Chapter 10
Ethanol Production from the Mexican Sugar Industry: Perspectives and Challenges

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10.1 Introduction

Sugarcane is one of the major crop commodities of the world. It has initially been used for sugar production all around the globe; however, its potential as a fuel and energy source, and for various other products of economic importance, has increased over time (Khan et al. 2017). The combined engenderment of sugar and bioethanol from cane is a viable system to increase the competitiveness of mills in this agribusiness.

Bioethanol is a renewable transport fuel from the millennial biotechnology process of fermentation. Some bioethanol-based fuels programs are E5 (UK), E10 (EU), E15 (United States of America), and E25-100 (Brazil). Molasses is one of the most established feedstocks for ethanol production, contributing about 32 % of the world biofuels (Licht's 2017). Yet, sugarcane has not been used to its full potential for bioenergy in many countries, including Mexico. Several fallow wastes are generated, and the efficiencies of extracting energy contents of the bagasse, and especially the trash, are low. In spite of advancements in fermentation, pretreatment operations, and ethanol chemistry, there is still considerable room for improvement (Fig. 10.1).

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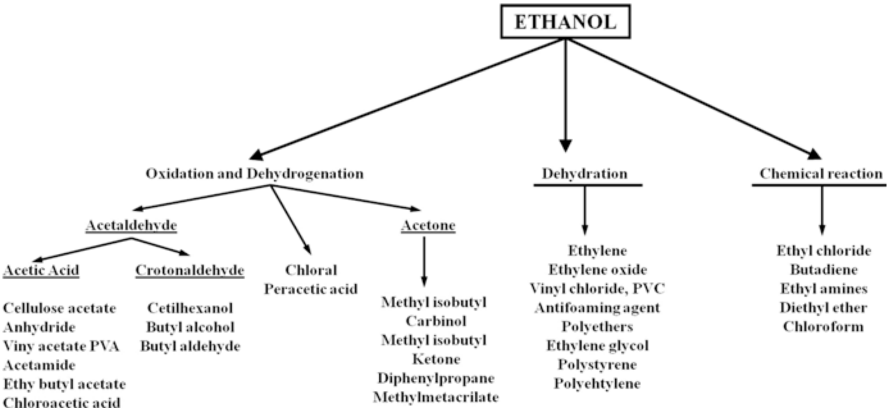


Fig. 10.1 Ethanol chemistry. (Modified from Gálvez et al. 2000; Maity 2015)

Sugarcane is one of the main crops of Mexico. The cultivation of sugarcane, as raw material, is important for Mexico in terms of acreage and jobs created as well. Approximately 184,000 Mexican growers are involved in sugarcane cultivation. The sucrose market also has various types of related interests involving soft drinks production units and bakery and confectionery industries.

10.2 Mexican Sugar Industry: Status, Products, and Economics

Mexico is world's tenth largest producer of sugar from sugarcane, which is cultivated at around 783,515 ha, producing over 53.3 million tons of crop. The Mexican sugar industry yielded 5.95 Mt of sugar and 13.8 million liters (Ml) of ethanol in the 2016/2017 harvest season. The sugar fraction was constituted by 3.8 Mt raw, 1.6 Mt refined, 0.26 Mt white, and 0.26 Mt muscovado sugar (National Chamber of the Sugar and Alcohol Industry [CNIAA] 2018). Mexico is self-sufficient in sugar and a modest exporter to various countries, United States being the main buyer within the North American Free Trade Agreement (NAFTA) (Figs. 10.2 and 10.3).

There are 51 sugar mills operating in the country. The mills are owned by 17 sugar groups called Beta San Miguel, Zucarmex, PIASA, Santos, Grupo Azucarero México, Porres, Sáenz, La Margarita, Grupo Azucarero del Trópico, Pantaleón, Motzorongo, Puga, Menchaca, Fanjul, Perno, Grupo González, and Jiménez Sainz. Beta San Miguel and Zucarmex belong to "The One Million Tonnes Sugar Club."

The Mexican sugar industry is characterized as having medium to low productivity because of high acreage and heterogeneous yields in the field and factories (Sentíes-Herrera et al. 2017). The sugar mills are located in 15 states, namely, Veracruz, Jalisco, San Luis Potosí, Oaxaca, Chiapas, Nayarit, Tabasco, Morelos,

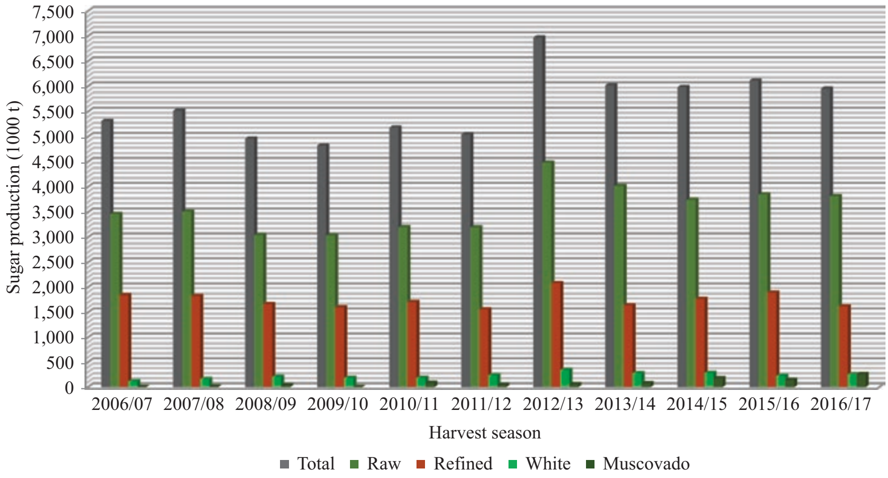


Fig. 10.2 Mexican sugar industry's production by type of sugar. (National Committee for the Sustainable Development of Sugarcane [CONADESUCA] 2017)

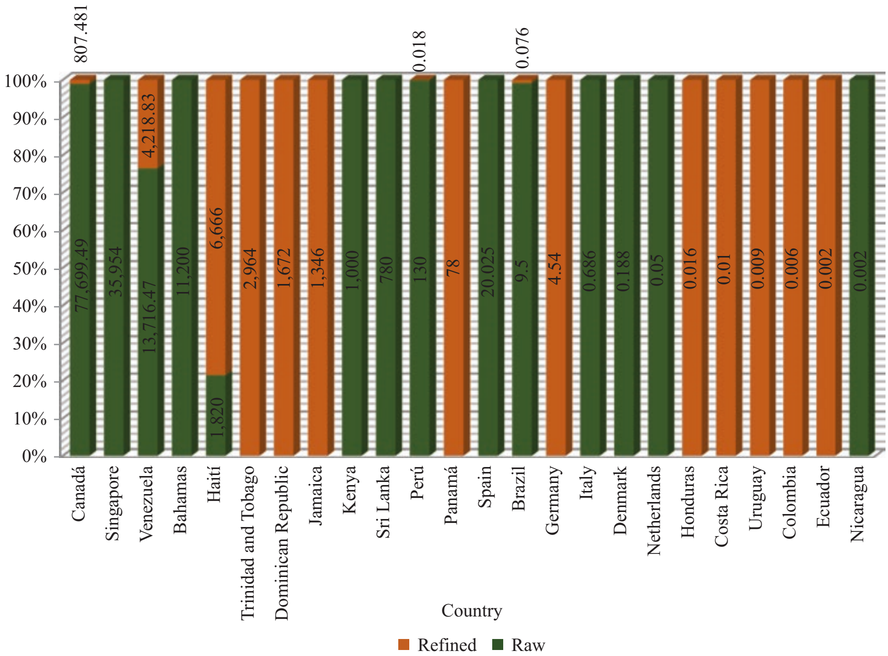


Fig. 10.3 Mexican sugar exports. (CONADESUCA 2017)

Puebla, Tamaulipas, Quintana Roo, Colima, Michoacán, Campeche, and Sinaloa, and spread over seven Administrative Regions (Center, Cordoba-Gulf, Northeast, Northwest, Pacific, Papaloapan-Gulf, and Southeast). The states of Veracruz, Jalisco, and San Luis Potosí alone account for 61.5 % of the domestic sugar in Mexico. Six sugar mills have stopped operating because of various technical and economic problems in previous years (Aguilar-Rivera et al. 2018) (Fig. 10.4).

The southeastern and mid-western regions are characterized as high sugarcane yield-producing areas. Mills in these regions have competitiveness because of added value cane bagasse with off-season electricity generation and ethanol production. The highest productivity has been recorded at the Atencingo and Central Casasano sugar mills located in Morelos with 110.04 and 109.9 t ha^{-1} yields, respectively. Many of the mills in other areas are running less efficiently, mainly because of the facility ageing, poor operating procedures, and the heterogeneous quality of the sugarcane crushed. The lowest productivity has been seen at Azsuremex, having a production of 45.47 t ha^{-1} $year^{-1}$ cane crushed (CNIAA 2018) (Figs. 10.5, 10.6, 10.7, 10.8, 10.9, 10.10, and 10.11).

The variability in the production of sugarcane fields in relation to average sugarcane (t) and acreage (ha) to produce one ton of sugar in Mexico (8.95 t cane and 0.13 ha) depends on multiple factors, including differences between agroclimatic conditions, management practices, and the crop varieties. Although the national average yield is very low, i.e., 68 t ha^{-1}, notwithstanding, the sugarcane regions in Mexico have important comparative advantages regarding soil types and climatic conditions to become more competitive, as one of the most viable strategies to increase the sugar industry's efficiency is to increase the productivity in crop fields.

The output of a Mexican sugar mill depends on the supply of sugarcane and capital goods, land, technology, and government legislation. The main products (sugar, ethanol, and energy) are sold to distributors, the food industry, retailers, exporters, and the public electrical grid. By-products are destined to other industries, wholesalers, and retailers of other sectors such as the animal feed and food industry, or for exportation. In addition, sugarcane mills use, or trade, residues such as vinasses and cake filter as biofertilizers (Fig. 10.12).

