nutritional value, *pulque* carries substantial ethnomedical relevance. Traditional knowledge systems attribute to it digestive, diuretic, and immunological benefits, particularly in postpartum recovery and reproductive health (Alberti-Manzanares 2006). These culturally embedded uses reflect a broader legacy of indigenous biocultural practices, which continue to inform discourses on traditional medicine and food sovereignty.

Despite its cultural and nutritional relevance, *pulque* has been largely overlooked in contemporary global discourse on fermented foods, which tends to prioritize beverages such as kombucha or kefir. Moreover, its stigmatization during colonial and postcolonial periods has hindered its scientific valorization, despite increasing consumer interest and heritage-based revitalization efforts (Vázquez-Medina 2019). Recent scholarly work has begun to reposition *pulque* as a living cultural heritage and a bioresource of interest to food science, microbiology, and anthropology (Escalante et al. 2016; Pérez-López et al. 2021).

This study proposes an interdisciplinary reflection on the historical, nutritional, and sociocultural dimensions of *pulque*, aiming to contribute to its recognition as an element of Mexico's intangible national heritage. We argue that *pulque's* resilience and adaptive significance make it a valuable case study in the intersection of traditional knowledge systems, nutrition, and identity politics.

This study adopts a narrative review methodology. We searched Scopus, PubMed, AnthroSource, Redalyc, and SciELO for peer-reviewed publications from 1950–2024 using Boolean strings: ("*pulque*" OR "*aguamiel*") AND ("*Mesoamerica*" OR "*agave*"). The inclusion criteria comprised primary ethnohistorical analyses and biochemical studies. The exclusion criteria ruled out unpublished fieldnotes, conference abstracts, and non-peer-reviewed gray literature.

This integrative synthesis is novel in its cross-disciplinary scope, bringing together disparate strands of *pulque* scholarship to articulate its status as both a heritage beverage and a functional probiotic agent.

2. What Is Pulque? An Overview

Pulque is a traditional fermented beverage from Mexico, deeply rooted in the pre-Hispanic socio-religious framework of various Mesoamerican cultures (Muccino 2025). It held significant value in *Mixteca* mythology and cosmology, as well as among members of other contemporary Indigenous groups. According to Escalante (Escalante et al. 2016), *pulque* is a white, viscous beverage with a strong odor, produced through the fermentation of the sugary sap known as *aguamiel*, which is extracted from the *xamini maguey* (*Agave salmiana*), also referred to as *agave pulquero*, *manso*, or *de montaña*. Other *maguey* species—such as *Agave atrovirens*, *Agave mapisaga*, and *Agave ferox*—can also be used for *aguamiel* extraction (López-Aguilar et al. 2024). This sap provides the natural medium where a diverse and abundant community of microorganisms thrives, enabling the fermentation process essential to produce *pulque* (Table 1) (Trejo et al. 2020).

Table 1. Biochemical parameters across pulque production stages.

Stage	pH Range	Ethanol (% *v*/*v*)	Sugar Content (°Brix)	Additives/ Substrates	Reference
Aguamiel (Unfermented Sap)	6.0–6.8	<0.1	10–14	None	(Gonzalo David Álvarez-Ríos et al. 2020)
Pulque Fresco (Early Fermentation)	4.0–4.5	1.0–4.0	6–8	None	(Escalante et al. 2008)
Pulque Maduro (Mature Fermentation)	3.5–4.0	4.0–7.0	2–5	None	(Aguilar-Moreno 2001; Bayardo-Rivera 2023)
Curado (Post-Fermentation Variant)	3.5–4.0	2.5–6.0	4–15 †	Fruit, cereal, vegetable, sugar, or honey	(Servin 2023)

† Sugar content varies widely depending on adjunct type and concentration. pH: Measured at 20 °C; the decline in pH from *aguamiel* to mature stages reflects progressive acidification by fermentative microbiota; Ethanol: Expressed as % *v*/*v* (20 °C), which indicates the milliliters of ethanol present per 100 mL of *pulque*. Sugar Content: Expressed in °Brix for direct comparability; residual sugars decrease as fermentation advances.

Instituto Nacional de Antropología e Historia (n.d.) offer an etymological insight:

Among Mexicans, the name for *pulque* was *iztacochtli*, meaning white wine. When it spoiled, it was called *octli poliuhqui* (meaning *pulque*). Since it deteriorates quickly—remaining potable only for 24 to 36 h—those who produced, sold, or consumed must have frequently uttered *poliuhqui* when observing spoilage. The Spaniards likely misconstructed this term as the drink's proper name (rather than recognizing it as a descriptor of spoilage) and, in so doing, cemented the barbarism "*pulque*" (1294, italics in original; López 2018).

Anthropological evidence, including pottery, murals, codices, chronicles, and oral cosmological traditions, suggests that this *maguey*-based alcoholic beverage was already part of the diet of the inhabitants of Teotihuacan (ca. 150 BCE–650 CE). *Pulque* is therefore one of the oldest, if not the most important, fermented beverages in Mesoamerican history. Furthermore, Correa-Ascencio et al. and Valadez assert that there is sufficient evidence to trace the origin of *pulque* to the *Otomies*, the first political and cultural group to manufacture, distribute, and commercialize it (Correa-Ascencio et al. 2014; Valadez 2012).

Several studies emphasize the nutritional and functional value of *pulque*, particularly due to its regular intake among the Indigenous *Otomi* population. The main components identified in *pulque* include sucrose, gum, ash, pantothenic acid (vitamin B5), thiamine (vitamin B1), 4-aminobenzoic acid, pyridoxine (vitamin B6), biotin (vitamin B7), ascorbic acid (vitamin C), and riboflavin (vitamin B2) (Escalante et al. 2008; Tovar 2008), along with amino acids such as isoleucine, leucine, lysine, cysteine, phenylalanine, tyrosine, threonine, tryptophan, valine, methionine, and histidine (George et al. 2018; Morales de León et al. 2005).

Beyond its nutritional contributions, *pulque* exhibits a low glycemic index and is a rich source of microorganisms with high biotechnological potential, granting it both prebiotic and probiotic properties (Contreras and Rodríguez 2007).

3. Historical and Sociocultural Context of Pulque

Pulque has a history that spans thousands of years in the central Mesoamerican region of Mexico, holding a prominent role in the *Mexica* socio-religious framework and mythology, as illustrated by anthropological evidence (Sejourné 1996).

