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Bioethanol production as a strategy for the sustainable energy transition in Jalisco, State, Mexico

Producción de bioetanol como estrategia para la transición energética sustentable en el Estado de Jalisco, México

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Resumen

La tendencia mundial de años recientes parece orientarse al uso del bioetanol como un aditivo en las gasolinas. México sigue en proceso hacia una transición energética sustentable, por lo que es necesario analizar el contexto nacional para encontrar áreas de oportunidad que permitan desarrollar la industria del etanol en el país.

Jalisco destaca como una entidad federativa líder en la producción de materias primas de interés (agave, caña de azúcar y maíz) para la producción de alcohol anhidro.

El presente estudio consideró los objetivos planteados por la Secretaría de Energía de México (SENER) [1] para llevar a cabo un análisis del panorama actual del país ante la posibilidad de producir a gran escala bioetanol.

Los resultados obtenidos mostraron que Jalisco se encuentra en una buena posición respecto a otras entidades federales para la generación de etanol de segunda generación. Produce una gran cantidad de desechos agrícolas (bagazo de caña de azúcar y agave) y cuenta con una infraestructura sólida establecida como lo son los ingenios azucareros.

En un escenario óptimo y utilizando el 50% del bagazo de agave y caña rescatados anualmente en Jalisco, es posible generar 614 y 128 millones de litros de bioetanol de cada desecho respectivamente.

El principal impedimento son las políticas actuales que aún no permiten la libre distribución de etanol E10 en las zonas metropolitanas del país. Por lo que la inversión de proyectos de generación de biocombustibles no resulta atractiva para los inversionistas.

Palabras clave: Bioetanol, biocombustibles, soberanía alimentaria, biomasa.

Abstract

The global trend in recent years has shown a growing inclination towards the utilization of bioethanol as an additive in gasoline. As Mexico continues its journey towards a sustainable energy transition, it becomes imperative to dissect the national landscape to identify potential areas for fostering the development of the ethanol industry within the country.

Jalisco emerges as a frontrunner among federal entities due to its significant production of key raw materials (such as agave, sugarcane, and corn) essential for anhydrous alcohol production. This study aims to align with the objectives outlined by the Secretary of Energy of Mexico (SENER) [1] by conducting an in-depth analysis of the current scenario regarding the feasibility of large-scale bioethanol production in the country.

The findings reveal Jalisco's advantageous position compared to other federal entities for the generation of second-generation ethanol. With a substantial amount of agricultural residues available, particularly sugarcane and agave bagasse, and a robust infrastructure comprising established sugar mills, Jalisco presents fertile ground for bioethanol production.

In an optimal scenario, utilizing 50% of the agave and sugarcane bagasse annually recovered in Jalisco could yield approximately 614 and 128 million liters of bioethanol, respectively. However, a significant hurdle lies in current policies restricting the free distribution of E10 ethanol in metropolitan areas across the country. Consequently, the lack of conducive policy frameworks renders investment in biofuel generation projects unappealing to potential investors.

Keywords: Bioethanol, biofuels, food sovereignty, biomass.

I.- Introduction

Climate change has emerged as a paramount concern both in public discourse and on the global scientific and political agenda. As the world grapples with dwindling natural resources to meet the ever-growing needs of its populace, the disparity between resource replenishment and consumption rates has widened. According to the Nationally Determined Contributions (NDC), Mexico emitted 804 million tons of carbon dioxide equivalent (CO2e) greenhouse gases in 2018, constituting approximately 1.3% of global emissions (Figure 1) [3].

Furthermore, the erratic nature of oil production coupled with the extensive use of its by-products has significantly contributed to the phenomenon of global warming. Consequently, the exploration and adoption of alternative energy sources have become imperative. The concept of biofuels has gained traction, championed by governments worldwide, notably Brazil, renowned for bioethanol production from sugarcane, and the United States, which focuses on corn-based biofuels.

Initially hailed as a clean energy solution, biofuels were seen as a means to substitute non-renewable fuels like oil with organic matter, potentially benefiting rural development and enhancing the quality of life in agrarian communities [4]. However, practical experience in biofuel production and utilization has unveiled unintended consequences. Environmental and economic repercussions under scrutiny include the escalation of food prices, land use alterations, as well as impacts on water and air quality [5].

Despite its abundant oil reserves, Mexico remains reliant on foreign countries for hydrocarbon fuel production, as per data from the Secretary of Energy (SENER) [6]. Dependency on external sources exposes Mexico to various challenges, including fluctuations in the exchange rate between the Mexican peso and the US dollar and volatility in international oil prices, underscoring the vulnerabilities inherent in such dependence.

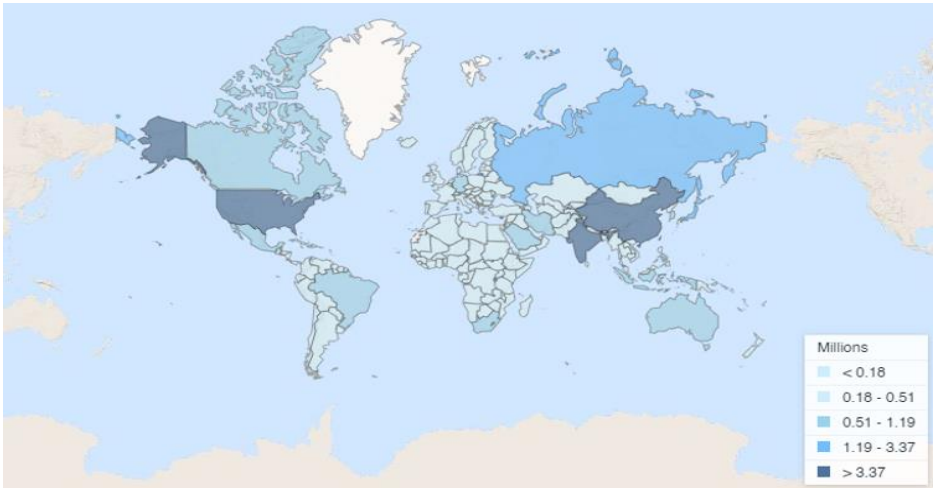


Figure 1. Greenhouse gas emissions [7].

This has had a profound effect on the volatility of diesel and gasoline prices. Furthermore, over the past three decades, Mexico has experienced an exponential surge in the number of vehicles on its roads (Figure 2), consequently leading to heightened pollution levels and greenhouse gas emissions [8].

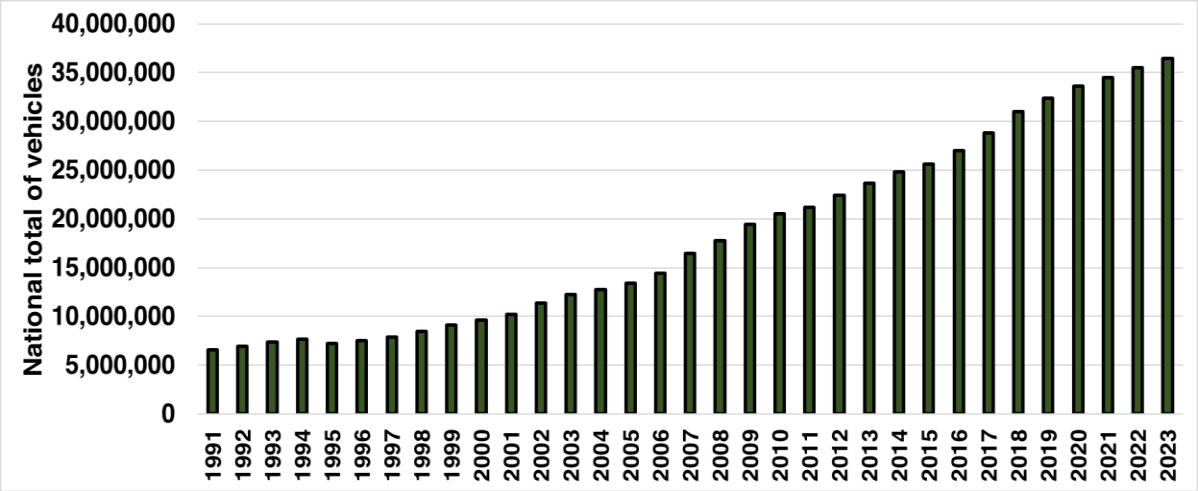


Figure 2. Registered motor vehicles in circulation in Mexico.
Own elaboration with data from [9].

Amidst the dwindling international supply and the concurrent surge in fuel prices, there is a discernible trend towards exploring alternative energy sources. However, the production of raw materials for biofuel generation is in direct competition with food, fiber, and wood production.