Sugarcane sector has huge potential for Mexico. However, since the introduction of sugarcane by Hernan Cortes and the Spanish conquistadors, the establishment of sugar mills has been carried out for sugar production alone. There are numerous competitive and sustainable production schemes and business opportunities, which still have not been exploited by the Mexican industry. The biorefinery concept can increase the profitability of mills and competitiveness of sugarcane as a commodity in the country. Figure. 10.13 enlists some of the business opportunities available for the industry, and the hurdles which need to be tackled, for adoption of all these concepts at industrial level.

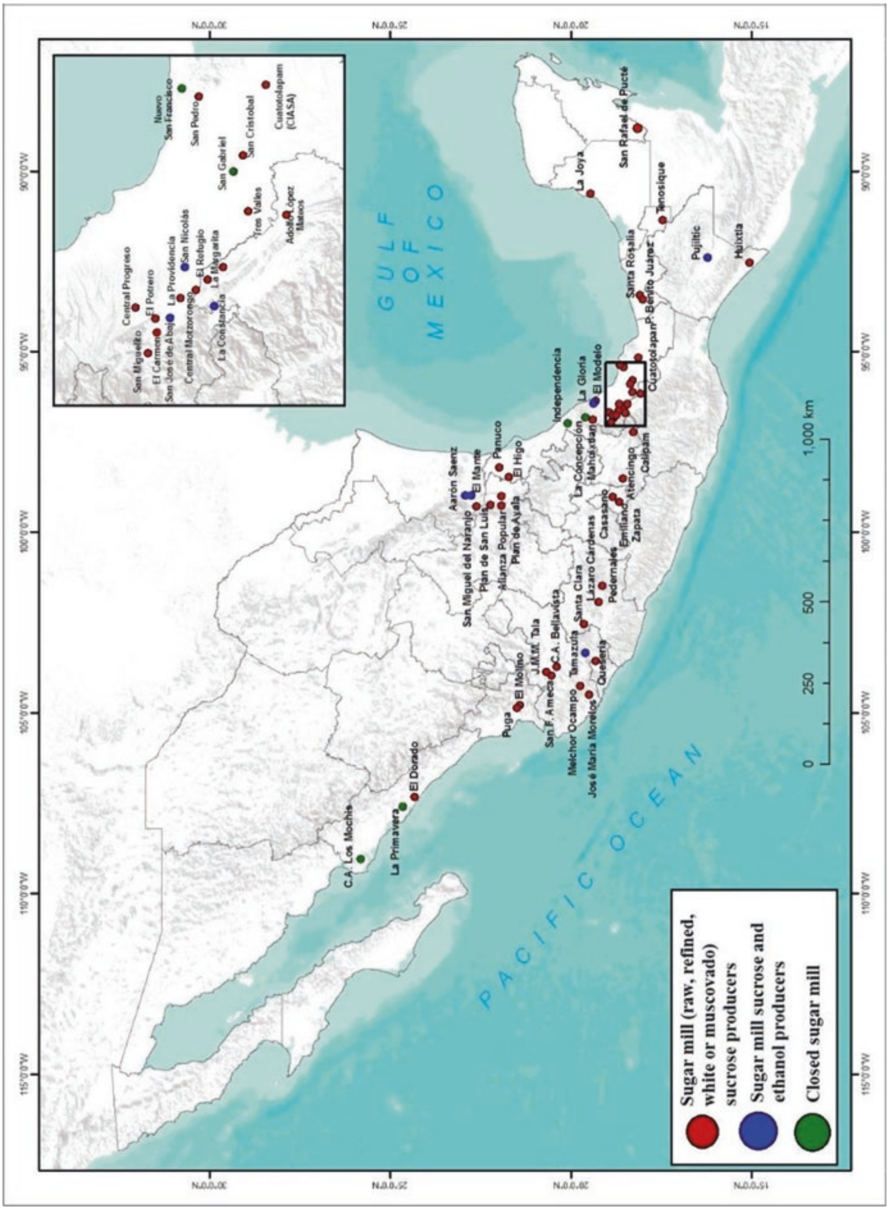


Fig. 10.4 Sugar mills in Mexico. (CONADESUCA 2017; CNIAA 2018)

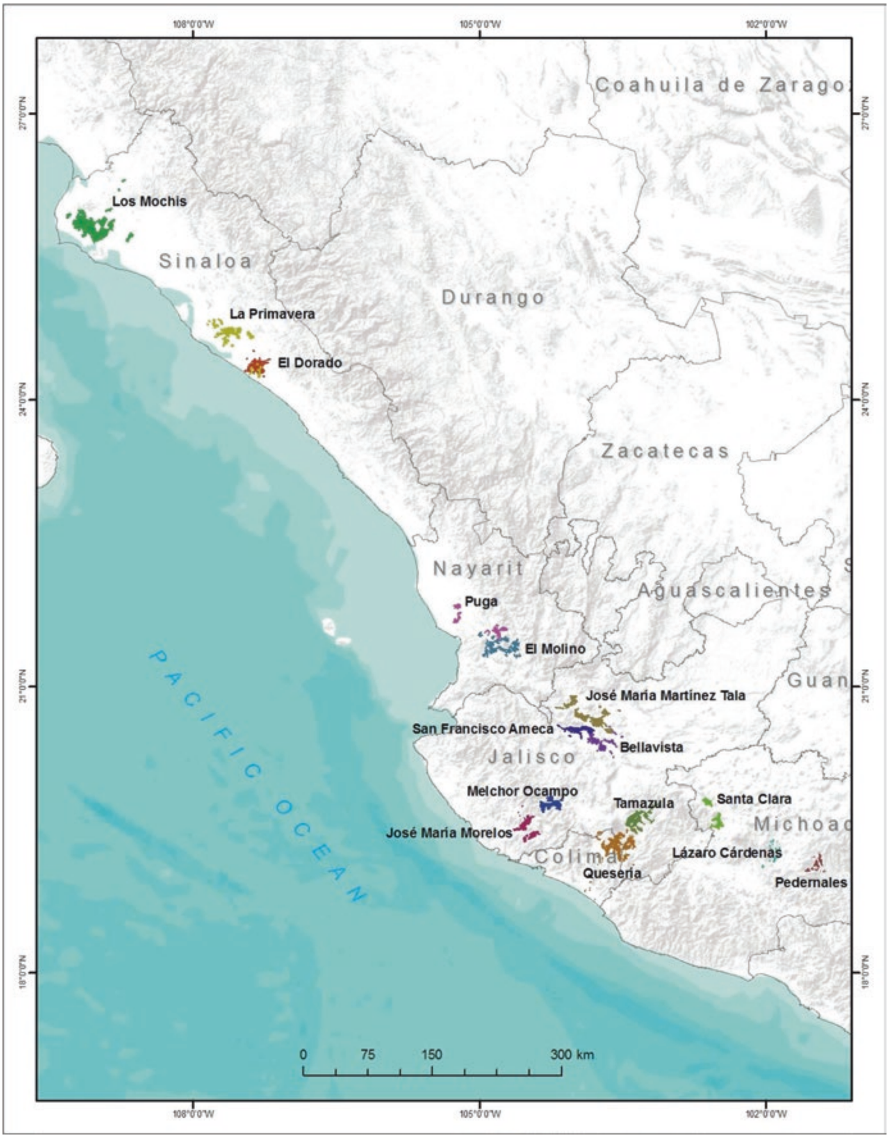


Fig. 10.5 Sugarcane supply zones for sugar mills of Northwest and Pacific region (Michoacán, Colima, Jalisco, and Nayarit states). (CONADESUCA 2018)

10.3 Ethanol as a Product of Mexican Sugar Industry

The production of biofuel from sugarcane has several technical advantages. It can be generated using the whole of the sugarcane plant, juice, syrup, and the by-products resulting from sugar processing such as intermediate and final juices and

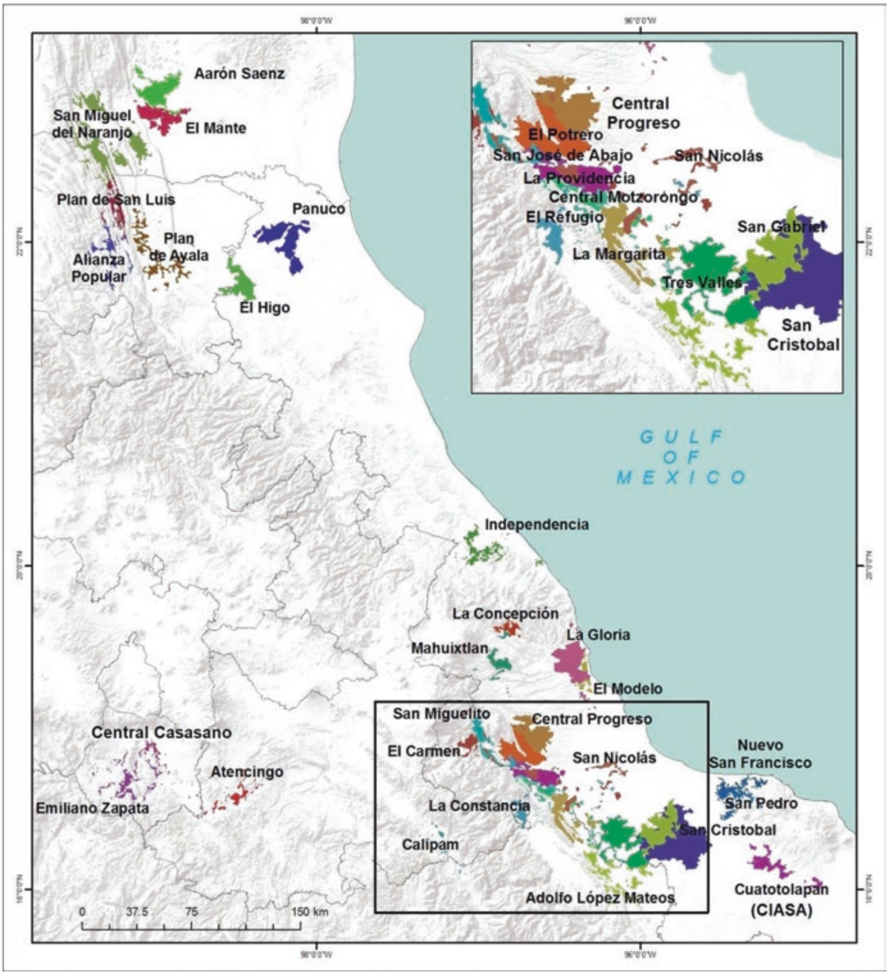


Fig. 10.6 Sugarcane supply zones for sugar mills of Center, Cordoba-Gulf, Northeast, and Papaloapan-Gulf regions (San Luis Potosi, Tamaulipas, Morelos, Puebla, Oaxaca y Veracruz states). (CONADESUCA 2018)

molasses according to the available technology and the markets. Bioethanol can be considered as an inexhaustible source of biofuel since it is obtained from plant material. Apart from finding applications in fuel and energy sector, it can also be used by the chemical industry for production of esters, organic compounds, detergents, cosmetics, paints, aerosols, soaps, and perfumes, among other items (Aguilar-Rivera 2007).