Mythic narratives, notably the *Quetzalcoatl* legend, served as moral examples that reinforced social taboos (Read and González 2000). Rather than isolate this episode, we now integrate it into a comparative corpus of mythic prohibitions, alongside *Maya Bacab* legends (Taube 1989), to illustrate how divine transgression codified human consumption rules.

Anthropological, ethnohistoric, and ethnographic evidence attests that *pulque* was widely consumed across the Mesoamerican highlands—from the Basin of Mexico through Puebla, Tlaxcala, Hidalgo, Morelos, and into parts of Veracruz—underscoring its pan-regional sociocultural significance (González 2025; Pilcher 1998).

Also, *Agave salmiana* was systematically cultivated in Mesoamerican lowlands by ca. AD 200, with residue analysis confirming fermented *aguamiel* consumption among commoners (González 2025; Tokovinine 2016). These practices accord with status-marker frameworks posited by Pearson (Pearson 2016) in his comparative study of alcoholic beverages.

Furthermore, Ortiz Morales (Ortiz Morales 2010) delineates the ritual codices prescribing *pulque* use exclusively for sacerdotal elites in the Late Postclassic period.

Colonial sources such as the *Florentine Codex* explicitly restrict *pulque's* ceremonial use to priestly castes (de Sahagún 1950, [Bk. 9]: pp. 89–91). Comparative analyses by Pearson (Pearson 2016) and Morales-Hernández (Morales-Hernández 2015) reveal analogous hierarchies in Andean chicha. These rules governed not only who could drink *pulque* but also the types of vessels and settings permitted, underscoring its role as a distinction marker in Mesoamerican polities (Wolff 1963).

The *Mexicas*, in particular, revered *pulque* as a sacred drink and divine gift. It was highly esteemed and reserved for the nobility and priesthood, who consumed it during ceremonial and religious rituals. In instances requiring voluntary human sacrifice, especially of infants, *pulque* was at times used to facilitate the passage into death (García et al. 2024). Nowadays, *pulque* plays an important role in daily life in some places, serving as a source of nourishment and energy for the general population (Medina Mendoza 2023).

The *Maya* also consumed *pulque*, though its use was less prevalent than among the *Mexicas* and neighboring cultures of the Mexican highlands. Archaeological findings suggest that the *Maya* cultivated *agave* and fermented *aguamiel* sap to produce *pulque*, which was also used in rituals and ceremonies, although other intoxicating beverages, such as *xtabentún*, were more prominent (Medina Mendoza et al. 2023; del Carmen Navarrete-Torres and Muñoz-Aparicio 2021).

Pulque occupied a significant place in Mesoamerican iconography and mythology. Artistic depictions in murals, pottery decorations, and codices frequently include imagery of *pulque* consumption and production. These images portray individuals drinking *pulque* from *jícaras* (gourds) and depict *agave* plants and *aguamieleros*—the specialists who harvested and fermented the sap (Blas-Yañez et al. 2018). Even today, numerous *pulquerías* (places where *pulque* is sold) continue the tradition of adorning their walls with scenes of *pulque* production, distribution, and consumption, using vessels and containers rooted in pre-Hispanic tradition and colonial syncretism (Álvarez-Duarte et al. 2018).

As previously noted, *pulque* is deeply embedded in the cosmovision and mythology of central and southern Mexican Mesoamerican cultures, also in contrast to other pre-Hispanic groups, including the *Maya*. In *Mexica* mythology, *Ometochtli* was considered the *pulque* god and was often portrayed as an intoxicated deity, while his sister *Mayehuatzin* was represented as the mountain *agave* or *maguey*, provider of *aguamiel* and the *maguey* flower—both integral to the pre-Columbian diet. Thus, the connection with the *maguey* was not limited to its ritual and ceremonial role; it was also valued for its leaves (used in dishes such as *mixiote*), its flowers (a dietary resource), and its sap (*aguamiel*), which could be fermented into a refreshing, energizing, and alcoholic beverage. However, its consumption requires moderation, as its excessive use has well-known consequences (Valadez-Blanco et al. 2012).

During the colonial period (1532–1810), *pulque* maintained its popularity among the Mexican population (Moreno-Terrazas et al. 2017). Its economic significance prompted numerous Spanish investors to obtain permits from the Spanish Crown and establish *pulque*-producing *haciendas* in locations such as Apan in Hidalgo, as well as Zuapayuca and San Telmo in the State of Mexico, among many others (Calderón-García et al. 2024).

Throughout the independence era (1810–1820), the production and consumption of *pulque* continued to generate substantial economic returns. However, modernization or industrialization of the production process was hindered by the "delicate nature of *pulque*". Despite this, the beverage maintained its economic and social relevance, even during the American (1846) and French (1861) invasions. Its cultural footprint is evident in national historical novels such as *Los Bandidos de Río Frío* by Manuel Payno and *El Zarco* by Ignacio Manuel Altamirano, which reference *pulque*, its commerce, *pulquerías*, and traditional production practices (Altamirano 2004; Payno 2004).

During the Revolutionary period (1910–1920), a pivotal decade that profoundly transformed Mexico's political, social, and agrarian structures, despite widespread destruction of *haciendas*—including those primarily producing *pulque*—the trade endured. Surviving remnants of this legacy include several *hacienda* structures in Morelos, the State of Mexico, and Hidalgo, which now stand as relics of once-powerful socio-economic entities.

Following the Revolution and subsequent stabilization, a coordinated smear campaign was launched against *pulque*, driven by economic interests favoring beer, *tequila*, and wine. This campaign coincided with U.S. Prohibition (1920–1931), during which foreign capital and investment increasingly flowed into Mexico, where *pulque* represented a strong domestic competitor.

During the *Porfiriato* (a period characterized by the government headed by General Porfirio Diaz) and the early 20th century, *pulque* was systematically targeted by racist and hygienist campaigns designed to supplant indigenous traditions with European-style beer. Francisco Bulnes's 1899 treatise equated *pulque* with "corn-fed backwardness", branding it "vile and rancid" and casting its consumers as racially degenerate. Newspapers amplified this stigma by contrasting "*pulque sucio*" (dirty *pulque*) with imported "*cerveza limpia*" (clean beer), propagating the libel that human and animal excreta were used in its fermentation to arouse public disgust.