The production of ethanol from grains such as corn and wheat is poised to impact global food trade dynamics [10]. Mexico's biofuel introduction program mandates the substitution of Tert-Butyl Methyl Ether (MTBE) with bioethanol for gasoline oxygenation in key metropolitan areas, including Guadalajara, Monterrey, and the Valley of Mexico [11]. According to NOM-086 specifications, gasoline sold in these metropolitan regions must contain between 1% and 2.7% of its weight in oxygen [12].

Presently, gasoline in these cities contains 2% oxygen, achieved through a blend of chemical additives. Mexican Petroleums (PEMEX) has determined that achieving this oxygen percentage necessitates a 5.8% bioethanol blend [13]. Veracruz, as per the Energy Secretariat (SENER), boasts optimal product, climatic, technological, and land conditions for large-scale ethanol production, meeting the nation's requirements and future export potential [14].

Since 2015, United Nations Member States, including Mexico, ratified the 2030 Agenda for Sustainable Development. By May 2020, modifications to guidelines governing clean energy certificates and their acquisition requirements were consolidated, notably the Transition Strategy aimed at fostering cleaner technologies and fuels [15].

The implementation of these strategies has yielded tangible results, with Mexico reporting in 2021 that 11.25% of its electricity was generated through renewable sources (Figure 3). Furthermore, underutilized hydroelectric plants in the southern regions are being rehabilitated to bolster this contribution and fortify public generation efforts [16].

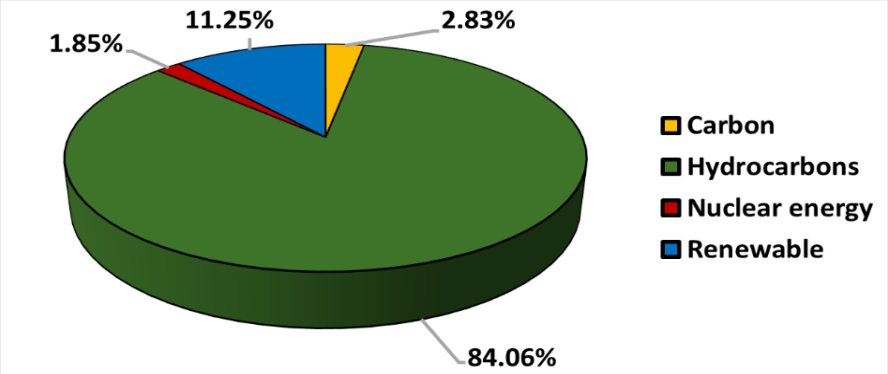


Figure 3. Energy sources used in 2021 in Mexico for the generation of national electricity.
Own elaboration with data from [17].

In Mexico, the sale and use of biofuels, namely ethanol and biodiesel, are permitted under the condition of compliance with relevant permits and regulations; however, their production and consumption remain restricted.

Jalisco emerges as a federal entity poised for significant strides in large-scale bioethanol production projects. Renowned for leading agave production and ranking second nationally in corn and sugarcane cultivation, Jalisco boasts three pivotal raw materials for bioethanol production. Moreover, the region hosts six robust sugar mills with established infrastructure and expertise in sugar production, offering a seamless transition towards bioethanol production.

The future trajectory of biofuels pivots towards achieving circular production by repurposing waste generated by the corn and sugarcane industries. Scholars such as [18] and [19] advocate for utilizing agricultural residues such as sugarcane fibers and fruit waste to produce ethanol. Additionally, novel, cleaner, and more efficient methodologies are emerging to drive biofuel generation.

Alternative approaches for biofuel generation, including bioethanol, encompass waste fermentation utilizing bioreactors [20], pressure swing adsorption for ethanol extraction from mixtures containing undesired components [21], and molecular sieves [22]. These methodologies herald a promising shift in waste management practices, emissions reduction, and pollution mitigation attributed to food industry waste. Given the nascent and evolving nature of the biofuels sector, regular review and analysis are imperative.

This study's primary contribution lies in its comprehensive analysis of the current state of the bioethanol industry in Jalisco and Mexico, encompassing legal and agricultural facets. Leveraging data from prevailing energy laws and studies from various Mexican energy and agricultural agencies, such as Mexican Petroleums (PEMEX), the Energy Secretariat (SENER), and the Secretariat of Agriculture, Livestock, Rural Development, Fisheries, and Food (SAGARPA), among others, a nuanced understanding of the potential implications of introducing this new bioenergy sector nationwide is elucidated. Furthermore, the study presents the existing conditions of raw material production for biofuel generation across different Mexican states.

Structured into five sections, the study unfolds various dimensions of the topic. The second section scrutinizes the ethanol industry in Mexico, assessing the country's current landscape, Jalisco's production

capacity, and the Mexican government's stipulated requirements for bioethanol production. The third section delves into the prevailing nutritional scenario in Mexico and Jalisco, exploring the ramifications of introducing new industries like bioethanol while analyzing the political landscape concerning food security protection. The fourth section investigates Mexico's and Jalisco's productive capacities, juxtaposing current records of corn and sugarcane production and imports of these raw materials. Lastly, the fifth section evaluates biomass's current status as a potential substitute in second-generation bioethanol generation, delineating its advantages and disadvantages in biofuel production.

In conclusion, this study synthesizes the presented data to draw pertinent conclusions, offering valuable insights into the prospects and challenges of advancing the bioethanol industry in Jalisco and Mexico as a whole.

II. Materials

The methodological framework employed in conducting this study aligns with the objectives delineated by SENER as published in [1]. These objectives, focused on fostering sustainable energy transition, are enumerated as follows:

I. Foster a gradual increase in clean energy's participation in the electricity industry to meet prescribed goals for clean energy generation and emissions reduction.
II. Facilitate adherence to clean energy and energy efficiency targets outlined in the LTE in an economically viable manner.
III. Factor externalities into the assessment of costs associated with the operation and expansion of the electricity industry, including impacts on health and the environment.
IV. Establish obligations concerning the sustainable utilization of energy and energy efficiency.
V. Implement mechanisms to promote clean energy adoption and curb polluting emissions.
VI. Economically viable reduction of polluting emissions in electricity generation processes.
VII. Support objectives outlined in the General Law on Climate Change (LGCC) concerning the reduction of greenhouse gas emissions and the transition to clean energy sources for electricity generation.
VIII. Promote sustainable energy use in final consumption and energy transformation processes.
IX. Advocate for the utilization of renewable resources and waste in energy production.
X. Standardize obligations concerning clean energy and emissions reduction across products consumed within the national territory, irrespective of their origin.

To gather information, terms including clean fuels, food sovereignty, intensification of corn and sugarcane cultivation, bioethanol production, and challenges towards sustainable development in Jalisco were queried. Additionally, statistical data from reputable sources was considered:

a). Data from the Bank of Mexico regarding the importation of corn and sugar from Mexico over the past decade.

b). Data from the Institute of Statistical Information and Geography pertaining to the production of corn and sugarcane in all Mexican states in 2020. Moreover, data on corn and sugarcane production in Jalisco from 1981 to 2019 was analyzed to ascertain trends over thirty-eight years. This extended timeframe provides a robust understanding of

production dynamics crucial for ensuring food sovereignty.

The collection and analysis of this information are elaborated upon to elucidate the challenges and opportunities encountered in bioethanol production in Mexico presently. Furthermore, recommendations are offered regarding optimal raw materials, ideal scenarios, and alternative approaches for bioethanol generation in Jalisco.

III. Discussion of results

A. Ethanol industry in Mexico

The ethanol industry has been a longstanding presence in Mexico, primarily utilizing sugar cane as its raw material within the country's sugar mills equipped with distilleries. Predominantly, ethanol production relies on traditional methods of fermentation and distillation, often leveraging sugar cane molasses. This process not only embodies recognized technological practices but also holds significant cultural heritage value within Mexican society, finding applications in beverages, medicine, and various industrial sectors.

Ethanol-gasoline blends are categorized based on their ethanol content, with three main variants: E85, E15, and E10, each playing a pivotal role in the fuel industry:

- E85, boasting high ethanol content of up to 85%, is favored by flex-fuel vehicles. However, not all vehicles are compatible with E85 due to variations in engine design.
- E15, comprising 15% ethanol, represents a concentrated option gaining traction in international markets, albeit with limited availability.
- E10, a standard gasoline variant enriched with 10% ethanol, is prevalent in the United States [23].

The early 2000s witnessed growing environmental concerns, prompting the Mexican federal government to introduce legislation promoting the use of alternative fuels in gasoline. These legislative initiatives culminated in the publication of guidelines and quality specifications for bioethanol, biodiesel, and bioturbosine by the "Diario Oficial de la Federación" in 2014. Subsequently, NOM-016-CRE-2016 was issued in 2016, amended in 2017 to permit nationwide use of E10, excluding major metropolitan areas such as the Valley of Mexico, Guadalajara, and Monterrey. This restriction, grounded in the precautionary principle, remains in force until robust technical evidence attests to the absence of adverse environmental impacts from ethanol at this concentration [12].