The production of ethanol in distilleries annexed to sugar mills is marginal in Mexico. Of the total number of sugar mills, only five produced ethanol in the season 2016/2017. Developing a biofuel market involves various stakeholders, viz., growers, sugar mills, distilleries, vehicle manufacturers, transport sector, and the govern-

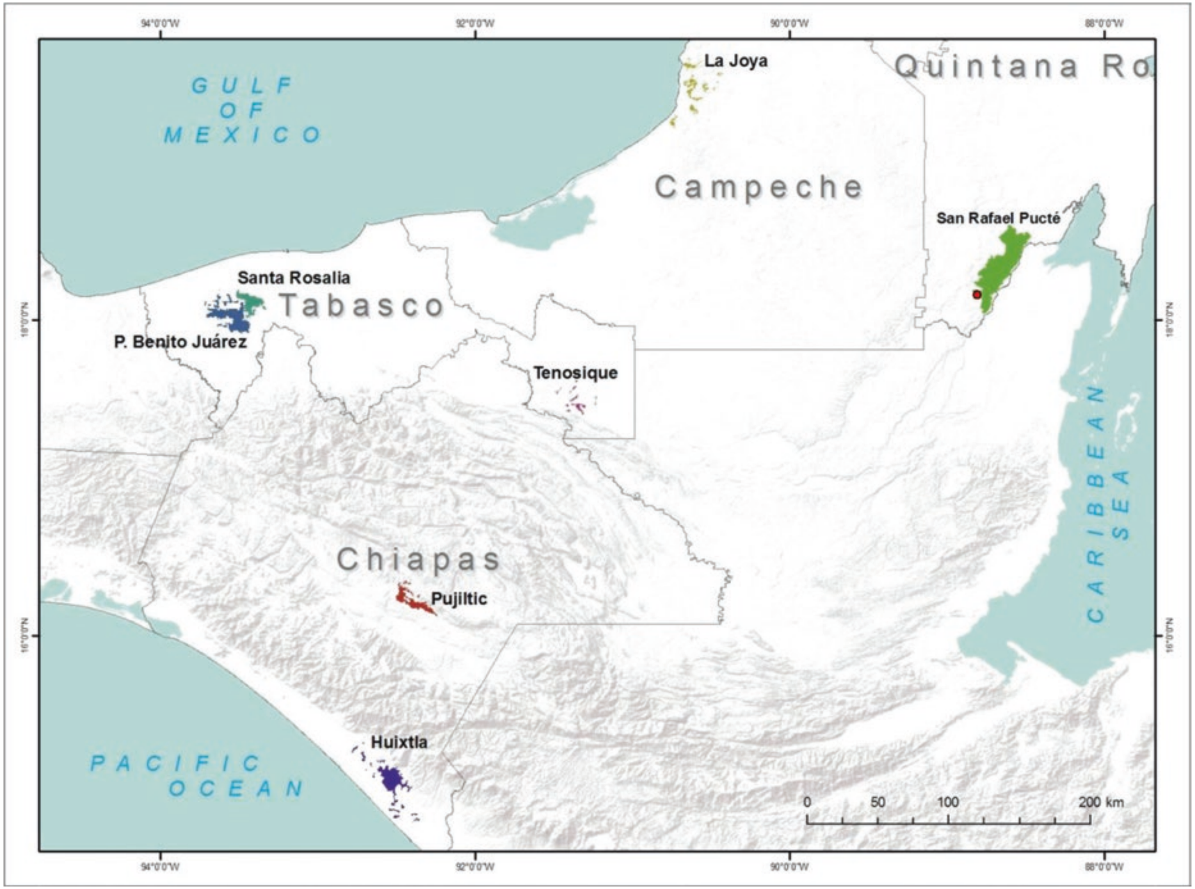


Fig. 10.7 Sugarcane supply zones for sugar mills of Southeast region (Tabasco, Chiapas, Campeche, and Quintana Roo States). (CONADESUCA 2018)

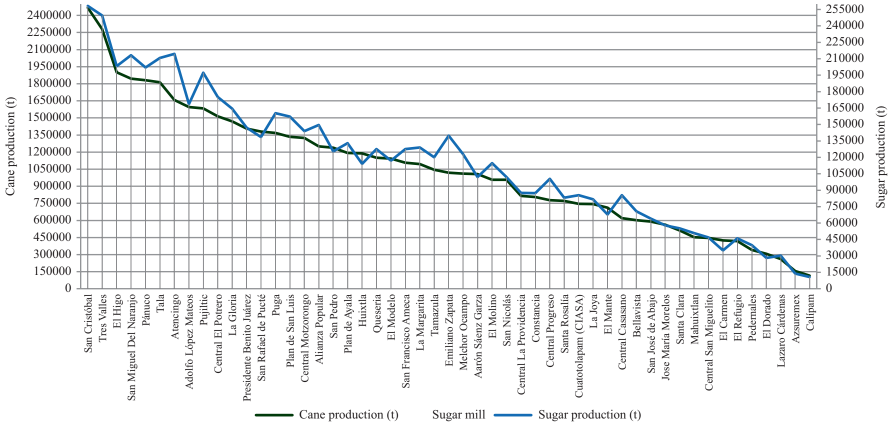


Fig. 10.8 Production of sugarcane and sucrose in Mexico in 2016/2017 harvest season. (CONADESUCA 2017)

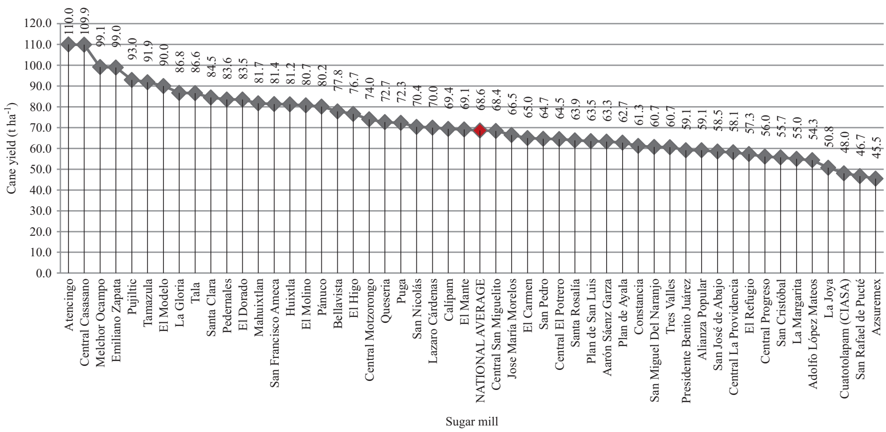


Fig. 10.9 Sugarcane yield (t ha^{-1}) in harvest season 2016/2017. (CONADESUCA 2017)

ment. Therefore, a national program for producing ethanol from sugarcane has been identified as the major starting point. Any such program should aim for socioeconomic and environmental targets, not only technological ones. In addition, it is necessary to emphasize that Mexico is a producer and exporter of oil, but net importer of gasoline and petrochemicals, which highlights the role of corporate culture and hints toward a significant constraint against competitive ethanol production in the country (Elizondo and Boyd 2017). (Figure 10.14).

Lora et al. (2014a, b) discussed the major technological changes needed for the implementation of large-scale cogeneration and biofuel production in conventional sugar and alcohol industry. They suggested that improvements in steam consumption in milling, installation of new hydrolysis and gasification technologies, and

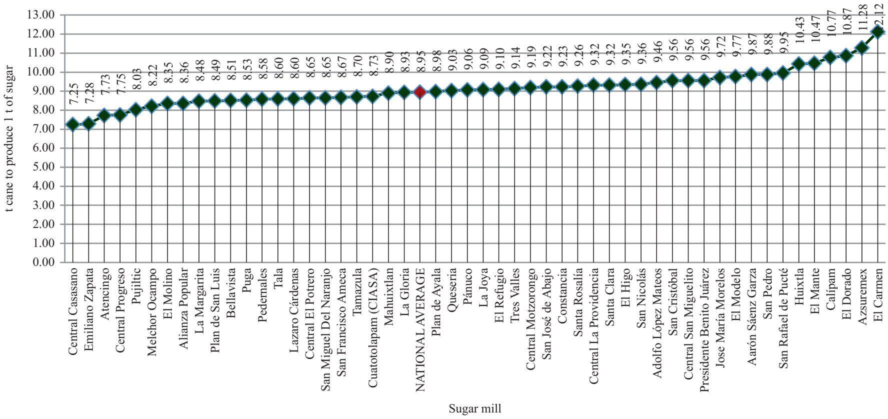


Fig. 10.10 Raw material (t) used to produce one ton of sugar in harvest season 2016/2017. (CONADESUCA 2017)