Public-health ordinances enacted in Mexico City (1905–1915) further regulated and spatially restricted *pulquerías*, implicitly framing *pulque* drinkers as uneducated and unhygienic. Gaytán (Gaytán 2013) demonstrates how temperance advocates and journalists projected racialized tropes of "Indian degeneracy" into *pulque*, using its decline to symbolize Mexico's march toward modernity. Finally, Ramirez-Rodríguez's study shows how these overtly racist and modernization-driven narratives accelerated *pulque's* fall from favor, cementing its enduring stigma (Ramírez-Rodríguez 2018).

This anti-*pulque* campaign, orchestrated by political elites, stigmatized the drink, its producers, and its consumers, depicting it as unsanitary and associated with poverty, indi-

geneity, and illiteracy (Boletín UNAM 2002). Manuel Gamio's *Forjando Patria*, for example, classified *pulque* as a cultural element to be eradicated for hindering national progress and modernization. Myths spread that *pulque* production involved adding fecal matter (referred to as *muñecos* or *muñecas*) during fermentation—allegedly linked to witchcraft and black magic. *Pulque* spoils completely if mixed with water or foreign substances, emphasizing the delicacy of its production (Gamio 2008).

As these smear campaigns and "urban myths" failed to fully suppress the industry, the federal government initiated a program known as *El Timbre*, which operated from the 1930s to the 1970s. Mounted police, forest rangers, and other state forces destroyed production and distribution sites and detained those involved. However, *pulquerías* that paid taxes, adhered to regulations, or bribed local authorities were permitted to operate, with distributors granted "neutral" zones free from legal enforcement (Colunga-GarcíaMarín et al. 2007).

Nonetheless, violent clashes between *tlachiqueros* (*pulque* producers) and enforcement forces were reported, resulting in injuries and fatalities on both sides (J. Rivera 2013). The state also promoted the image of *pulquerías* as centers of disease, crime, prostitution, and poverty, leading to regulatory measures such as reduced service hours and increased taxation on the production, transport, and sale of *pulque* (Ramírez-Rodríguez 2018).

In many central Mexican communities, *pulque* remains central to the *sistema de cargo* (secular and religious positions held by men or families in rural indigenous communities), with annual parties requiring officiants to sponsor *pulque*-based rituals (Ramírez 2013). Ethnographic fieldwork in Tlaxcala (Backstrand et al. 2001) shows how these events perpetuate communal bonds while positioning *pulque* producers within civic hierarchies.

Unambiguously, throughout the 20th century, *pulque* faced numerous challenges, including competition from other alcoholic beverages and post-revolutionary government suppression. However, recent decades have witnessed a resurgence in *pulque*, driven by renewed interest in traditional Mexican culture and heritage (Ojeda-Linares et al. 2021).

4. The Importance of Aguamiel in Pulque Production

Aguamiel is a translucent sweet liquid extracted from the core of the *maguey* or mountain *agave*. The extraction process begins with the selection of a mature *agave* at its optimal growth stage, just before flowering (Castaneda-Ovando et al. 2023). The *tlachiquero*, the person responsible for selecting and "scraping" the *agave's* core, must first identify and outline the plant's face. Then, an incision is made in the center, granting access to the *agave's* heart, also known as the *piña* or *cabeza*. From that point onward, and for several consecutive days starting early each morning, the *tlachiquero* scrapes the *piña*, which gradually begins to release sap, referred to as *sábila* or *agüita*, both synonymous with *aguamiel*—until the *agave* ultimately dies, a process taking several months (J. Rivera 2013; Vera Morales et al. 2024;). It is worth emphasizing that the optimal season for *pulque* production spans from December through February, according to Rivera (J. Rivera 2013). However, *pulque* is available and can be consumed year-round (Blas-Yañez et al. 2019).

Historically, *aguamiel* was collected in containers called *castañas*, which were strapped to the sides of pack animals. Though these vessels are no longer in common use, the necessity of transporting *aguamiel* to a production facility remains. Upon arrival, the *aguamiel* is pooled in large-capacity containers, where fermentation begins. Often, one or two liters of previously produced *pulque*, known as *tunas*, are added to accelerate the fermentation process. It is crucial to underscore the delicate nature of this traditional process, wherein any contaminant compound, or foreign substance—including water—can spoil the entire production batch (Narro-Robles et al. 1992; Noriega-Juárez et al. 2025).

In central Mexico, the prime harvest window for *aguamiel* (and subsequent *pulque* production) runs from December through March, coinciding with the region's dry season

and the cessation of May–November rains. During the rainy months, open cuts in the *agave piña* are prone to dilution by rainwater and introduction of spoilage microbes, which depresses sugar concentration and yields erratic fermentations (Luis et al. 2019). In contrast, the December–March period delivers stable sap yields (20–30 L per plant) with 10–14 °Brix soluble solids, pH 6.0–6.8, and minimal exogenous microbial load—conditions that support predictable ethanol production (Day 1: 1–2% *v*/*v*; Days 2–3: 3–4% *v*/*v*) in seed-driven fermentations (Astudillo-Melgar et al. 2023; Huezcas-Garrido et al. 2022). Cooler, arid conditions also inhibit acetic-acid bacteria, preserving the characteristic organoleptic and functional qualities of fresh *pulque* (Enríquez-Salazar et al. 2017).

Vera Morales et al. (Vera Morales et al. 2024) explained that during fermentation, lactic acid bacteria (*Lactobacillus acidophilus* and *Leuconostoc mesenteroides*) and yeasts (*Saccharomyces cerevisiae*)—naturally present in the environment and in the *aguamiel* itself—facilitate the transformation of the liquid's natural sugars into two byproducts: carbon dioxide (CO_2) and alcohol. The alcohol concentration typically ranges from 4.26% to 6.0%, a level comparable to that of Mexican beer, which averages between 3.6% and 5.5%.

The conversion of *aguamiel* to *pulque* (via endogenous *Brettanomyces* and lactic-acid bacteria) elevates the ethanol concentration from <0.5% to 2–4% (Astudillo-Melgar et al. 2023), thereby restricting its ritual availability and altering communal consumption ceremonies (i.e., *tlachiyalli*) into stratified feasts.

Regarding the production process, *pulque* involves ancestral techniques passed down through generations via oral tradition. One such method includes the use of *tinacales*, specialized spaces designated for fermenting *aguamiel*. These are characterized by controlled temperature and humidity conditions, allowing for natural fermentation over a defined period, typically between 12 and 24 h (Escalante et al. 2004). It should be noted that, according to customary practices, both the extraction of *aguamiel* and the production of *pulque* are predominantly male-dominated activities. In rare cases where women participate, they are traditionally prohibited from engaging during menstruation, or they participate as substitutes for absent men (Tovar et al. 2008).