Integrating ethanol into gasoline as a complementary fuel component presents novel challenges in Mexico, encompassing agricultural costs, raw material transportation, investment, processing, storage, distribution, and marketing.

Presently, bioenergy production in Mexico is governed by:

- Provisions within the Political Constitution of the United Mexican States, including Article 4, Paragraphs V, Article 25, and Article 27, Section XX.
- The Law for the Promotion and Development of Bioenergy (Ley de Promoción y Desarrollo de los Bioenergéticos or LPDB).
- Regulations accompanying the Law for the Promotion and Development of Bioenergy (Reglamento de la Ley de Promoción y Desarrollo de los Bioenergéticos or RLPDB).
- Guidelines stipulating quality specifications and characteristics for

anhydrous ethanol (bioethanol), biodiesel, and bioturbosine.

Table 1 delineates the requisite characteristics and specifications for anhydrous ethanol-type biofuels in Mexico, as mandated by these guidelines, ensuring adherence to quality standards and fuel integrity.

Table 1. Quality specifications and characteristics of bioethanol or anhydrous ethanol [24].

Property	Units	Test Method	Limit Value
Appearance	Dimensionless	Visual	Clear, bright, and free from impurities
Color	Dimensionless	Visual	Orange ASTM L1.0
Ethanol and higher alcohols C3-C5	% vol	ASTM D 5501 IN 15721	99.5 minimum
Ethanol	% vol		97.5 minimum
Higher alcohols C3-C5	% vol	IN 15721	2.0 maximum
Methanol	% vol	ASTM D 5501	0.5 maximum
Density at 20 °C	kg/m^3	ASTM D 4052	Report
Electric conductivity	µS/m	ASTM D 1125	500 maximum
Acidity (as acetic acid CH_3COOH)	%(m/m)	ASTM D 1613	0.007 maximum
pH	Dimensionless	ASTM D 6423	6.0 - 9.0
Washed rubber	kg/m^3 (mg/100mL)	ASTM D 381	0.050 maximum (5 maximum)
Water content	% vol	ASTM D1193 ASTM E 203, ASTM E 1064	0.5 maximum
Inorganic chloride content	mg/kg (mg/L)	ASTM D 512 ASTM D 7319, ASTM D7328-07	10 maximum (8 maximum)
Copper content	mg/kg	ASTM D 1688	0.1 maximum
Total sulfur	mg/kg	ASTM D 5453 ASTM D5453-06	10 maximum
Sulfates	mg/kg	ASTM D 7319, ASTM D7328 ASTM D7328-07	4 maximum
Phosphorus	mg/L	IN 15487	Report
Denaturant			Undenatured

Note: To conduct specific tests, the addition of 15 mg/L of liquid colorant to the oil is necessary to achieve an orange color ASTM L1.0, characterized by an absorbance ranging between 0.15 and 0.19 at the wavelength of 420 nanometers. The colorant must exhibit solubility in alcohol, insolubility in water, and must not compromise the specified properties of anhydrous ethanol.

Similar to other technological advancements, biofuels present both advantages and drawbacks. Among their benefits, the primary objective of utilizing biofuels is to mitigate greenhouse gas emissions responsible for exacerbating global warming and accelerating climate change [25].

Upon the consolidation of biofuel utilization on a national scale, widespread environmental advantages and a substantial

reduction in pollution stemming from combustion gases emitted by vehicle engines can be realized [26].

An analysis conducted by the "Asociación para la Movilidad con Biocombustibles en México, A. C." spanning from 2010 to 2019 underscores the benefits of incorporating bioethanol as an additive to conventional gasoline in the country. A blend comprising 10 percent bioethanol stands to yield significant financial savings for Pemex. Specifically, a reduction of 70 cents per liter translates to an estimated national savings of nearly 18,000 million Mexican pesos annually [27].

Sugar mills play a pivotal role in ethanol generation in Mexico. Jalisco, boasting six operational sugar mills annually, is strategically distributed across its territory (Figure 4), contributing significantly to the bioethanol production landscape.

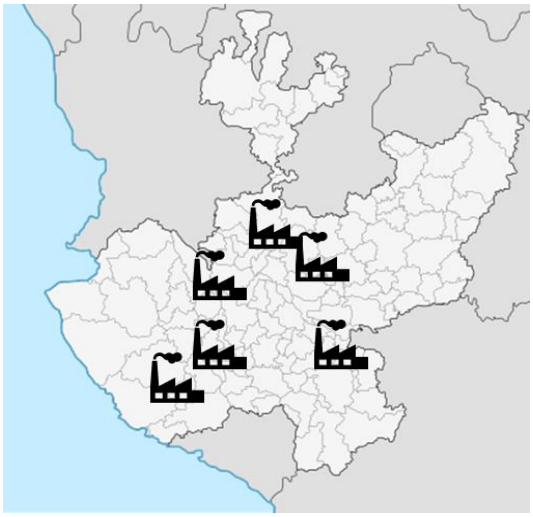


Figure 4. Location of sugar mills in Jalisco.
Own elaboration.

The sugar mills serve as the primary purchasers for local farmers, consequently generating around 300 thousand direct jobs. Moreover, they play a crucial role in manufacturing various products derived from sugarcane, including refined sugar, molasses, and alcohol, with a potential alcohol content of up to 96° GL.

Table 2 provides a concise summary of the harvest report from the sugar mills for the year 2020/21 in Jalisco.

Table 2. Production report of the Jalisco sugar mills in the 2020/2021 harvest [28].

Sugarmill	Total produced sugar (t)	Molasses produced (t)	Alcohol produced (L)	Raw ground cane (t)
Bellavista	70,197.50	30,857.00	0.00	644,660.02
José María Morelos	66,576.75	26,044.00	0.00	625,371.55
Melchor Ocampo	140,351.85	41,618.00	0.00	1,163,278.47
San Francisco Ameca	117,079.50	46,580.00	0.00	1,032,385.68
Tala	184,850.70	66,000.00	0.00	1,719,066.78
Tamazula-Sáenz	154,119.00	49,392.49	4,931,000.00	1,291,735.75
Total	**733,175.30**	**260,491.49**	**4,931,000.00**	**6,476,498.25**

The primary traded commodity among sugar mills is refined sugar, with key producers including Tala, Tamazula-Sáenz, and Melchor Ocampo, averaging around 180,000 tons and totaling 733,175 tons throughout the harvest period. Molasses, another byproduct, is produced across all sugar mills in Jalisco, yielding 260,491 tons. Notably, ethanol production in Jalisco is predominantly carried out by Tamazula-Sáenz, with an output reaching nearly 5 million liters during the 2020-2021 period. Additionally, private enterprises like "Alcoholera de Zapopan" also contribute significantly to large-scale ethanol production in Jalisco.

In the realm of the current energy landscape, there is a growing consensus among various global organizations that the existing energy system is unsustainable. This viewpoint is grounded in three key factors: the availability of resources to meet energy demands, the environmental repercussions of energy supply and consumption methods, and the glaring inequity in access to this fundamental element for human development. Presently, these factors remain unmet, with considerable room for improvement [29].

Amidst concerns over dwindling oil reserves, biofuels have emerged as a viable alternative, derived from biomass. Biomass encompasses organic matter sourced from diverse activities such as agriculture, forestry, aquaculture, and industrial processes, along with their derivatives, produced through sustainable technological processes [30]. It encompasses a wide array of organic materials derived from recently living organisms or their metabolic waste [25].

Bioethanol, a prominent biofuel, is produced through the fermentation of carbohydrates found in biomass, including crops rich in sugars or starches, and lignocellulosic materials [31]. Leading bioethanol-producing nations like Brazil and the United States predominantly utilize sugar cane and corn, respectively, owing to their abundant availability in these regions.

Various raw materials rich in carbohydrates or hemicellulose serve as sources for bioethanol production, including potatoes, corn, wheat, cassava, and oilseeds, alongside residues like sugar molasses and wastepaper. [14]. Different generations of bioethanol production are delineated, with each utilizing distinct feedstocks and technological processes. [15].

In the first generation, bioethanol is primarily sourced from agricultural products intended for human consumption, boasting high concentrations of starch, sugars, and oils. Key raw materials for this generation include sugar cane juice, corn kernels, beet or beet juice, sunflower seed oil, soybean oil, palm oil, castor oil, cottonseed oil, coconut oil, peanuts, and their respective oils. Additionally, animal fats and waste oils from cooking and food processing, as well as organic solid waste, are utilized as inputs.