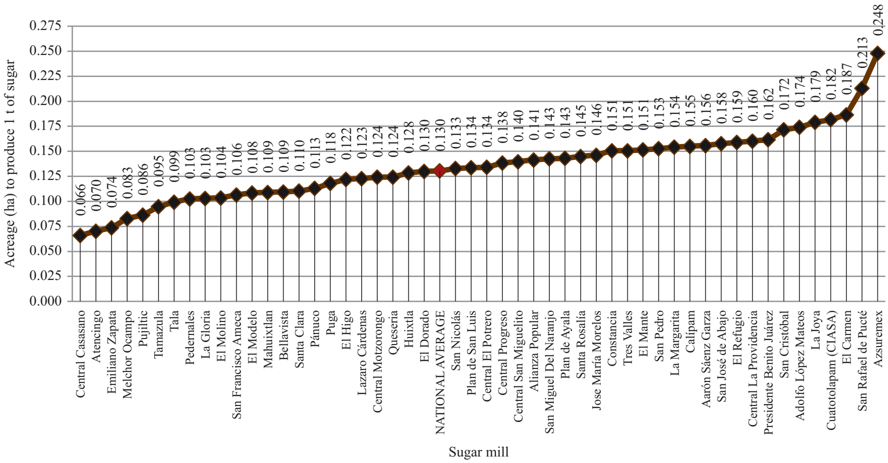


Fig. 10.11 Harvested area (ha) to produce one ton of sugar during harvest season 2016/2017. (CONADESUCA 2017)

proper utilization of sugarcane trash and vinasse can help the process of integration and implementation of biorefinery concept making the milling for bioethanol more cost-effective. They also concluded that investments in research, development, and innovation (RD & I) are essential to enable new ethanol projects to be lucrative. In general, the RD & I investments can lead to development of new sugarcane varieties, greater agricultural and industrial yields, and soil management techniques tailored to the agroecological conditions. Investments in RD & I can favor greater agricultural efficiency, whereas the modern approaches of genetic engineering can significantly enhance sugar and biomass availability.

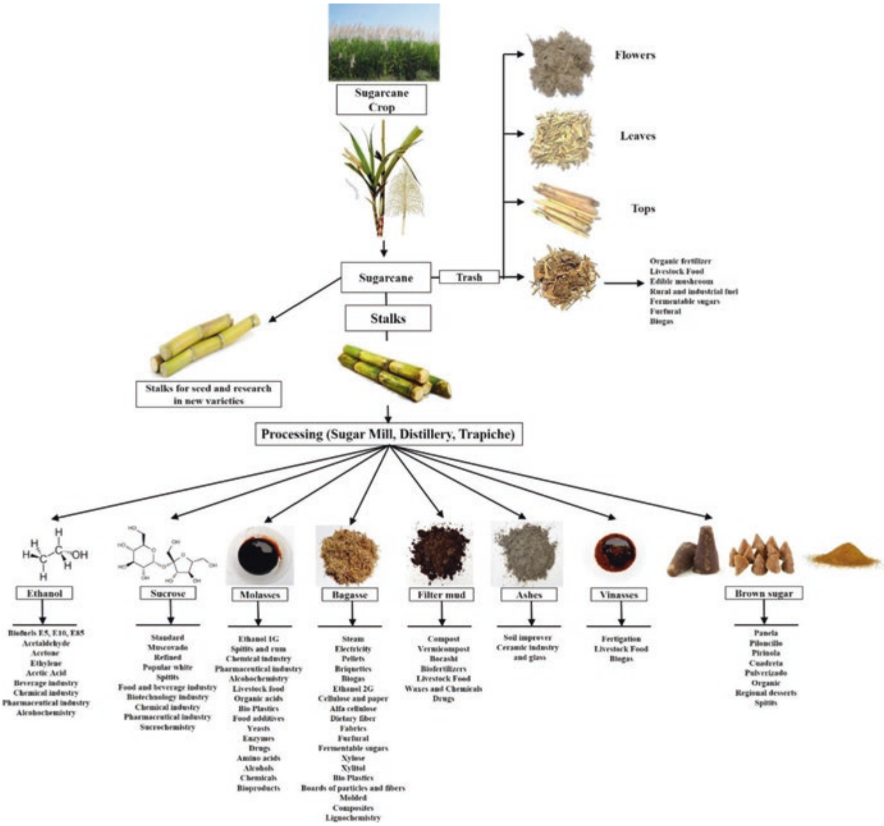


Fig. 10.12 Various products and by-products from sugarcane. (Modified from Aguilar-Rivera 2017)

However, in Mexico, there is still considerable uncertainty throughout the value chain because of unstable sugarcane yields in various regions, heterogeneous processing technologies in sugar mills, high fuel and water consumption in cane processing, and the energy market that ignores the effects of ethanol fuel use on vehicle emissions and environmental benefits. Therefore, even in Mexico City, Monterrey, and Guadalajara (the largest cities in the country with substantial automobile-generated environmental pollution problems), there is hesitation about the adoption of bioethanol fuels. Although it is recognized that ethanol fuels can help mitigate GHG emissions, changes required in vehicle engines for the purpose discourage the consumers (Alvim et al. 2017). Conventional vehicles do not support high levels of ethanol; to minimize the adverse effects of using higher levels of ethanol, combustion and emission control systems need to be optimized for blended fuel. Furthermore, role of Mexican research bodies is also expected to have limited impact on country's legislation and strategic direction to lessen the dependence on gasoline for environmental and social reasons (Gracida Rodríguez and Pérez-Díaz

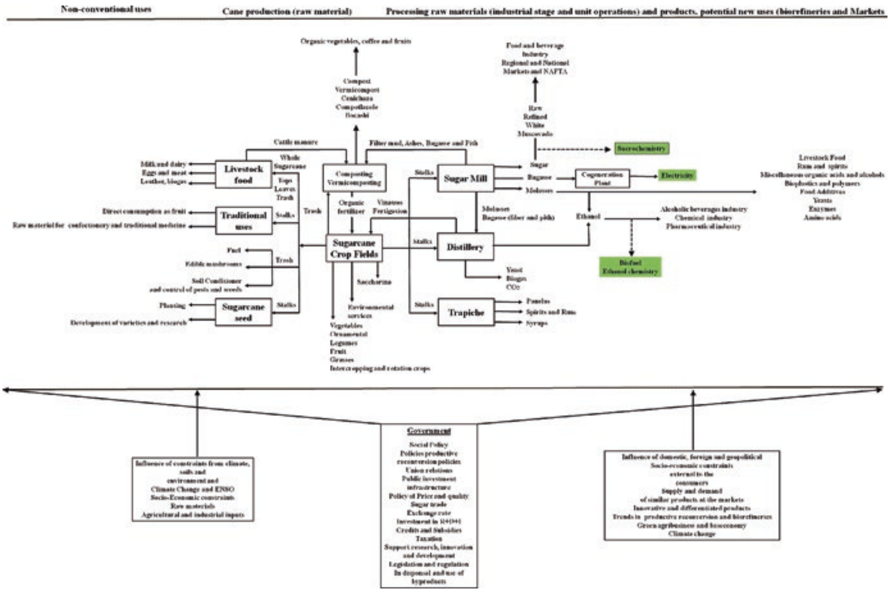


Fig. 10.13 Business opportunities and the associated constraints for sugarcane sector in Mexico. (Sentíes-Herrera et al. 2017)

2014). It is anticipated that biofuel usage will increase in the urban zones in some years; however, to a limited extent, that is unlikely to significantly improve the air quality in such areas (Ruiz et al. 2016).

In spite of the hurdles, keeping in view current production capacity and distilling technologies available, only sugarcane industry can generate enough supplies to target ethanol blending in Mexico. García et al. (2017) reported that, currently, imports account for 48% of the country's overall gasoline consumption. Thus, the price of gasoline in Mexico is dependent on the exchange rate and international oil geopolitics. Adopting ethanol blends can help Mexico reduce its gasoline imports and assist in saving foreign exchange and ensuring energy security. For achieving this goal, the Mexican sugar industry needs to maximize the bioethanol yields of sugarcane, minimize the energy consumption by the sugar and ethanol mills, and maximize surplus electricity production through process and technological improvements.

10.4 Gasoline Resources of Mexico: In a Perspective to Ethanol Fuels

Mexico ranks among the top 10 oil producers worldwide. Oil reserves allow it to be a net exporter of the primary energy; however, for its secondary energy's needs, the country is a major importer of liquefied gas, natural gas, petroleum coke, coal, gasoline, and naphtha (Becerra 2009). According to data provided by the Energy

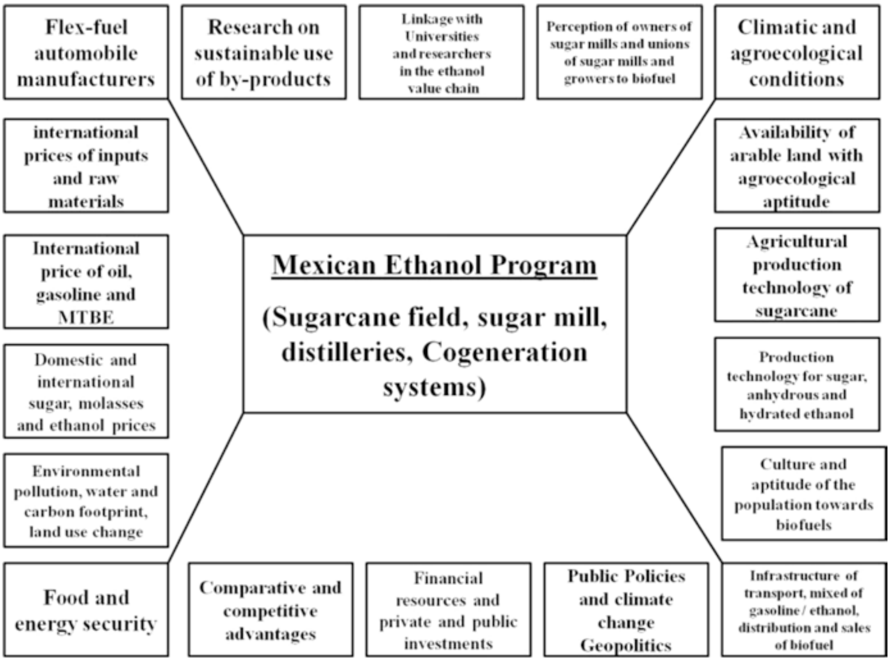


Fig. 10.14 Constraints and challenges for competitive ethanol fuel program in Mexico. (Aguilar-Rivera et al. 2017; de Man and German 2017)

Information System (SIE for its initials in Spanish) of the Mexican Energy Secretariat, Petróleos Mexicanos (PEMEX; state-owned oil and gas company) is a net crude oil exporter (Maya, Olmeca, and Istmo); however, it does not have the capacity to produce the gasoline that is currently demanded at the national level. Therefore, to satisfy domestic fuel demands, it imports gasoline from different countries.