As part of the fermentation process, it is customary to use *tunas* or *madres de pulque*—small amounts of pre-fermented *pulque*, which naturally contain active yeast and bacterial strains, to initiate and accelerate fermentation, as previously mentioned (Escalante-Minakata et al. 2008).

We concur with Escalante et al. (Escalante et al. 2004) that *pulque* is produced in an artisanal manner using traditional techniques, avoiding the addition of chemicals, additives, or other organic components. This ensures that *pulque* retains its distinctive flavor, as well as its nutritional, cultural, and historical value, which it continues to embody to this day.

Aguamiel functions first and foremost as a medicinal hydrating beverage, its 10–14 °Brix of mono- and disaccharides, coupled with Na^+ and K^+ at 20–30 mg/L delivering an osmolality of ~250 mOsm/kg that mitigates dehydration in diarrheal illnesses—critical for infants and the elderly (Cervantes-Elizarrarás et al. 2019; Hernández-Ramos et al. 2025). When held for 1–2 days as a *curado* (1–2% *v*/*v* ethanol) with added fruits or sweeteners, it provides 200–300 kcal/L from fermentable sugars and organic acids, making it a staple energy tonic for agrarian and construction laborers (Camacho Ruiz n.d.; Luis et al. 2019). As spontaneous fermentation advances (Day 2–3), ethanol rises to 3–4% *v*/*v* and *pulque* acquires its characteristic viscous texture and functional metabolites (e.g., exopolysaccharides, B vitamins), after which it transitions from medicinal tonic to inebriant (Escobar-Zepeda et al. 2020; Huezo-Sánchez et al. 2023). As summarized in Table 1, the temporal variation in pH and °Brix readings demonstrates the progressive acidification and concomitant reduction in sugar concentration throughout the *pulque* fermentation stages (Flores-Rodríguez and Miranda-López 2023).

In many contemporary *pulquerías*, vendors also add refined sugars (sucrose or high-fructose corn syrup) to fresh *pulque* or *curado*, both to extend shelf life and to enhance sweetness. These additions can raise its caloric density to 350–400 kcal L^{-1} and drive *pulque's* glycemic index above 70, comparable to sugar-sweetened beverages (Gómez Aldapa et al. 2016; Malik et al. 2006). Frequent consumption of sugar-enriched *pulque* therefore carries the same risks of dental caries, weight gain, and dysglycemia as other sugar-sweetened drinks, especially in populations with limited access to dental care (Malik et al. 2006). In light of Mexico's high prevalence of metabolic syndrome (World Health Organization 2015), public-health guidelines now recommend that free sugars constitute less than 10% of daily energy intake, underscoring the need to frame sugar-sweetened *pulque* within broader sugar-reduction strategies (World Health Organization 2015).

Also, *agave salmiana* plantations across central Mexico have contracted sharply—by as much as 80% in the Valle de México—due to land-use change, soil erosion, and loss of traditional agroecological practices that once maintained soil fertility and water retention. Urban expansion and conversion to intensive crops fragment *maguey* stands while overgrazing and conventional tillage accelerate topsoil loss and reduce seedling survival (Roldán-Cruz et al. 2023). Following this decline, Table 2 summarizes how each indigenous term corresponds to a distinct *pulque* production stage and highlights the specific ecological pressures—such as *agave* stand contraction, soil erosion, and water depletion—that jeopardize sap yield, sugar concentration, and adjunct availability at each phase.

Table 2. Principal indigenous terms and production stages under ecological pressure.

Term	Language	Gloss	Production Stage	Ecological Pressure	References
tsihui	Mazahua	"sweet liquid"	*Aguamiel* (Unfermented Sap)	*Agave salmiana* stands in the Valle de Mexico have contracted by ~80%, reducing sap yield and °Brix in early-stage harvests.	(Colunga-GarcíaMarín et al. 2007; Roldán-Cruz et al. 2023)
octli	Nahuatl	"fermented sap"	*Pulque Fresco* (Early Fermentation)	Soil erosion, overgrazing, and land-use change fragment *maguey* groves, lowering sugar availability and batch volumes.	(de Sahagún 1950)
juyá	Mixtec	"beer, tonic"	*Pulque Maduro* (Mature Fermentation)	Declining rainfall and groundwater depletion during the rainy season diminish *aguamiel* concentration, compromising flavor and alcohol yield.	(Aguilar-Uscanga et al. 2024)
curado	Spanish [1]	"flavored *pulque*"	*Curado* (Post-Fermentation Variant)	Loss of traditional agroecological practices limits availability of adjuncts (fruit, cereals), reducing *curado* diversity and quality.	(Luis et al. 2019)

[1] Included to complete the production-stage lexicon.

Moreover, declining rainfall and groundwater depletion during the May–November rainy season compromise *aguamiel* sap yields and sugar concentration, undermining both the quantity and quality of raw materials for *pulque*. These environmental pressures threaten the sustainability of traditional *maguey–pulque* systems and underscore the need for integrated land-management and water-conservation policies to preserve both ecological and cultural heritage (George et al. 2018).

5. Nutritional and Functional Attributes of Pulque

Nutritional analyses have shown that *pulque* is a source of carbohydrates $(C\ H_2O)_n$–, proteins, vitamins, and minerals (Pérez-Armendáriz and Cardoso-Ugarte 2020).

Concerning carbohydrates, *pulque* contains natural sugars such as fructose and glucose, which supply energy to the body. Proteins are also present in *pulque*, although in smaller quantities, and contribute to the structural integrity and function of body tissues (Pérez-Armendáriz and Cardoso-Ugarte 2020). Concerning vitamins, *pulque* is a source of vitamin C, essential for immune system function and skin health. It also contains B-complex vitamins, which play a critical role in metabolism and energy production (Pérez-Armendáriz and Cardoso-Ugarte 2020).

As for inorganic nutrients, *pulque* mainly contains calcium (Ca), potassium (K), magnesium (Mg), and zinc (Zn). These minerals are vital for the proper functioning of the body, participating in processes such as muscle contraction, fluid balance, and bone health (Pérez-Armendáriz and Cardoso-Ugarte 2020).

Historically, *pulque* has been valued as a source of energy and nutrients in the communities that consume it. Its carbohydrate content—$(C\ H_2O)_n$—provides a quick source of energy, making it an energizing drink, particularly under physically demanding circumstances (George et al. 2018).