On the other hand, the second generation relies on agricultural and forestry residues, predominantly comprising cellulose. These include sugar cane bagasse, corn stubble (stalks, leaves, and cobs), wheat straw, sawdust, dry tree leaves, branches, and similar materials. Advanced technological processes such as pressure swing adsorption, membranes, extractive distillation with salts, and vacuum distillation are essential for the production of bioethanol from this second generation [21], [32]–[36].

In the third generation, the focus shifts to fast-growing non-food crops characterized by their high energy density stored in their chemical constituents, earning them the designation of "energy crops." These crops encompass a variety of perennial grasses, rapid-growing trees and plants, as well as

green and blue-green algae. Production of bio-ethanol from this generation necessitates the utilization of biological or chemical bio-reactors capable of creating anaerobic conditions conducive to the action of bacteria and yeasts. These microorganisms play a pivotal role in enzymatically converting the complex molecules present in the biomass into ethanol [37]–[39].

The fourth and final generation of biofuels explores the production of fuels derived from genetically modified bacteria, engineered to utilize carbon dioxide (CO2) or alternative carbon sources for biofuel synthesis. Presently, this generation of biofuels remains largely theoretical, with only the potential synthesis pathway of ethanol from carbon dioxide identified. However, its realization hinges entirely on the genetic makeup of engineered bacteria and may encounter significant thermodynamic limitations [24].

B. Food sovereignty

The energy transition encounters various impediments, many of which are inherent to the implementation process within the energy sector. Amidst gradual institutional changes in the energy landscape, two critical aspects pose challenges for public policies and current long-term development strategies: the environmental and social sustainability of renewable energy production, particularly biofuels, and the energy provision for the entire population amidst escalating demand.

One notable concern is the potential for increased consumption of agricultural materials in bioethanol production, which could lead to shortages in human and animal consumption.

Hence, it is imperative that biofuel production be comprehensively regulated by governments with policies grounded in food sovereignty. Food sovereignty entails the unrestricted determination of a nation in terms of food production, distribution, and access for its populace, primarily centered on domestic production [19].

The concept of food sovereignty emphasizes the right of peoples to define their own policies for food production, distribution, and consumption, ensuring the availability of locally produced, healthy, nutritious, and culturally appropriate food [40].

Given that Mexico lacks a legal definition of food sovereignty in its laws or constitution, there arises a pressing need for governmental regulation.

Food sovereignty represents a strategic objective and a state obligation to ensure that individuals, communities, peoples, and nations achieve self-sufficiency in healthy and culturally suitable food on a sustained basis [41].

Governments bear the responsibility of guaranteeing the availability of essential products for human nutrition, such as corn, sugar cane, sunflower seeds, and other agricultural commodities, to meet the needs of their citizens.

To safeguard against the potential impact of first or second-generation bioethanol production on food sovereignty or nutritional equilibrium, it is essential for agricultural product production for bioethanol to be extensive and self-sustaining.

Through an entity-based analysis utilizing data from the National Council for the Evaluation of Social Development Policy (CONEVAL), estimates were made regarding the percentage of the population experiencing deficiencies in food access (Figure 5).



Figure 5. Scale of people with lack of access to food in Mexico.
Own elaboration with data from [42].

States with the highest percentages of food insecurity include Guerrero with 35.6%, Tabasco with 46.8%, Oaxaca with 27.9%, Campeche with 27.4%, and Veracruz with 27%. Conversely, states with the lowest percentages are Nuevo León with 12.2%, Aguascalientes with 13%, Querétaro with 13.9%, Mexico City with 13.9%, Baja California with 14.1%, and Jalisco with 15.1%.

Mitigating food shortages should be a primary concern for state governments when considering projects that could impact the availability of key dietary staples for Mexicans, such as corn. This positions Jalisco as a promising candidate for bioethanol generation projects.

Given the absence of constitutional provisions guaranteeing food sovereignty in Mexico, bioethanol production should primarily focus on utilizing agricultural sector waste. Although production conditions are not formally outlined, Mexico regulates the use of corn for bioenergy production. The Secretariat of Agriculture, Livestock, Rural Development, Fisheries, and Food (SAGARPA) grants permits for corn production for bioenergy, contingent upon surplus inventories, to be determined with input from the Energy Secretariat (SENER). [43].

If corn imports are intended for bioenergy production, notification to SAGARPA is mandatory, which will verify alignment between corn imports and the interested party's bioenergy production. SAGARPA must respond to requests within fifteen days, with non-response constituting denial. Permits are valid for one year and may be extended upon request three months before expiration. [25]

The request must include the promoter's details, permit number, legal representative's name, address for notifications, and email. SAGARPA has ten business days to alert the applicant of any omissions, with a five-day window for rectification, failing which the request is rejected [38, p. 6]. [15].

Environmental conservation is paramount in bioenergy production. Land-use change from agricultural forestry is prohibited, and expansion of the agricultural frontier is restricted. Environmental protection standards issued by the Environment and Natural Resources Secretariat

(SEMARNAT) govern bioenergy production activities, emphasizing rational water use, air pollution prevention, greenhouse gas reduction, and soil contamination avoidance [43]

On the other hand, the Energy Secretariat (SENER) oversees the activities and services related to the production, storage, transportation, and distribution of pipelines, as well as the commercialization of Bioenergetics [6].

Furthermore, the Environment and Natural Resources Secretariat (SEMARNAT) will issue Official Standards, guidelines, criteria, and guides to safeguard the environment from activities involved in bioenergy production. These regulations will encompass the following aspects:

I. Promoting the rational and sustainable use of water to preserve its availability and enhance its quality.
II. Enforcing measures to avoid and mitigate air pollution, aiming to minimize greenhouse gas emissions while considering the overall net environmental benefit.
III. Implementing strategies to prevent, reduce, or eliminate soil contamination, with an emphasis on adopting consumption reduction and reuse systems within bioenergy production processes [38, p. 16].

Conversely, the Secretariat of Energy (SENER) is responsible for overseeing activities and services related to bioenergy production, including storage, transportation, and distribution via pipelines, as well as the commercialization of bioenergy products [38, p. 10].

C. Productive capacity of raw materials in Jalisco

Jalisco stands out as one of Mexico's primary agricultural hubs, owing to several key factors. The state boasts a diverse range of climates, and each region features varying soil types, creating an ideal environment for cultivating a wide array of crops and ensuring year-round harvests.

In developing nations, the production of bioethanol presents a significant dilemma when it competes with crops designated for food production, such as corn and sugar. Initially, this competition can drive up the costs of essential food products and exacerbate issues of food scarcity [44]. The competition for agricultural land usage is a crucial aspect to consider. Moreover, biofuel production entails increased fertilizer and pesticide application, potentially compromising water and soil quality. Additionally, this process necessitates changes in land usage, often leading to the conversion of forested areas into agricultural land, with profound implications for biodiversity and environmental sustainability. These challenges underscore the intricate interplay between biofuel production, food security, and environmental conservation in developing nations. Given this context, conducting a comprehensive analysis of the agri-food landscape in Mexico and Jalisco becomes imperative to propose pragmatic and impactful solutions that address present-day challenges.

Table 3 delineates the crops with the largest planted and harvested areas as reported by the Agro-Food and Fisheries Information Service (SIAP) at the close of the 2022 agricultural production cycle [45]. Although corn and sugar cane exhibit higher yields in terms of land utilization compared to agave, the latter commands a higher value in the current market.

Table 3. List of the 5 most important crops in Jalisco.

Crop	Surface (ha)		Production value (dollars)
	Sown	Harvested	
Corn (grane and forage in green)	787,828.67	787,403.67	1,871,680
Pastures and meadows	441,960.99	441,960.99	368,534
Sugarcane	79,935	79,276	420,977
Agave	73,585.22	11,381	1,276,478
Avocado	28,647.79	27,832.79	552,683

Own elaboration with data from [45].

Agave cultivation in Jalisco constituted 25% of agricultural production in 2021, making it the foremost producer of this crop nationwide, accounting for 1,025,899 tons (60%) [46]. Figure 6 illustrates the planting areas in the state of Jalisco from 2011 to 2022 for sugarcane and agave. The graph depicts a decline in agave cultivation from 2011 to 2015, followed by an increase in planting area from 2016 to 2020, which then stabilized until 2022. Conversely, sugarcane cultivation exhibited a tendency to grow from 2011 to 2016, remaining steady until 2020. However, in 2021 and 2022, there was a reduction in the area dedicated to sugarcane cultivation. This decline could be attributed to various factors, including producers perceiving other crop types as more profitable, insufficient social assistance for most farmers, high costs of supplies, machinery, and services, as well as soil fertility depletion [47].