Figures 10.15 and 10.16 show the behavior of the volume of PEMEX-produced gasoline, the volume of gasoline imported, and the volume of gasoline sold by Mexican gas stations in the period from 2012 to 2018 (October). Data are presented in thousands of barrels per day with monthly average.

Unfortunately, PEMEX does not have the necessary infrastructure for refining petroleum products; therefore, gasoline has to be imported to satisfy the domestic demands of the country. The volume of imported gasoline is considerable; in 2012, 50% of gasoline sold in Mexico was of foreign origin. As of October 2018, about 80% of the gasoline consumed in Mexico was imported.

Mexico has significantly invested on PEMEX's infrastructure as well as reforms in energy sector for crude oil extraction (González-López and Giampietro 2018; Vietor and Sheldahl-Thomason 2017). However, the volume of gasoline produced in the refineries, Salamanca, Tula, Madero, Cadereyta, Salina Cruz, and Minatitlán, has decreased since 2013 to date. Furthermore, the price of gasoline has also increased significantly since December 2016, because of the increase in international

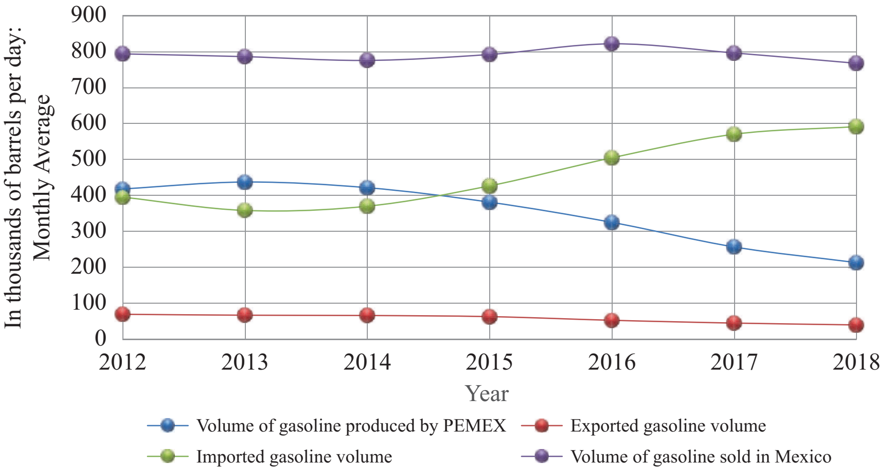


Fig. 10.15 Origin and consumption of gasoline in Mexico (data till October 2018). (SIE 2018a)

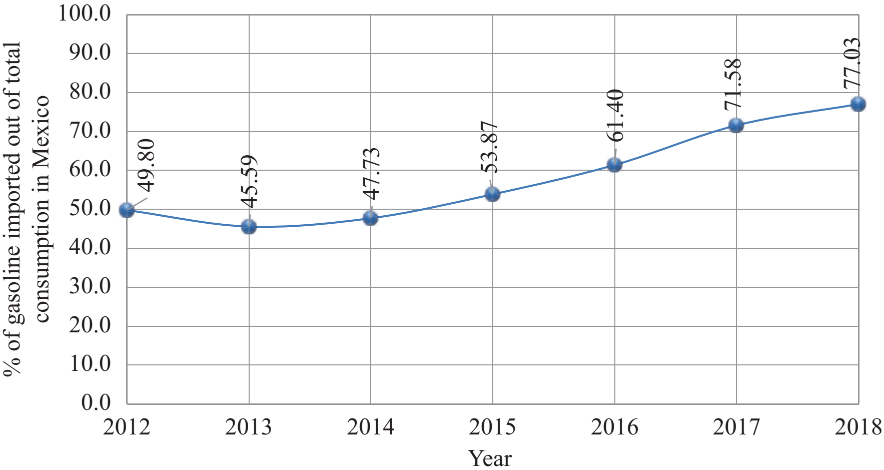


Fig. 10.16 Annual behavior of gasoline imports in Mexico (data till October 2018). (PEMEX 2018)

gasoline prices and exchange rate. Therefore, it must be emphasized that, to meet the domestic fuel demands, PEMEX is importing significant volumes of gasoline (Rodríguez 2017).

Gasoline is expensive in Mexico as compared to the prices in many of the other countries. The tax burden is also high in the Mexico. The international price of fuel type called "Magna" is 1.35 US$ gal^{-1}, whereas after the profit margins, taxes, fiscal

Table 10.1 Structure of gasoline prices in Mexico (December, 2016)

	Gasoline less than 92 octane (Magna) (US$ gal^{-1})[a]	Gasoline greater than or equal to 92 octane (Premium) (US$ gal^{-1})[a]
Reference price	1.35	1.45
Margin	0.34	0.49
Special tax on production and services (IEPS)	0.49	0.35
IEPS waw	0.78	0.66
Fiscal stimulus	-0.09	-0.11
Supplementary fee	-0.20	-0.19
Other charges	0.44	0.48
Maximum price	2.62	2.77

[a]Exchange rate as of December 2016, 1 USD$= 20.5 MEX Peso
SIE (2018b)

stimuli, supplementary rates, and other charges, its price rises up to 2.62 US$ gal^{-1} (SIE 2017), which represents an increase of 94%. Table 10.1 shows a comparison for the price structure of "Premium gasoline," which has an octane rating of 92 or more, against the prices for "Magna" having octane number less than 92. Currently, the retail price of gasoline in Mexico is liberalized and adjusted daily according to international prices.

Vehicles of diverse model years and brands are in circulation in Mexico (Figs. 10.17 and 10.18). Although a high percentage of cars (34%) are of recent years (2010 to 2015), for the rest, age is a limiting factor which would hinder the success of ethanol as a biofuel. The heterogeneity of vehicles would prevent vast majority of them from being able to use a blend of fuel ethanol with gasoline or biodiesel. It is therefore necessary to create a pilot program for these vehicles using different blending levels and then evaluate their performance and emission to establish an ethanol program considering cities, elevation, and ambient temperatures.

The use of bioethanol in internal combustion engines does not require major modifications as long as the proportion does not exceed 20% of ethanol in the blend. The addition of even 10% (v/v) bioethanol to the gasoline can increase the quality of the fuel as it contributes a greater amount of oxygen, increasing the efficiency of combustion, and reduces proportion of sulfur, aromatic compounds, and olefins (Cavalett et al. 2013). Currently, Methyl Tert-Butyl Ether (MTBE) is used in Mexico as a gasoline oxygenator. This additive was first used in unleaded gasoline to increase its octane rating in cities with a high population density such as Mexico City, Guadalajara, and Monterrey, keeping in view the atmosphere's increased carbon dioxide content in winters (Hernandez et al. 2014).

The implementation of bioethanol as a biofuel, either directly at 100% or as a gasoline additive, presents serious problems of acceptance in Mexico. The consumers are reluctant to espouse any new kind of fuel due to lack of information about the capacity of their cars to utilize the blended fuel. Moreover, sometimes, the

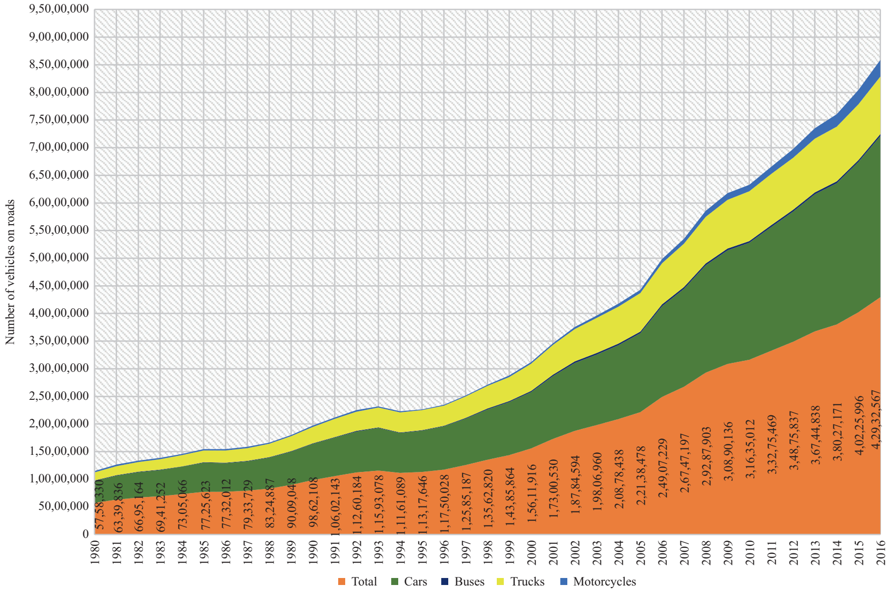


Fig. 10.17 Motor vehicles in circulation in Mexico. (National Institute of Statistics and Geography [INEGI] 2017)

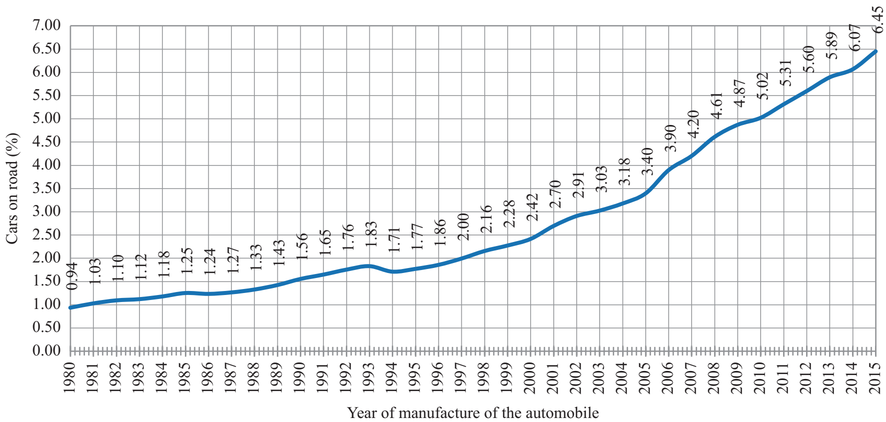


Fig. 10.18 Cars in circulation in Mexico classified by year of manufacture. (INEGI 2017)

entities that are responsible for producing or importing fuels also do not encourage bioethanol due to economic interests in the use of petroleum. However, the effectiveness of bioethanol is being demonstrated in many countries that are implementing measures and mandates to favor the use of this fuel not only for economic but mainly for environmental implications based on decision-making oriented toward the pursuit of sustainable development.