Aguamiel—the sap tapped from incised *Agave inflorescences*—exhibits a total soluble solids content of 10–14 °Brix and a native pH of 6.0–6.8, with sucrose, glucose, and fructose comprising >85% of its carbohydrates (Huezcas-Garrido et al. 2022; Luis et al. 2019). Immediately upon collection, *aguamiel* contains 10^3–10^4 CFU/mL of lactic-acid bacteria and 10^2–10^3 CFU/mL of environmental yeasts, which serve as the inoculum for spontaneous fermentation when exposed to a *pulque* starter culture (Escalante et al. 2008; Huezo-Sánchez et al. 2023).

Furthermore, *pulque* has traditionally been used to help combat malnutrition and provide essential nutrients, especially during times of food scarcity. Its protein, vitamin, and mineral content help meet the nutritional needs of its consumers (Pérez-Armendáriz and Cardoso-Ugarte 2020). This cultural valuation is encapsulated in the popular saying: "*Pulque* is only one degree away from being meat" (Fieldwork note, R. Rivera 2013b).

In recent years, the illicit production and sale of counterfeit *pulque*—colloquially dubbed "*huachicol de pulque*"—have raised serious safety and cultural heritage concerns. Adulterators often blend industrial ethanol with water, add synthetic flavorings (e.g., fruit essences), and use food-grade thickeners to mimic *pulque's* viscosity and taste, deceiving consumers and undercutting traditional producers (Franco-Mora et al. 2024; Vega Lojano and Guamantario Fernandez 2024). Such practices risk methanol contamination, acute intoxication cases, and long-term liver damage, as documented in regional health department reports (Bautista and Arias 2008). Moreover, these counterfeit products erode market trust and jeopardize the livelihoods of artisanal *pulque* families, who lack the economies of scale to verify and certify product authenticity (Grummon et al. 2020).

Moreover, *pulque* has been aggressively marketed as a "completely natural" beverage, leveraged by health-tourism operators in central Mexico to appeal to wellness-seeking travelers. Vendors and tour promoters emphasize *pulque's* artisanal produc-

tion, lack of additives, and purported probiotic benefits, framing it alongside spa and *agave*-therapy experiences (Franco-Mora et al. 2024). While this positioning bolsters demand and supports local economies, it raises regulatory and ethical questions: how to verify "natural" authenticity, ensure food-safety standards, and prevent green- or health-washing of a product whose traditional producers lack formal certification pathways (Vega Lojano and Guamantario Fernandez 2024).

6. Pulque and Its Relationship with the FODMAP Diet: A Consideration

FODMAPs (Fermentable Oligosaccharides, Disaccharides, Monosaccharides, and Polyols) are short-chain carbohydrates known for their poor absorption in the small intestine and subsequent fermentation by colonic microbiota, leading to gas production and osmotic imbalance. This can result in abdominal pain, bloating, and altered bowel habits, particularly in individuals with irritable bowel syndrome (IBS) (Ki Cha 2012). To address these symptoms, the low-FODMAP diet has emerged as a well-supported therapeutic strategy.

While restrictive, this diet has been associated with significant improvements in gastrointestinal symptoms. However, it is also accompanied by a potential downside: the reduction of beneficial microbial populations and their metabolic byproducts, particularly short-chain fatty acids (SCFAs). SCFAs such as acetate, propionate, and butyrate play pivotal roles in maintaining colonic pH, modulating immune responses, and providing energy to colonocytes (De Roest et al. 2013; Tuck et al. 2019).

Recent research has identified different subtypes of gut microbiota in IBS (irritable bowel syndrome) patients, each showing distinct responses to FODMAP intake. This supports a personalized approach to dietary management (Vervier et al. 2022). Importantly, dietary FODMAPs are metabolized into SCFAs, which have demonstrated anti-inflammatory effects in models of intestinal inflammation and play a protective role against IBS and inflammatory bowel disease (IBD) (Banerjee et al. 2023; Luis et al. 2019).

In this context, fermented foods like *pulque* present a compelling area of study. *Pulque* undergoes spontaneous fermentation facilitated by a diverse microbial consortium (Tripathi and Giri 2014). This process is known to reduce the concentration of fermentable sugars and oligosaccharides, potentially lowering the FODMAP content of the final product (Kårlund et al. 2020). The microbiota involved in *pulque* fermentation includes lactic acid bacteria and wild yeasts, organisms capable of degrading fructans and other FODMAP constituents.

Moreover, the fermentation of *pulque* not only modifies its sugar profile but may also enhance its functional properties by enriching it with SCFAs and probiotic microorganisms. Fermented beverages, including *pulque*, *tejuino*, and *kvass*, have been recognized for their potential in modulating gut microbiota and restoring microbial diversity, which is crucial for patients with IBS and post-infectious dysbiosis (Calderón-Martínez et al. 2024; Leeuwendaal et al. 2022; Savo Sardaro et al. 2023).

Additionally, studies on fermented vegetables and legumes have demonstrated that lactic acid bacteria can reduce FODMAP concentrations, reinforcing the concept that similar processes in *pulque* fermentation may offer analogous benefits (Blajman and Zarate 2020). Therefore, *pulque* could serve as a culturally appropriate, nutritionally enriched alternative to beer and wine for FODMAP-sensitive individuals, if fermentation processes are standardized and individual tolerance is assessed.

7. Pulque Consumption: Implications for Public Health and Probiotic Potential

Emerging evidence suggests that moderate *pulque* consumption may confer gut-health benefits by delivering viable probiotic microorganisms and prebiotic substrates. *Pulque* har-

bors lactic acid bacteria (e.g., *Lactobacillus acidophilus*, *Leuconostoc mesenteroides*) and yeasts (e.g., *Saccharomyces cerevisiae*) that meet World Health Organization criteria for probiotics ("live microorganisms which, when administered in adequate amounts, confer a health benefit on the host") (World Health Organization 2015). These taxa can enhance intestinal barrier function, modulate immune responses, and outcompete pathogens (Ki Cha et al. 2012; Escalante et al. 2008). Concurrently, fructans—indigestible oligosaccharides present at 1.2–2.8 g/100 mL—act as prebiotics by selectively stimulating commensal bacterial growth (Alvarado et al. 2014; Peralta-Garcia et al. 2020).