Throughout the tequila production process, various byproducts are generated, including agave leaves, residual fibers, roots, stems, and seeds. Among these, agave bagasse emerges as one of the most significant residues. This fibrous material is obtained after crushing, cooking, and grinding agave heads to extract the sugars necessary for tequila production. Despite being a byproduct, agave bagasse holds substantial potential value in terms of sustainability and resource utilization. Its versatility extends beyond tequila production, finding application in renewable energy generation, textile fiber, and paper production.

The sugars present in agave bagasse can be anaerobically digested to produce biogas or hydrolyzed and fermented to yield bioethanol [48]. Steam explosion and enzymatic hydrolysis are among the technologies with the highest potential for utilizing this waste, enhancing biodegradability and maximizing sugar profits from the bagasse [48]. While the yield of agave bagasse may vary depending on the species, it typically produces around 320 liters of ethanol per ton of dry bagasse [49]. In 2019, tequila production generated 3,842,960 tons of agave bagasse [46]. If half of this bagasse (1,921,480 tons) were repurposed, it could potentially yield up to 614 million liters of ethanol annually. This underscores the feasibility of repurposing such waste for recycling purposes.

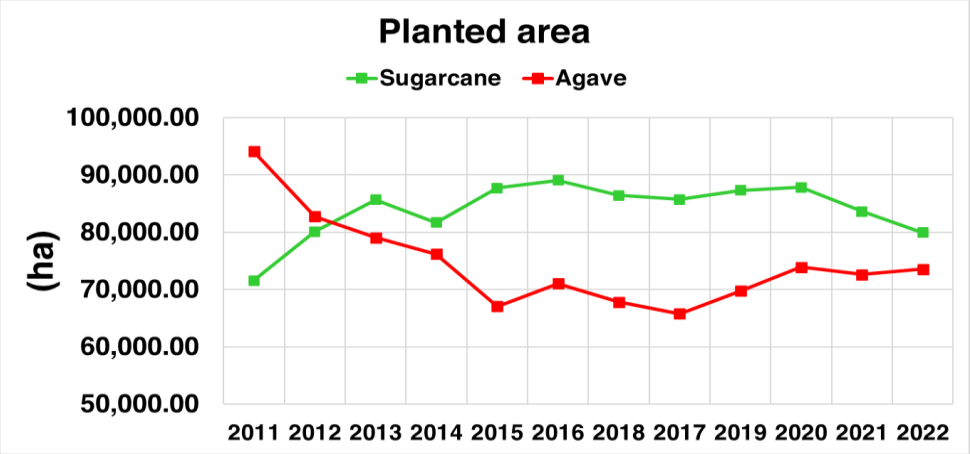


Figure 6. Area planted with sugarcane and agave in Jalisco 2011-2022.
Own elaboration with data from [45].

Corn exhibits a trend similar to agave, starting in 2012 and reaching its lowest point in 2015 (Figure 7). Thereafter, it experienced a robust recovery in 2016, maintaining stability until 2020. However, in the subsequent years (2021 and 2022), corn cultivation has shown a decreasing trend.

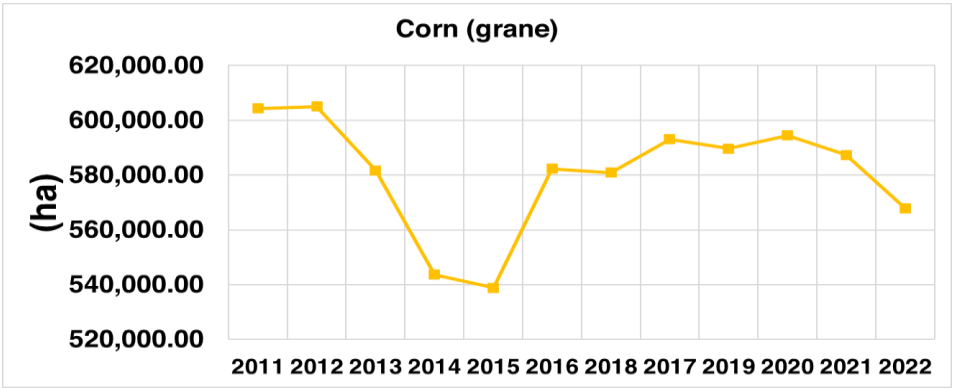


Figure 7. Area planted with corn in Jalisco 2011-2022.
Own elaboration with data from [45].

The utilization of organic waste in agriculture within Jalisco holds paramount importance for both agricultural and environmental sustainability. Organic residues, including crop remnants, can be repurposed into valuable compost or biomass.

The sugar sector, in particular, boasts significant potential regarding biomass utilization. For every 100 tons of processed cane, approximately 10 to 12 tons of sugar, 25 to 30 tons of bagasse, and between 10 and 20 tons of agricultural residues remain in the field, along with 5 to 7 tons of straw [28].

However, the agro-industry in Jalisco exhibits poor diversification and inefficiencies across various technical parameters. Notably, the sugarcane agroindustry relies on purchasing around 6.3% of its electrical energy from the Federal Electricity Commission (CFE) to facilitate sugarcane grinding operations in Mexico, consequently driving up operational costs [50]. In essence, the sugarcane agroindustry lacks self-sufficiency in electricity generation for internal consumption, a situation applicable to five out of the six sugarcane

mills in Jalisco. Conversely, Ingenio Tala has reported an energy surplus since 2013, which it sells to the CFE and distributes within the electricity grid of Tala municipality [51]. However, it's worth noting that achieving this surplus requires substantial burning of sugarcane bagasse, resulting in significant air pollution emissions.

Table 4 illustrates the national agricultural production figures reported in 2019 by the SIAP, additionally providing a comparison of production across five states in Mexico. Veracruz and Sinaloa emerge as the leading producers of sugarcane and white corn, with Jalisco following as the second-largest producer of these two crops. This distribution may be attributed to various factors, including the significant cultivation of agave within the state, which competes for planting areas. Furthermore, Chihuahua stands out as the producer of nearly 50% of the country's yellow corn.

Table 4. National production and by states of sugar cane and corn.

	Crop	Production
National	**Sugarcane**	**53,315,792.79**
	Yellow corn	**5,400,839.40**
	White corn	**25,811,328.12**
Jalisco	**Sugarcane**	7,773,719.04
	White corn	3,410,048.91
Veracruz	**Sugarcane**	18,156,050.71
	White corn	1,113,138.53
Oaxaca	**Sugarcane**	3,248,455.72
	White corn	633,798.37
Chihuahua	**Sugarcane**	No data
	Yellow corn	2,481,299.06
	White corn	101,107.46
Sinaloa	**Sugarcane**	246,856.87
	White corn	7,484,681.07
Other states	**Sugarcane**	31,664,429.49
	Yellow corn	2,919,540.34
	White corn	14,815,490.68

Own elaboration with data from [45]and [28].

To effectively contrast sugar production, it's essential to compare two critical variables: cane yields per unit area and the amount of sugar recovered from each ton of cane, alongside factory performance. Figure 8 depicts the expansion of agribusiness in Mexico from 2012 to 2022.

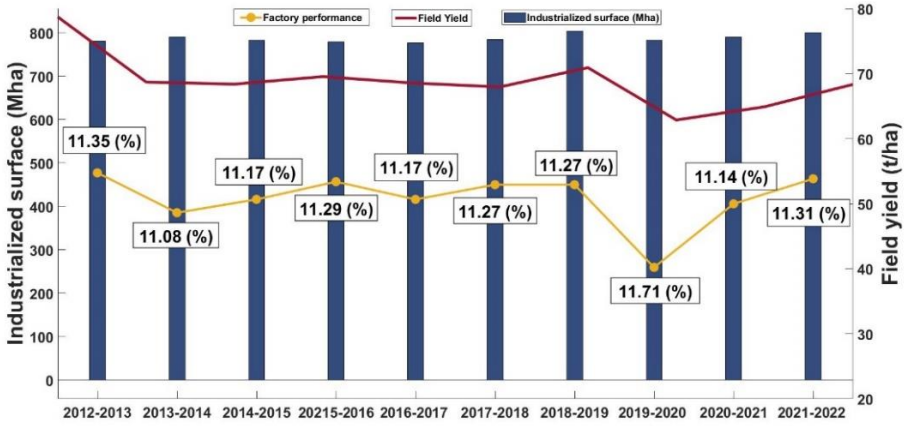


Figure 8. Comparison of the industrialized surface, field performance and factory efficiency from 2012 to 2022 in Mexico.
Own elaboration with data from [52], [53].