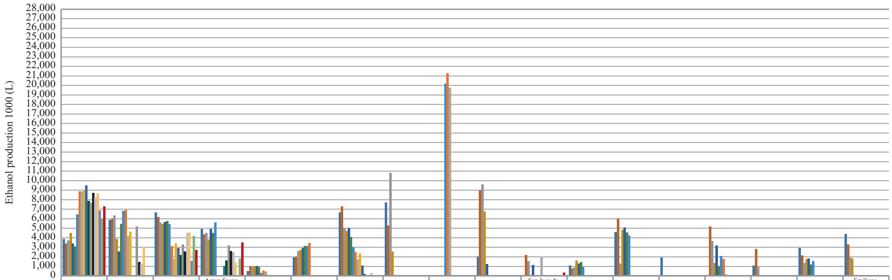
Castillo-Hernández et al. (2012) conducted the physicochemical characterization of commercial Mexican gasoline (PEMEX Magna and Premium) using 10% and 15% blends of anhydrous ethanol. They reported that the ethanol-gasoline blends had higher Octane Numbers as compared to the commercial gasoline, while conserving an appropriate Distillation Index at the same time. The Cetane Number showed a substantial decrease, whereas the Heating Value was negatively affected by the addition of ethanol. Nevertheless, taking into account the carbon credits for using a renewable fuel, reformulated conventional gasoline in Mexico would imply a maximum theoretical reduction of 7.5% in CO_2 emissions, whereas ethanol blends would represent a 9.2% decline.

The Mexican sugar industry has good potential for ethanol production (García et al. 2017). The country has harvested a surplus of sugarcane in recent years for a diversified production of food, feed, liquid and solid biofuels, and green chemicals, to some extent. However, no industrial-scale fermentation or distillation facilities have been available to turn sugarcane into biofuel. Furthermore, no serious efforts have been devoted to develop domestic biofuel market for the transportation sector (Nunez 2016). To take advantage from bioethanol blending, a comprehensive policy promoting the ethanol production and use in Mexico is required. The first step in this regard is to replace the use of oil-derived oxygenates that are imported by PEMEX and the second one is to blend ethanol with the gasoline to serve the purpose (Galicia-Medina et al. 2018; Garcia-Chavez 2015).

10.5 Current Status of Sugarcane Ethanol Production for Fuel Purposes

In Mexico, molasses is most abundantly available feedstock for ethanol production. Its production was 1.7 million tons (Mt) in 2016/2017 harvest season (CONADESUCA 2017). However, the environmental and socioeconomic sustainability of biofuel (ethanol) production for use as a potential additive for gasoline remains uncertain as this area of opportunity has been totally untapped among the socioeconomic and environmental goals by Mexican government, the sugar industry, and other stakeholders. This has already led to approximately 80% reduction in ethanol production in sugar mills having the capacity for converting sugars into ethanol, remaining at practically the same level throughout the last decade, as 97.2% of the main raw material, molasses, has been allocated for other uses or exports (Figs. 10.19, 10.20, 10.21, and 10.22).

In last decade, 17 of 64 sugar mills were producing ethanol (San Sebastian, Emiliano Zapata, San Cristobal, Calipam, La Joya, San José de Abajo, La Providencia, Independence, San Pedro, El Carmen, El Mante, Constancia, Aarón Sáenz Garza, San Nicolás, Tamazula, Pujiltic and La Gloria); by 2013, the number reduced to only 6 of 57 operating sugar mills (Pujiltic, San Nicolás, Tamazula, Aarón Sáenz Garza, Constancia and La Gloria), whereas four autonomous distilleries



	Pujiltic (La Fe)	San Nicolas	Tamazula	Aaron Saenz Garza	Calipam	El Carmen	Constancia	San Cristobal	La Gloria
1999	38,62,095	58,89,347	66,31,380	49,29,511	4,80,949	19,15,800	66,43,000	77,09,082	
2000	34,10,968	59,74,729	61,94,600	43,62,575	10,41,174	20,08,000	72,69,000	52,69,538	
2001	36,87,604	63,21,279	55,78,000	44,99,250	9,10,220	25,96,000	49,97,040	1,08,09,678	
2002	44,83,954	38,52,460	54,20,000	38,30,300	10,38,471	26,88,600	46,86,300	25,77,645	
2003	33,73,004	25,75,437	56,43,750	49,48,000	10,00,758	29,23,000	49,97,400		
2004	30,73,299	54,17,627	57,46,895	44,86,671	9,39,618	31,52,100	40,55,000		
2005	64,58,594	68,09,642	54,37,342	55,81,691	3,02,087	31,39,200	30,15,000		2,01,68,528
2006	88,69,274	69,02,106	31,31,710		5,62,244	34,64,800	24,78,806		2,12,61,090
2007	88,39,667	41,59,085	17,59,000		4,25,579		17,09,023		1,97,50,705
2008	90,06,145	46,45,552	34,09,430				23,66,399		
2009	94,91,980		29,16,370	10,21,927			10,74,196		
2010	78,55,990		21,72,712	16,07,991			1,90,000		
2011	76,65,395	51,96,380	32,84,777	31,95,965					
2012	87,25,000	14,24,000	25,77,000	25,84,000					
2013	82,30,028	12,14,095	44,80,870	24,80,422			2,80,548		
2014	86,28,820	30,11,663	45,80,000	13,87,371					
2015	68,46,633		15,65,500						
2016	60,45,103		41,85,000	17,98,986					
2017	72,73,942		27,34,800	34,81,710					0

	Independencia	San Jose de Abajo	La Joya	El Mante	Los Mochis	San Pedro	El Potrero	La Providencia	Emiliano Zapata
1999	20,51,000		10,90,000	45,82,250	19,27,640		10,89,270	29,16,338	44,09,566
2000	89,58,934	21,83,000	7,59,700	60,33,000		51,79,904	28,10,873	21,18,147	32,65,577
2001	96,11,879	15,52,000	8,68,325	12,66,805		36,55,000	9,10,575	13,25,000	19,08,777
2002	67,54,702		15,95,588	48,05,085		13,51,000		17,52,360	18,24,727
2003	12,50,908	11,18,000	13,07,000	50,82,300		32,06,000		18,18,471	
2004			14,35,700	45,37,008		10,45,000		11,71,886	
2005			9,08,371	42,58,305		20,76,000		15,64,238	
2006			56,828			17,77,000			
2007		20,26,900				1,96,000			
2008									
2009									
2010									
2011									
2012									
2013									
2014									
2015									
2016									
2017		3,26,000		95,697					

Fig. 10.19 Ethanol production in sugar mills. (National Confederation of Rural Property Owners [CNPR] 2017 and CONADESUCA 2018)

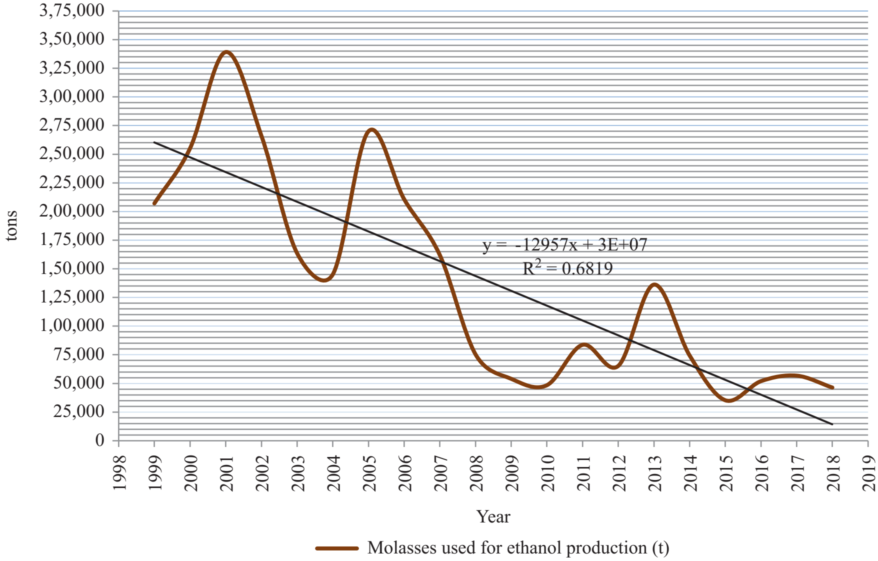


Fig. 10.20 Molasses (t) for ethanol production in sugar mills. (CNPR 2017; CONADESUCA 2017)

employing cane juice as feedstock for fermentation were operational in the same year. In 2016/2017, 13,816,452 L of ethanol was produced in 6 sugar mills (11.7%) out of the 51 mills in operation (Figs. 10.23, 10.24, and 10.25). The decline in ethanol production had a direct relationship with the prices of cane, sugar, raw material,