For a dose comparison, one liter of *pulque* (4–7% *v*/*v* ethanol) delivers ~40–70 g ethanol—roughly equivalent to two 300 mL beers or two 100 mL glasses of wine, or two 1-ounce (28 mL) glasses of *tequila*, rum, cognac, whiskey, or vodka (Noriega-Juárez et al. 2025). Importantly, the ethanol concentrations typical of mature *pulque* do not abrogate probiotic viability, as indigenous strains exhibit 50–80% survival under simulated gastric pH (Escalante et al. 2008; Lappe-Oliveras et al. 2008). Nevertheless, human clinical trials remain sparse; rigorous randomized studies are required to quantify *pulque's* net health effects and establish evidence-based consumption guidelines.

Benefits of Moderate Pulque Consumption

Health guidelines generally recommend limits on alcohol consumption, advising no more than one alcoholic drink per day for women and no more than two for men (Narro-Robles et al. 1992).

In recent years, there has been growing scientific interest in studying *pulque*, a traditional Mexican fermented beverage, due to its potential health benefits, as outlined below (Dávila-Ortiz et al. 2022; Kerry et al. 2018; Şanlier et al. 2019):

- *Digestive Health Benefits:*

Pulque (unfermented *aguamiel*) contains probiotic microorganisms and prebiotic compounds such as fructans that promote a beneficial environment in the gastrointestinal tract. These components support the growth of beneficial gut bacteria, enhance intestinal functionality, and may alleviate symptoms of disorders like irritable bowel syndrome (IBS) and inflammatory bowel disease (IBD) (García-Arce and Castro-Muñoz 2021).

During the fermentation process of *aguamiel* into *pulque*, beneficial microorganisms such as yeasts and lactic acid bacteria are generated. These microbes participate in the fermentation of carbohydrates ($C_n(H_2O)_n$) in *pulque*, improving its digestibility (Todorovic et al. 2024).

Additionally, probiotics in *pulque* contribute to the balance of intestinal microbiota, composed of trillions of microorganisms, thereby improving nutrient absorption and gastrointestinal function.

Pulque naturally contains enzymes such as amylases and proteases, which facilitate the breakdown of carbohydrates and proteins during digestion, promoting efficient digestive processes and reducing postprandial discomfort (Bovell-Benjamin 2010).

Its anti-inflammatory and antioxidant properties are attributed to bioactive compounds like polyphenols and flavonoids, which help reduce gastrointestinal inflammation and protect cells from oxidative damage (Šikić-Pogačar et al. 2022).

- *Immunomodulatory Effect:*

Moderate consumption of *pulque* has shown stimulatory effects on the immune system by enhancing the body's natural defense mechanisms. Specific bioactive peptides in *pulque* exhibit antimicrobial and immunomodulatory properties, potentially reducing infection risk (Banerjee et al. 2023).

Pulque's antioxidant and anti-inflammatory compounds, such as flavonoids, can modulate the immune response by attenuating oxidative stress and cellular inflammation. A balanced inflammatory response is critical for immunological health, and preliminary studies indicate *pulque* may help regulate cytokine activity, key signaling molecules in immune modulation (Quiñones-Muñoz et al. 2022).

- *Cardiovascular Potential:*

Phenolic compounds, including flavonoids present in *pulque*, exhibit antioxidant and anti-inflammatory effects (Almaraz-Abarca et al. 2013). These properties help mitigate oxidative stress and systemic inflammation, which are linked to cardiovascular diseases such as hypertension and coronary artery disease (Frías et al. 2016).

- *Psychological and Emotional Benefits:*

Emerging research suggests that moderate *pulque* consumption may have a beneficial impact on mood and mental health. Opioid peptides found in *pulque* are believed to exert relaxing and anxiolytic effects, thereby contributing to stress and anxiety reduction (Bovell-Benjamin 2010).

In summary, *pulque*, beyond its cultural and historical significance, demonstrates potential as a functional beverage with probiotic, immunomodulatory, cardiovascular, and psychological benefits. These findings warrant further clinical investigation to substantiate their effects and elucidate the mechanisms involved (Narro-Robles et al. 1992).

Nevertheless, *pulque* should not be considered a standalone medical treatment and should not replace professional healthcare advice. Consultation with a physician, nutritionist, or healthcare professional is recommended before making dietary changes, especially for individuals with specific conditions.

8. Current Situation of Pulque in Mexico

The production and commercialization of *pulque* have experienced a resurgence in recent decades. While in the past its manufacture was mainly carried out by small-scale producers, there are now companies engaged in the commercial production of *pulque*. These enterprises have attempted to implement modern production and bottling processes to meet both domestic and international demand (Valadez 2012). Nevertheless, the delicate nature of *pulque* continues to hinder industrial processing and bottling efforts, often necessitating a return to traditional methods.

As part of the commercial landscape emerging around *pulque*, tourist circuits have been developed. These typically involve visits to three to five well-known *pulquerías* located within the same city. Tourists are customarily treated to tastings of local *pulque* and encouraged to purchase the beverage, whether in its natural state or its *curado* form—a mixture of *pulque* with fruit, cereal, or vegetable extracts or pulp. This variant is typically recommended for same-day consumption, as the beverage rapidly spoils.

In addition, festivals dedicated to the production, marketing, and consumption of *pulque* have been devised and popularized. Notable examples include the celebration surrounding the stewardship (*mayordomía*) of the *tlachiqueros* in the municipality of Tepetlaoxtoc de Hidalgo, State of Mexico, as reported by Rivera (R. Rivera 2013a), or the *Mayehuatzin* festival held in the town of Huexotla, municipality of Texcoco de Mora, State of Mexico. Other festivals provide opportunities for visitors to learn about the history and production process of *pulque*, and to sample various types of the beverage (Sánchez and Domínguez 2019). These tourism initiatives have contributed to the preservation and dissemination of *pulque* traditions while also fostering economic development in the producing communities (Valadez 2012).

In Mexico City, an initiative has emerged to recognize *pulque* as an integral component of the country's gastronomic heritage (Bayardo-Rivera 2023). This step advances efforts to have *pulque* acknowledged as part of the intangible cultural heritage of humanity within the gastronomic heritage category defined by UNESCO. It underscores the historical and cultural significance of *pulque* in Mexico, which has grown in popularity among both domestic and international consumers due to its unique flavor and deep ties to Mexican tradition and identity. Its increasing presence in specialty restaurants and bars has further promoted its commercialization and attracted a new generation of consumers (Milenio n.d.).

Table 3 provides a detailed quantification of *pulque's* physicochemical and macronutrient profile, systematically collating pH, ethanol concentration, total carbohydrates, fructans, and protein levels to facilitate cross-parameter comparisons.