These factors fluctuate over the years, reflecting the true situation of the agricultural sector. Over the past decade, the industrialized area has experienced an annual growth rate of 1.4% [52], while field yields have remained relatively stable, ranging between 65 and 75 tons per hectare, indicating minimal growth. Similarly, factory performance has remained stagnant at 11%.

These data illustrate that sugar production and the agricultural sector associated with this crop have remained relatively unchanged in recent years. Ideally, the goal would be to increase sugar production while maintaining or reducing the crop area.

As mentioned earlier, there are various raw materials available for producing bioethanol. However, a comparison was conducted to assess the feasibility of producing bioethanol in the State of Jalisco using either corn or sugarcane, while also considering the most environmentally suitable generation method and respecting food sovereignty.

Over the past decade in Mexico, there has been a significant increase in grain imports, indicating a shortage of corn in the country, as depicted in Figure 9.

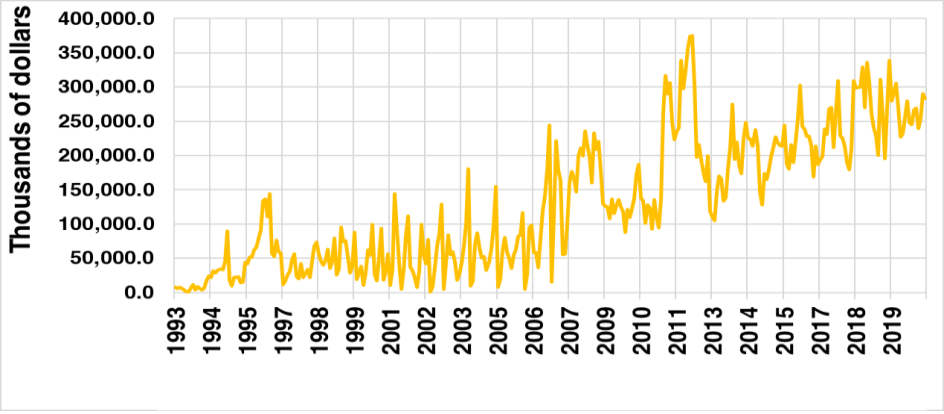


Figure 9. Corn import.
Own elaboration with data from [54].

As for sugar cane, the Bank of Mexico (BANXICO) does not provide a specific chart on imports. However, there is a chart available for sugar imports, which reveals minimal import activity over the past decade, except for the years spanning from 2009 to 2012 (Figure 10).

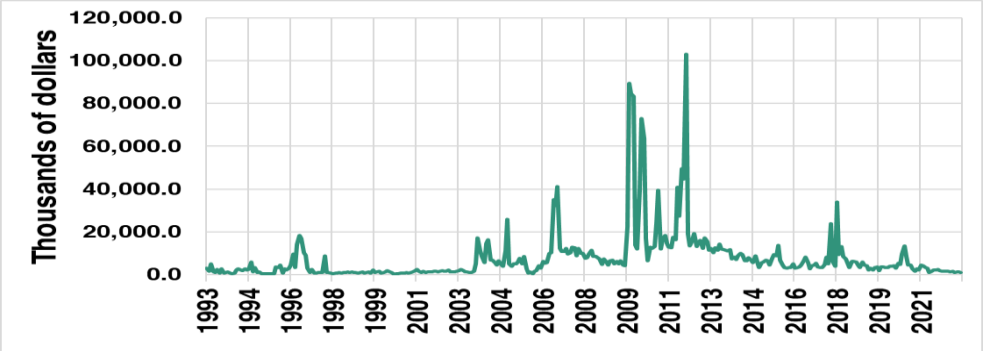


Figure 10. Sugar import.
Own elaboration with data from [54].

Regarding corn production in 2021, Jalisco ranked second nationally with 14.38% (Figure 11).

Increasingly, food industries in our country are undergoing a transformation process in their products. This transformation entails a notable reduction in the amount of sugar incorporated into their ingredients. The primary aim is to achieve a considerable decrease in the caloric density of their products, thereby circumventing the inclusion of the warning labels mandated by the new labeling regulations. Additionally, this strategy enables them to market their products as low-calorie or completely sugar-free alternatives. However, the mainstream consumers of these products are opting to substitute sugar with high fructose corn syrup (HFCS), which is sweeter and cheaper to produce than cane sugar. [55].

This shift is primarily driven by the significant influence of the soft drink industry in Mexico, as it is the leading consumer of sugar. [56]. In the event that this industry decides to replace sugar with HFCS, coupled with the decline in sugar exports resulting from the transition from the North American Free Trade Agreement (NAFTA) to the T-MEC, sugar mills will face substantial pressure to reassess their sugar production strategies.

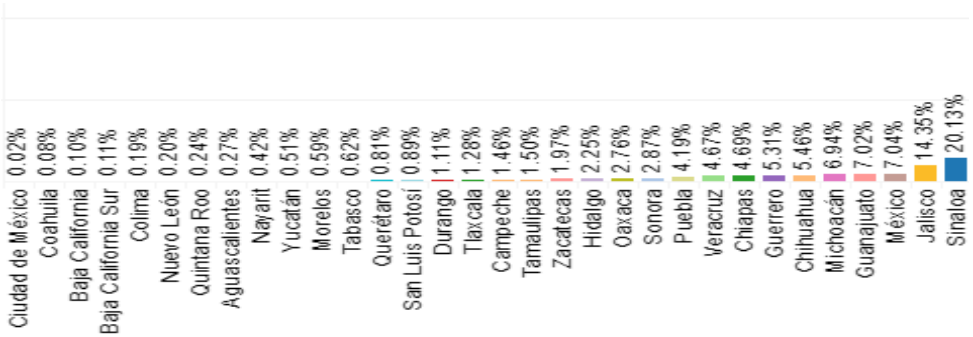


Figure 11. Corn harvest by federal entity.
Obtained from [46].

In 2021, Jalisco ranked second nationally in sugarcane production, accounting for 13.18% of the total output (Figure 12).

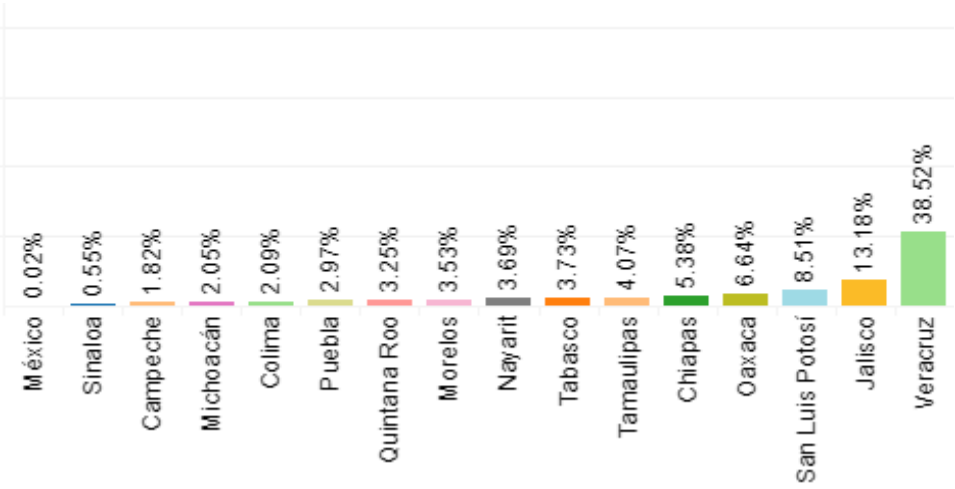


Figure 12. Sugarcane harvest by federal entity.
Obtained from [46].

As depicted in Figure 13, corn production in the State of Jalisco has exhibited a notable decrease from 1981 to 2019.

Analyzing the data from the table, we observe fluctuations in production over different periods. From 1987 to 2005, there was an increase compared to the preceding years (1981 to 1987). Subsequently, production declined from 2005 to 2015 compared to the previous period (1987 to 2005). However, there was a slight uptick in production from 2016 to 2019 compared to the period from 2005 to 2015. Despite this fluctuation, overall, corn production in Jalisco, Mexico, has experienced a significant decrease from 1981 to 2019.