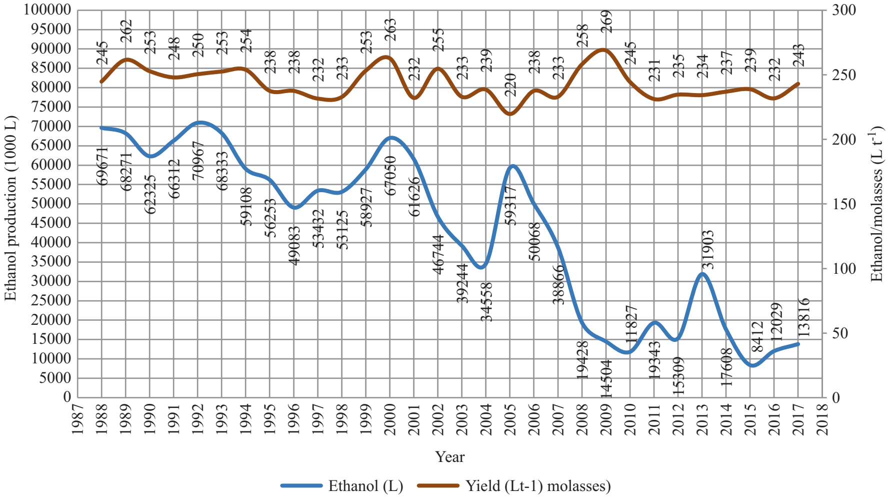


Fig. 10.21 Yield of ethanol from molasses in Mexico. (CNPR 2017; CONADESUCA 2017)

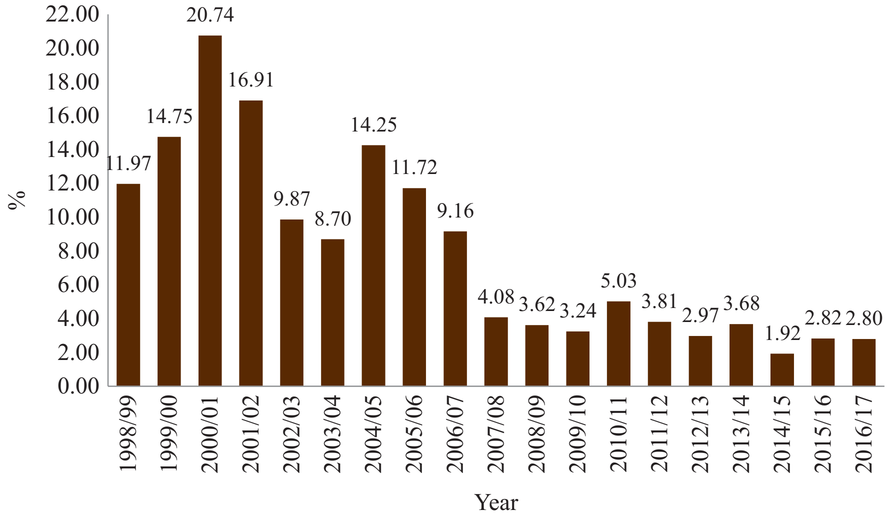


Fig. 10.22 Percentage of molasses used for the production of ethanol. (CNPR 2017; CONADESUCA 2017)

and the productivity (t ha^{-1}). With the passage of time, sugarcane yields have remained nearly constant, the harvested acreage has increased, whereas ethanol production has declined.

Ethanol production in Mexico is influenced by various factors (Fig. 10.26). While analyzing causal loops of ethanol production from sugarcane molasses and cane juice, it has been determined that the sugar/ethanol is dictated majorly by two

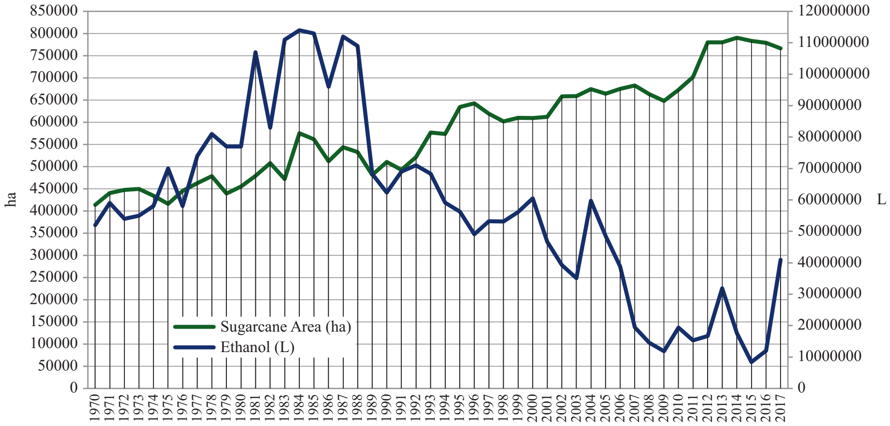


Fig. 10.23 Cane acreage and ethanol production (1970 to 2017). (CNPR 2017; CONADESUCA 2017)

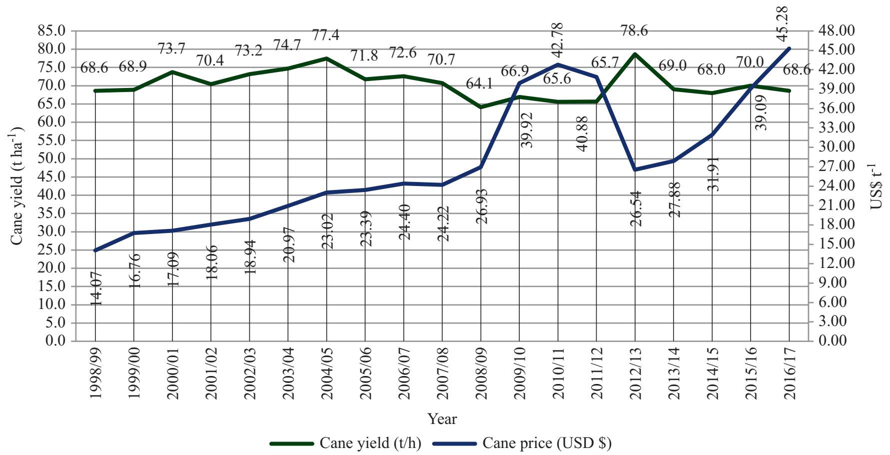


Fig. 10.24 Cane yield and price per ton over the years. (CNPR 2017; CONADESUCA 2017)

loops of balance. The relationship between molasses stock and bioethanol production is positive, while the relationship in the opposite direction is negative as higher the molasses stock is, the greater the production of bioethanol will be. Similarly, if bioethanol stocks increase, the sales of bioethanol would be higher, which would ultimately lead to reduction in the stocks. Moreover, if the demand for ethanol increases, sugar production may reduce and a certain amount of cane juice can be used for ethanol production while maintaining a fixed amount of sugar according to the market (R1).

The relationship between productivity, acreage, sugar production, and the declining ethanol production is due to several factors (Acosta 2011). Some of major elements are as follows:

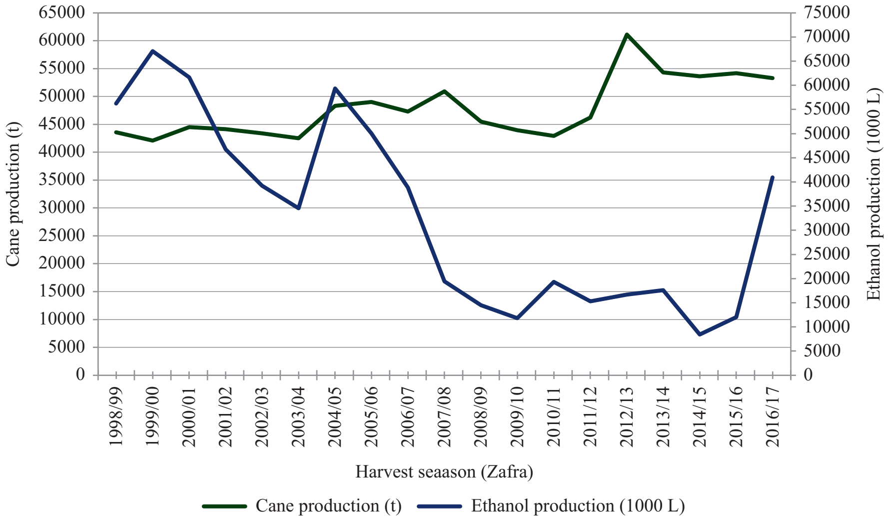


Fig. 10.25 Ethanol and sugarcane production over the years. (CNPR 2017; CONADESUCA 2017)

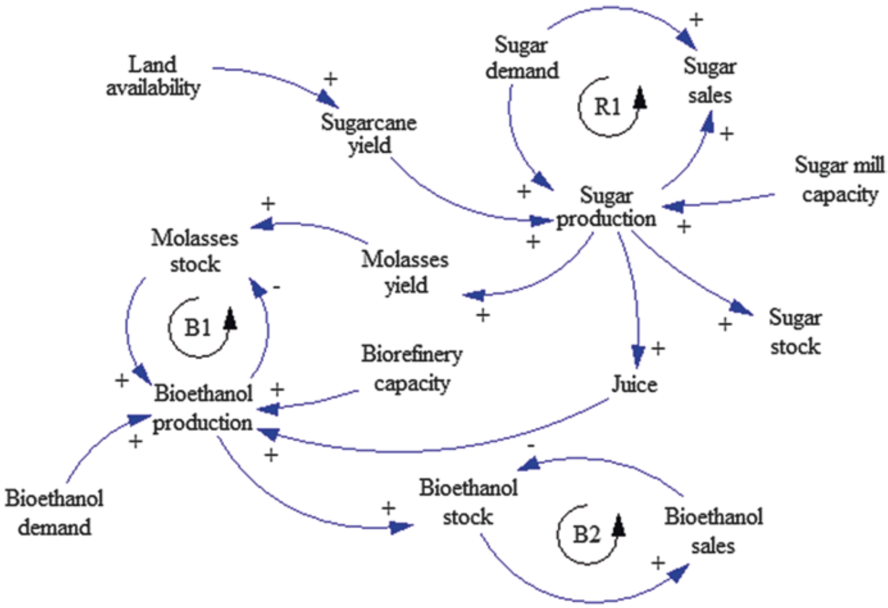


Fig. 10.26 Causal Loops Diagram for ethanol production from sugarcane juice and molasses. (Modified from Rendon-Sagardi et al. 2014)