Table 3. Physicochemical and Macronutrient Composition of Traditional Pulque [1].

Parameter	Range/Concentration	Functional Significance	Reference
pH	3.5–4.5	Acidic milieu fosters lactic-acid–bacteria growth and probiotic stability	(Gonzalo David Álvarez-Ríos et al. 2020)
Ethanol (% *v*/*v*)	2–4	Index of fermentation progress; balances functional versus ceremonial roles	(Gonzalo David Álvarez-Ríos et al. 2020)
Total Carbohydrates (g/100 mL)	4.0–6.5	Primary energy source; includes fermentable sugars and prebiotic oligosaccharides	(Gonzalo David Álvarez-Ríos et al. 2020)
Fructans (g/100 mL)	1.2–2.8	Prebiotic dietary fiber modulating gut-microbiota composition	(Peralta-Garcia et al. 2020)
Proteins (g/100 mL)	0.8–1.5	Supplies essential amino acids (lysine, threonine, tryptophan)	(Morales de León et al. 2005)

[1] Our own elaboration based on the indicated references.

The acidic milieu (pH 3.5–4.2) is shown to be optimal for lactic acid bacteria viability, while ethanol levels (2–6% *v*/*v*) serve as an indicator of fermentation progress and delineate the boundary between functional beverage and spirit (Gonzalo David Álvarez-Ríos et al. 2020).

Carbohydrate content (4.0–6.5 g/100 mL) reflects the combined pool of fermentable sugars and complex oligosaccharides, which underpin both caloric value and prebiotic action, and is complemented by fructan concentrations (1.2–2.8 g/100 mL) that selectively stimulate commensal gut microbiota (Peralta-Garcia et al. 2020).

Protein levels (0.8–1.5 g/100 mL) quantify essential amino-acid supply (lysine, threonine, tryptophan) and contribute to yield-adjusted calculations of fermentative biomass (Morales de León et al. 2005).

By presenting each parameter in standardized units and linking them to their principal functional roles (energy provision, microbial modulation, and biochemical biomarkers), Table 3 undergirds our argument that *pulque* qualifies as a nutrient-dense, bioactive fermentate, thereby reinforcing its classification as a paradigmatic functional beverage.

Table 4 delineates the fermentative microbiota of traditional *pulque* by quantifying viable cell counts (10^4–10^8 CFU/mL) of key lactic acid bacteria (e.g., *Lactobacillus plantarum*, *L. brevis*, *Leuconostoc mesenteroides*) and yeasts (e.g., *Saccharomyces cerevisiae*, *Zymomonas mobilis*), alongside their principal functional attributes (bacteriocin and exopolysaccharide synthesis, GABA and B-vitamin production, and immunomodulation) and their survival rates (50–90%) under simulated gastric acidity (pH 2.5).

Table 4. Dominant Microbial Strains in Traditional Pulque and Their Functional Attributes.

Microbial Taxon	CFU/mL Range	Key Functional Attributes	Acid Tolerance (% Viability at pH 2.5)	References
Lactobacillus plantarum	10^6–10^8	Bacteriocin synthesis; cholesterol-lowering; immunomodulation	High (>80%)	(Escalante et al. 2008)
Leuconostoc mesenteroides	10^5–10^7	Exopolysaccharide synthesis; antioxidant; gut-modulating activity	Moderate (50–80%)	(Escalante et al. 2008)
Lactobacillus brevis	10^6–10^7	GABA production; anti-inflammatory properties	High (>80%)	(Escalante et al. 2008)
Saccharomyces cerevisiae	10^5–10^6	Vitamin B synthesis; epithelial-barrier support	High (>70%)	(Lappe-Oliveras et al. 2008)
Zymomonas mobilis	10^4–10^6	Ethanol fermentation; mild probiotic potential	Low (<50%)	(Escalante et al. 2016)
Weissella cibaria	10^4–10^5	Immunomodulation; exopolysaccharide production	Moderate (60–80%)	(Escobar-Zepeda et al. 2020)

Acid tolerance denotes percent viability under simulated gastric conditions (pH 2.5) over 2 h; CFU: Colony Forming Units. Functional attributes: based on in vitro and in vivo studies; variability exists due to microbial consortia, fermentation time, and regional techniques.

By directly linking strain-specific bioactivity profiles with acid-tolerance metrics, this table provides a robust framework for evaluating probiotic viability and mechanistic contributions to gut-microbiota equilibrium.

These resilient microbial consortia have also catalyzed the innovation of *pulque*-derived food products (*aguamiel*-sweetened granola, sap concentrates, *pulque*-infused bread and cookies, and savory applications such as *salsas* and meat marinades), thereby translating traditional fermentative knowledge into novel nutritional and gastronomic contexts.

9. Discussion

Fermentation is a metabolic process in which microorganisms, specifically bacteria and yeasts, convert the sugars present in *aguamiel* into ethanol (C_2H_6O), or ethyl alcohol (C_2H_5OH), and carbon dioxide (CO_2). Therefore, fermentation conditions such as temperature, soil type, and time of year influence the composition and dynamics of microbiological communities, as well as the physical and chemical characteristics of the beverage (Gonzalo David Álvarez-Ríos et al. 2020).

Probiotics, on the other hand, are defined by the World Health Organization (WHO) as "live microorganisms which, when administered in adequate amounts, confer a health benefit on the host" (World Health Organization 2015).

Pulque, as a fermented product, contains a variety of microorganisms, many of which may have probiotic properties. These include bacteria from the genus *Lactobacillus*, well known for their health benefits, including improved digestion and immune modulation.

However, since *pulque* contains alcohol (a natural result of its fermentation), its classification as a probiotic may be compromised. Alcohol, in large quantities, is known to have detrimental effects on the gut microbiota, potentially damaging beneficial bacteria and disrupting the balance among the various microorganisms present in the intestinal environment. This leads us to ask: under what conditions can *pulque* be considered a probiotic? Such a premise must consider factors such as the amount of *pulque* consumed as well as the balance between its potential probiotic effects and the harmful effects of alcohol.

One possible interpretation is that *pulque*, when consumed in moderation, may provide probiotic benefits due to the beneficial microorganisms it contains. Moreover, it is important to note that the probiotic properties of microorganisms may vary depending on the individual consuming them, and thus the effects may not be uniform across different individuals.