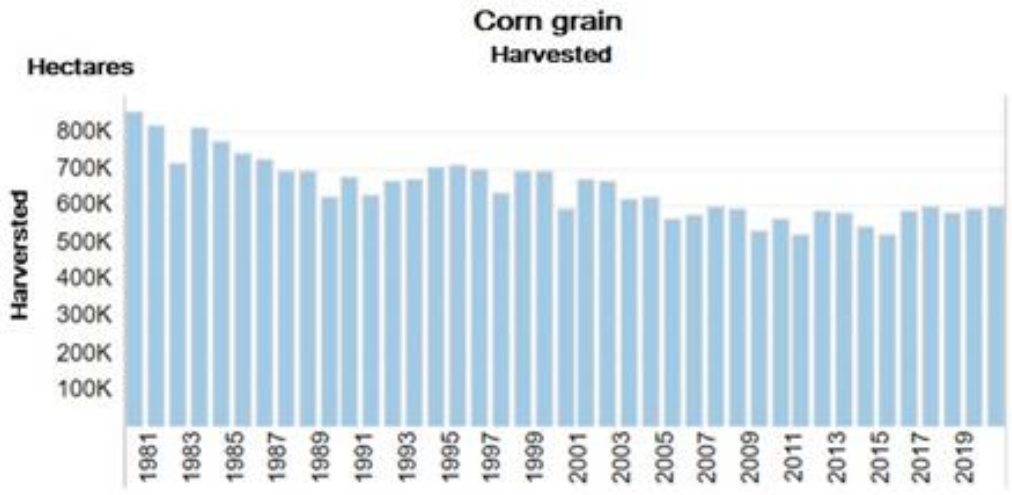


Figure 13. Corn production in the State of Jalisco.
Obtained from [46].

In contrast, the production of sugarcane has exhibited a gradual increase from 1981 to 2019, as illustrated in Figure 13. Notably, from 2015 to 2019, the harvested tons have remained consistently high.

Specifically, in 1985, there was a significant spike in production compared to the period from 1981 to 2019. The years from 1986 to 1995 saw a continued increase in production compared to the preceding period of 1981 to 1984. However, from 2000 to 2011, there was a decline in production relative to the period from 1996 to 1999. Subsequently, from 2012 to 2019, there was an uptrend in production compared to the period spanning from 1981 to 2019, excluding 1985.

Overall, the production of sugarcane in the State of Jalisco, Mexico, has demonstrated a steady growth trajectory from 1981 to 2019, with a sustained number of harvested tons from 2015 to 2019 (Figure 14).

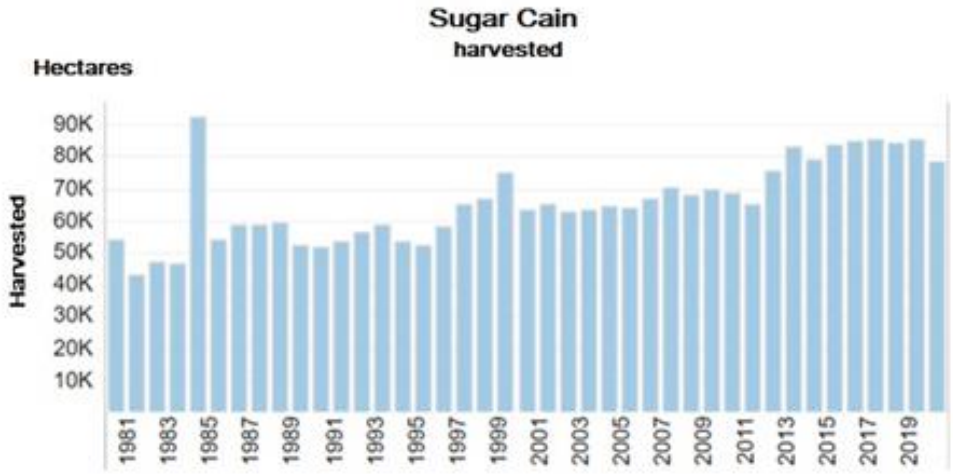


Figure 14. Sugarcane production in the State of Jalisco.
Obtained from [46].

Hence, the data depicted in the graphs reveal a trend of higher corn imports compared to sugar production, with exceptions noted in the years 2010 to 2012.

The production of both corn and sugarcane positions the State of Jalisco as the second-largest contributor nationally. However, a concerning trend emerges: while sugarcane production has seen sustained growth from 1981 to 2019, corn production in Jalisco has witnessed a significant decline over the same period, except for a slight increase from 2015 to 2019. This decline in corn production raises concerns about food security and underscores the need to bolster corn production to meet demand for food and other related products.

Given these statistics, utilizing corn as a raw material for bioethanol production presents challenges. Mexico's heavy reliance on corn imports indicates a lack of self-sustainability, posing obstacles to bioethanol production from corn. Moreover, Jalisco's diminishing corn production further underscores the need for self-sufficiency in corn production to ensure food sovereignty.

In contrast, utilizing sugarcane as a feedstock for bioethanol production appears more feasible. With minimal sugar imports and increased sugarcane production in Jalisco, the state demonstrates a level of self-sustainability in sugar production. However, producing first-generation bioethanol from

sugarcane may disrupt this balance, necessitating a prolonged period of overproduction to consider bioethanol production.

Alternatively, utilizing sugarcane bagasse for second-generation bioethanol production offers a viable solution. Since sugarcane bagasse is a byproduct of sugar production, its use does not directly impact the sugar economy of Jalisco. Leveraging sugarcane bagasse for bioethanol production ensures sustainability while maintaining the equilibrium of the sugar industry.

To enhance profitability and diversify the sugarcane agribusiness, investment in research and development is crucial. Initiatives such as genetic improvement, [57] pest and disease management, mechanization, and soil mapping can optimize sugarcane production [58]. Furthermore, collaboration between research institutions, farmers, and industry stakeholders is essential to promote sustainability and profitability in sugarcane production and its associated agribusiness.

In conclusion, considering the outlined factors, second-generation bioethanol production from sugarcane and agave bagasse emerges as the most viable option for the State of Jalisco, Mexico.

D. Current panorama of the use of biomass for the generation of bioethanol in the State of Jalisco, Mexico.

Bioenergy represents a vital component of renewable energy, sourced from biomass formed recently from organic matter of non-fossil origin. Second-generation bioethanol, derived from lignocellulosic biomass, is a key focus, albeit requiring costly and intricate pretreatment processes to fractionate and manage biomass subproducts.

Bioenergy production employs various processes—thermochemical, biochemical, or physicochemical—to convert biomass energy into usable forms. Direct combustion yields heat energy, while gasification and pyrolysis generate products like syngas and bio-oil. Anaerobic digestion produces biogas, and alcoholic fermentation and transesterification produce liquid fuels like ethanol and biodiesel.

Raw materials for biomass production, sourced from trees and crops, can be sustainably replenished, offsetting carbon emissions through respiration. Biomass offers advantages like easy storage for future use [60]. However, it's not without drawbacks. Mismanagement can lead to deforestation and soil degradation, and many biomass-generating plants rely on fossil fuels for economic viability. Burning biomass emits greenhouse gases, necessitating capture and recycling to make biomass a true alternative to oil and gas.

Valorizing waste from the food industry for bioethanol production has pros and cons related to pretreatment methods, chemical compound additions, and fermentation systems. Corn and sugarcane are prime crops for biofuel generation, with a focus now shifting to agricultural residues from these crops.

Data from CONADESUCA indicate that Jalisco has averaged 1.85 million tons of sugarcane bagasse production over the past decade.

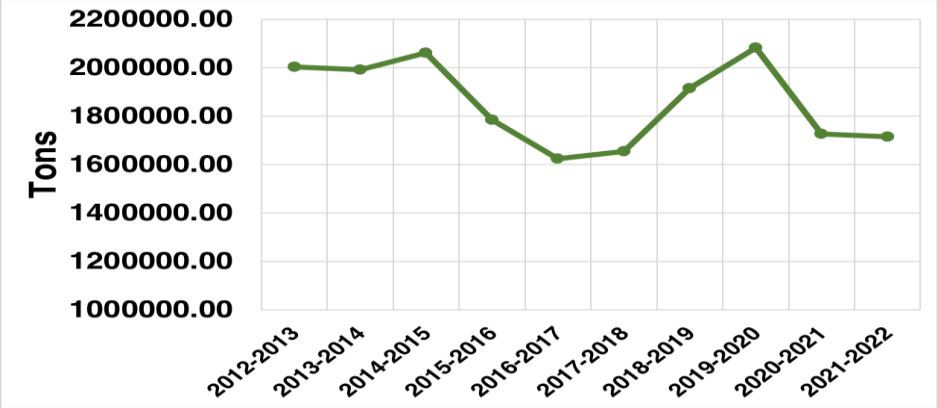


Figure 15. Cane bagasse obtained in Jalisco from 2012 to 2022.
Own elaboration with data from [62].

The utilization of this bagasse largely depends on the context; typically, it's used as fuel for boilers in sugar mills, with a smaller portion utilized as cattle feed and crop fertilizer.

Research by [63] conducted tests concluding that up to 149.3 liters of ethanol can be obtained per ton of processed bagasse. If Jalisco were to allocate 50% of the bagasse produced during the 2021-2022 harvest (857,597 tons), it could potentially yield up to 128.04 million liters of ethanol.