A review of the literature and related studies highlights that *pulque* is an ancient and traditional Mexican beverage, deeply embedded in the mythology, legends, and socio-religious frameworks of pre-Hispanic cultures. Its alcoholic and probiotic value, derived from its natural fermentation process, was traditionally recognized.

It is also worth noting that both the beverage and its fermentation process contributed to the development and perpetuation of other traditional knowledge systems and practices still present today.

From a probiotic standpoint, the fermentation of *pulque* from *agave* involves the activity of a diverse array of microorganisms, including multiple species of bacteria and yeasts. Some of these microorganisms are recognized for their probiotic potential, such as *Lactobacillus* and *Bifidobacterium* (Aguilar-Moreno 2001; Bayardo-Rivera 2023; Contreras and Rodríguez 2007). The presence of these microorganisms suggests that *pulque* may play a role in supporting intestinal health, an aspect corroborated by several studies. However, variations in fermentation practices and microbial diversity may affect the consistency of these probiotic properties.

From an alcoholic perspective, *pulque* contains a low alcohol content (generally around 4–7%) (Bayardo-Rivera 2023; Blas-Yañez et al. 2018). This contrasts with other fermented agave products such as mezcal or *tequila*, which have significantly higher alcohol concentrations. Nevertheless, any alcohol consumption carries associated health risks and should be considered when contemplating regular intake. Additionally, variability in the fermentation process may lead to differences in alcohol content across batches.

Most authors agree that this millenary beverage contains both alcohol and probiotics, noting that alcohol (ethanol, C_2H_5OH), as an organic compound, does not exhibit significant antibacterial activity at the concentrations found in *pulque* (Soccol et al. 2010).

Recent research indicates that the probiotics present in *pulque* include a variety of bacteria (*Lactobacillus* spp., endogenously produced, responsible for lactic acid production and commonly found in milk; and *Leuconostoc mesenteroides*, present in fermented dairy products) and yeasts (*Saccharomyces cerevisiae*, used in bread, beer, and wine production; as well as *Candida milleri*), which are naturally resistant to the alcohol concentrations present in *pulque*.

Revisiting the interaction between alcohol and probiotics from a chemical standpoint, it has been established that ethanol (C_2H_6O) acts as a solvent in *pulque* and, at higher concentrations, may damage the cell membranes of some microorganisms. However, the bacteria and yeasts in *pulque* are adapted to this environment and can survive in the presence of ethanol.

Moreover, it is known that ethanol does not alter the pH of the solution, and *pulque* generally maintains an acidic pH that is optimal for lactic acid bacteria and other beneficial microorganisms.

In some cases, alcohol may work synergistically with other compounds in *pulque* to preserve microorganisms. The presence of ethanol could even contribute to maintaining an anaerobic environment, favorable to certain fermentative bacteria.

This implies that the coexistence of alcohol and probiotics in *pulque* is not accidental. Throughout history, microorganisms that both produce and tolerate ethanol during *pulque* fermentation have been naturally selected, creating a unique and stable microbial ecosystem within the beverage.

Therefore, the presence of alcohol in *pulque* does not chemically interfere with its probiotic constituents due to the nature of ethanol, the specific characteristics of the resident microorganisms, and the evolutionary development of a fermentative environment that allows both components to coexist (Chacón-Vargas et al. 2020; Vera Morales et al. 2024).

Eventually, the response to the initial premise is that *pulque*, when consumed in moderation, may offer probiotic benefits due to its content of beneficial microorganisms. Therefore, further research is required to gain a more detailed and comprehensive understanding of the balance between the potential probiotic benefits and the effects of alcohol in *pulque*. It is essential to remember that these effects may vary among individuals and may be influenced by other factors, including diet and general health status.

Concomitantly, *pulque* has experienced an artisanal and commercial resurgence: small-scale *tlachiquero* cooperatives coexist with enterprises piloting pasteurization and bottling techniques to address shelf-life limitations, yet the beverage continues to necessitate rapid distribution channels and traditional artisanal methods (Valadez-Blanco et al. 2012).

Heritage-based tourism, manifested in curated *pulquería* circuits and annual festivals such as the Tepetlaoxtoc *Mayordomía* and Huexotla *Mayehuatzin* celebrations, has become a vehicle for economic development and cultural preservation (J. Rivera 2013) Efforts to register *pulque* as UNESCO Gastronomic Heritage, spearheaded in Mexico City, further attest to its societal resonance and appeal among domestic and international consumers.

By integrating biochemical, microbiological, ethnographic, and socio-economic dimensions, *pulque* emerges as a paradigmatic exemplar of biocultural resilience: human cultural practices and microbial ecology have co-evolved to yield a stable functional beverage.

10. Conclusions

Pulque is a beverage with deep historical roots in Mexico. In recent years, the commercial production of *pulque* has witnessed a resurgence, supported by tourism promotion and its recognition as part of Mexico's gastronomic heritage, fostering appreciation among both domestic and international consumers.

Its distinctive flavor, traditional production methods, and historical and cultural significance render *pulque* a unique treasure within the landscape of traditional Mexican beverages.

By uniting sociocultural history with microbial-metabolite profiles, we advance a new paradigm for understanding *pulque's* role in past and present health frameworks.

From a nutritional perspective, *pulque* has been shown to possess significant nutritive value. Its content of carbohydrates, proteins, vitamins, and minerals makes it a substantial source of energy and essential nutrients for those who consume it. Additionally, the presence of probiotic bacteria and their prebiotic effects on the digestive system have been highlighted, potentially contributing to improved gut health. As a substantial source of both macronutrients and micronutrients, *pulque* merits classification as a functional food; however, its moderate ethanol content (4–7% *v*/*v*) necessitates evidence-based consumption guidelines to mitigate hepatotoxicity and dependence risks.

Pulque represents an integral part of Mexico's culinary heritage, with its production and consumption deeply intertwined with oral tradition and national identity. Therefore, the preservation of the *tlachiquero's* craft entails safeguarding traditional production techniques and fostering awareness and respect for *pulque* as an emblematic Mexican beverage.

However, it is equally critical to promote the responsible consumption of this beverage. Emphasis must be placed on the health risks associated with excessive intake of *pulque*, including potential impacts on liver health and the risk of alcohol dependence. It is essential to inform consumers about recommended intake limits and possible health hazards, while also underscoring the nutritional benefits *pulque* can offer when consumed in moderation.

Future interdisciplinary research should integrate standardized analytical protocols, controlled clinical trials, and ethnographic-omics methodologies to further elucidate *pulque's* sustainable role within global nutritional and cultural frameworks.

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