Other studies [64] suggest the possibility of obtaining up to 192 liters of alcohol per ton. However, the pretreatment method significantly impacts the final performance of the raw material, necessitating further research into these treatments.

Research conducted by [65] has demonstrated the feasibility of establishing a bioethanol generation plant from sugarcane residues in Mexico under certain conditions. Their analysis proposes a $308 million investment for a biorefinery capable of producing 143 million liters per year. Such a project, if implemented in the state of Veracruz, could yield a return on investment in approximately 20 years, provided the ethanol price remains stable.

It's worth noting that in Mexico, 90 percent of farmers burn sugarcane before harvesting. The percentage of burned cane in Jalisco over the last decade is illustrated in Figure 16. This burning emits up to 2 million tons of CO2 per hectare burned [66].

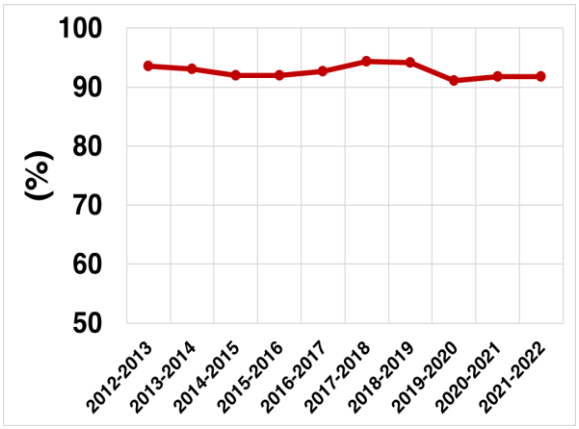


Figure 16. Percentage of cane burned by Jalisco farmers from 2012 to 2022.
Own elaboration with data from [62].

Highlighting the significant role of sugar cane burning in greenhouse gas emissions, it's imperative to transition to green harvesting methods. Green harvesting, which avoids burning, not only reduces emissions but also enhances environmental and agricultural sustainability.

In the production of sugarcane bagasse bioethanol, key stages include bagasse pretreatment, hydrolysis of pretreated

lignocellulose biomass into monosaccharides, and fermentation of sugars into bioethanol [67]. Presently, bagasse is primarily utilized for energy cogeneration through burning in boilers. However, due to its low calorific value (15.4 MJ/kg), energy generation efficiency is suboptimal. Conversely, research by authors like [67]–[69] indicates that sugarcane bagasse contains sufficient sugar levels for bioethanol production, making it a promising alternative fuel source.

Blend purification processes offer a viable means to increase ethanol concentration in blends. Techniques such as PSA can achieve ethanol concentrations of 99.5% wt, positioning it as a potential gasoline substitute [34]. However, further studies are needed to explore the long-term effects of bioethanol on car engines.

In [70], fermentation methods were applied to the most common fruit residues from 3 cities in the state of Guanajuato. Positive results were obtained, demonstrating that it is possible to synthesize ethanol from different fruit peels. [71] uses pineapple peels to obtain bioethanol. They mention that even though the alcohol obtained does not have a high concentration of ethanol, it is a viable option for the use of organic waste.

For its part in the corn industry, the residue of greatest interest is corn cob residue (CCR). The cob is the base of the corn on which the grain grows. CCR is the ear of corn after all kernels have been removed during feed processing. This remaining product is a potential feedstock for bioethanol production due to its high cellulose content. In [72], the production of second-generation bioethanol in Mexico from corn crops is studied. Through theoretical estimations, they demonstrated positive results regarding the use of CCR to synthesize bioethanol. [73] demonstrates that by means of the dilute acid hydrolysis method, it is possible to synthesize ethanol with a lower cost, better yield, and shorter production time. [69], [72], [73] compare the concentration of ethanol obtained from different biomasses of various agricultural wastes from Mexico. The use of lignocellulosic biomass from sugarcane bagasse and CCR stands out as raw material in obtaining bioethanol.

Other studies propose drying the waste from the most important crops in Mexico to obtain the maximum yield from these residues and thus become a feasible alternative for the production of second-generation bioethanol [71].

Currently, private companies can sell E10 and B5 blends in Mexico, which could create a new opportunity for the fuel market in Mexico [44]. This shows that strategies for the implementation of this technology on a larger scale are possible and economically profitable in Mexico.

Mexico then has two main raw materials from organic waste with which it could begin to implement effective strategies for its conversion into bioethanol and other biofuels. It must be considered that the value chain of the production of these materials adheres to not generating more pollution than is expected to be mitigated. That is why the combination with other renewable energy strategies such as solar and wind is of great interest to mitigate the climate crisis.

It should be added that in accordance with these statistics, the production of bioethanol using corn as raw material is not viable, for the following reasons:
Mexico heavily relies on importing large quantities of corn, indicating a lack of self-sustainability in corn production for both human and animal consumption. The insufficient domestic production not only

affects food security but also impacts the supply chain for products such as meat.

Despite being the second-largest contributor to national corn production, the State of Jalisco has experienced a significant decline in corn production. This decline in a key producing state suggests a nationwide decrease, leading to an increased reliance on imports. To ensure food sovereignty, Mexico must focus on boosting corn production within its borders to meet both human and animal consumption needs and to serve as a raw material for bioethanol production.

In contrast, the use of sugar cane as a raw material for bioethanol production appears more viable. Mexico's import of sugar is relatively low, and the increased production in Jalisco indicates a balance between production and consumption. However, using sugar cane for first-generation bioethanol may disrupt this equilibrium, emphasizing the need for a careful evaluation of the potential consequences.

In analyzing the adoption of second-generation ethanol, cost becomes a critical factor. PEMEX's price criterion for ethanol acquisition competes with high-quality ethanol from the US market. The decision to use second-generation ethanol should consider technical, economic, and social viability.

Determining ethanol demand is intricately connected to the planned replacement of MTBE and the percentage combination chosen by PEMEX. A strategic decision, considering technical, economic, and social aspects, is crucial for successful integration into Mexico's energy and economic matrix.

In the short term, ethanol demand is tied to oxygenant needs, while the medium term sees adjustments based on gasoline consumption, influenced by the country's vehicle fleet growth and economic conditions. This intricate web of factors highlights the necessity of a holistic and strategic approach when contemplating the integration of second-generation ethanol into Mexico's energy and economic landscape.

IV. Conclusion

The objectives outlined by [1] underscore the importance of seeking pragmatic solutions that establish a clean, renewable energy framework aligning with the country's political interests, ensuring public health, and maintaining economic viability.

Biofuels derived from agricultural sources like corn and sugarcane present a promising avenue as they utilize renewable materials without compromising food sovereignty. Despite Mexico's limited capacity for first-generation ethanol production due to food constraints, exploring waste as an alternative, considering the absence of defined protocols for agricultural waste use, presents a viable option.

The global and national decline in caloric sweetener consumption, including sugar, suggests a potential shift in subsequent years. Consequently, sugar mills must reassess the applications of raw materials such as sugar and molasses. In Jalisco, where five sugar mills currently do not produce ethanol, integrating distilleries into these facilities offers an opportunity to increase cane value in the market, enhancing profitability for local farmers.

Biofuels made from agricultural waste elements like CCR, agave, and sugar cane bagasse hold promise as they are renewable and environmentally friendly without compromising food sovereignty. Given sociopolitical factors, there is still an opportune window for the mass production

and marketing of such renewable energy in Mexico.

Certain states, including Jalisco, possess favorable conditions for bioethanol generation. The region demonstrated the potential to generate significant ethanol volumes from processing sugarcane and agave bagasse, showcasing economic viability under the right circumstances.

For bioethanol production in Jalisco and nationwide, any chosen raw material must experience overproduction for five to ten consecutive years, regulated by relevant laws, to ensure food sovereignty. Advocating for food sovereignty as a constitutional guarantee in the Political Constitution of the United Mexican States is crucial. In the interim, the federal government should enact laws facilitating bioethanol entry into the Mexican market, especially in major metropolitan areas, with the adoption of E10 in gasoline. Additionally, promoting green harvesting methods is essential to effectively mitigate greenhouse gas emissions from the sugar sector.

Considering statistics, bioethanol production with corn and CCR in Jalisco is not currently viable. However, it is viable with sugar cane, provided there is overproduction. Currently, second-generation bioethanol production in Jalisco, utilizing sugarcane and agave bagasse, stands as a feasible option. Furthermore, ethanol production methods must embrace renewable energy to be a realistic alternative for controlling greenhouse gas emissions.

Future research should focus on designing machinery tailored for bioethanol production using sugarcane bagasse, incorporating technology to enhance production efficiency at a reduced cost.

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