1. Limited domestic ethanol demand as biofuel
2. High production costs of sugarcane as feedstock
3. Increased acreage, but low productivity and quality of raw material
4. Volatility in prices of molasses at domestic and export markets
5. Sugarcane price exclusively connected to the price of raw sugar
6. Higher income from molasses through other applications such as livestock feed or even exportation
7. Institutional limitations, absence of subsidies, and lack of infrastructure
8. Absence of environmental commitments

10.6 Electricity Cogeneration

Cogeneration of electricity, as part of an essential coproduction system along with sugar and ethanol, has been known for decades in Mexico. Yet, cogeneration technology is not matured and considered less efficient. Electric power generation, transformation, and distribution, as a public service, is responsibility of the Mexican state managed by The Federal Electricity Commission (CFE for its initials in Spanish) and the Mexican Energy Policy and Regulatory Framework. The sugar industry reaches an estimated potential of almost 1000 MW which can further be increased even more (Pérez-Denicia et al. 2017; Rincón et al. 2014) (Fig. 10.27).

Cogeneration can additionally enhance the profitability of mills if they make use of bagasse and sugarcane trash for this purpose. The efficiency of the cogeneration can be increased by replacing the traditional boilers with high pressure boilers. In

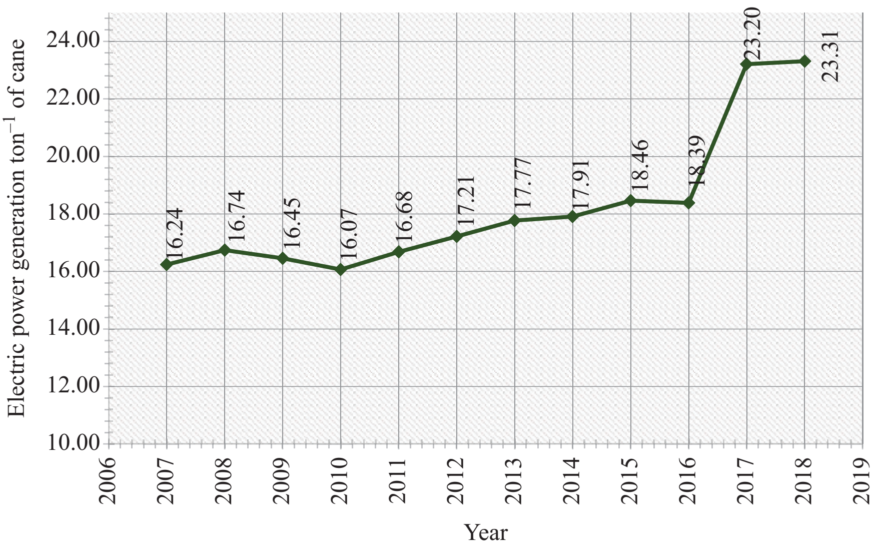


Fig. 10.27 Electric power generation ton^{-1} of cane. (CONADESUCA 2017)

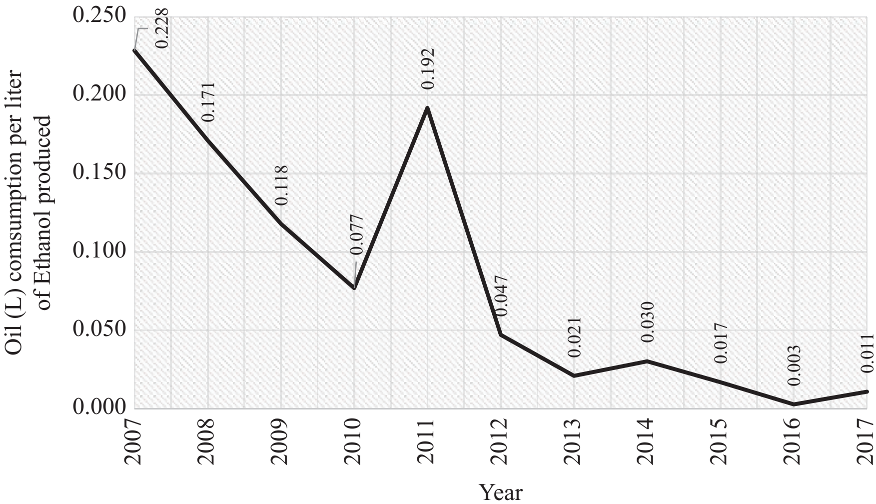


Fig. 10.28 Oil consumption per liter of ethanol produced in sugar mills. (CONADESUCA 2017)

most cases, low efficiency boilers and steam turbines are still employing oil as fuel. Additionally, at most of the units, energy production from bagasse is inefficient. Consequently, production units are not able to fully cover their own energy requirements. However, situation is improving over time, and the use of oil in ethanol production has declined in recent years (Fig. 10.28).

Mexican sugar mills focus only on the extraction of energy contained in the sugarcane juice, thus wasting the energy contained in the bagasse and straw (sugarcane crop residues, meaning tops, leaves, and straw). By only making use of the juice, one third of the energy contained in sugarcane is extracted efficiently. The remaining one third energy in sugarcane present in bagasse is heavily underutilized because of the low energy efficiency of the cogeneration systems. Straw, which forms another one third portion of energy contained in sugarcane, is not being used for this purpose at all, as it is burnt in the field before harvesting (Bustamante and Cerutti 2016).

According to the Mexican Ministry of Energy (SENER), in 2014, Mexico produced 8,826 PetaJoule of energy from the following sources: fossil fuels 91.31% (crude oil 63.42%, natural gas 23.56%, coal 3.44%, and condensates from natural gas production 0.89%), nuclear energy 1.14%, and renewables 7.56% (hydroelectric 1.59%, geothermal 1.47%, solar 0.10%, wind 0.26%, biomass 4.12%, and biogas 0.02%). These statistics indicate that fossil fuels dominate the Mexican energy matrix, and that biomass represents only a small proportion of the total (Alemán-Nava et al. 2015).

10.7 Major Uncertainties of Cane Energy Production in Mexico

Cane biofuels, when adopted, need to be kept under regulatory checks. Sugarcane expansion cannot be done in an unwise manner. García et al. (2017) reported that first-generation ethanol in Mexico can pose negative environmental impacts too such as increase in CO_2 emissions due to land use change from grasslands, jungles, and other forest crops; loss of biodiversity due to higher deforestation; and threats to food safety if the crop competes for the soil used for food growing soils, which can also cause soil erosion as well as depletion of water resources. Moreover, regarding ethanol engenderment in Mexico, water use is the most sensitive indicator of sustainability; hence, sustainable production of sugarcane can only be conducted in regions where there is an abundance of rainwater and suitable soils.

It can be estimated that Mexico is not expected to meet ambitious biofuel targets in the short term because of:

- Huge reserves of oil and natural gas in Mexico
- Poor economic and growth opportunities in traditional agribusiness
- Low level of investment in research, innovation, and development of domestic technologies for ethanol (1G, and 2G)
- Effects of unfavorable weather, El Nino, and La Nina (ENSO) on rainfed agriculture
- Low scale of production as 90% of Mexican sugarcane growers have small farms
- Low ethanol yield and production efficiencies
- Unavailability of optimized fermentation and pretreatment approaches
- High infrastructure costs for improvements in existing milling procedures
- Lack of interest and knowledge of drivers regarding ethanol-based fuels
- The food versus fuel issue if sugarcane is expanded over lands used for food production currently
- Absence of a prioritized national policy

Because of these uncertainties and challenges, bioethanol is currently produced only in some of the sugar mills which have infrastructure for distillation; however, most of the ethanol is employed for alcoholic beverages and for applications as a solvent in other industrial processes. Moreover, apart from sugar mills, units only involved in ethanol production are also operational in the country; nevertheless, ethanol yielded from them also meets the similar fates. It is clear that national ethanol policy is a multidimensional prerequisite for development of ethanol-based fuels in Mexico.

10.8 Possibilities of Crop Expansion: Agroecological Zoning (AEZ)

Agroecological Zoning (AEZ) is a plan to expand and technologically improve production of a crop in a particular region. AEZ is used as a tool to improve crop yields based on the analysis of climatic and edaphic information of the site, keeping in view the environmental conditions of soil and climate needs of the crop of interest. The main objective of AEZ is the identification of areas with agricultural potential for the given crop, using the spatial and simultaneous overlapping of information related to variables of interest about the environmental conditions. Geographic Information Systems (GIS) are used to identify the environmental limitations and, based on this, to estimate the optimum areas for crop cultivation evaluating climate, soil, and environmental variables. The AEZ and novel techniques such as maximum entropy modeling (MaxEnt), the Soil and Water Assessment Tool (SWAT), remote sensing, GIS and precision agriculture, and life cycle assessment (LCA) may contribute to achieving sustainability goals and supporting major strategic decisions to improve sugarcane crop yields and ethanol production (Aguilar-Rivera et al. 2010).

Valdez-Vazquez et al. (2010) concluded that Mexico is the third largest country in Latin America in terms of cropland area, and thus, it could become a central focus of attention for producing biofuels from biomass and crop residues in the future. Identification of potential municipalities or agroecological zones where the biomass (sugars and fiber) production would be high is important since it constitutes the first step toward evaluating the land suitability and helps in accurately estimating the possible crop and bioenergy production capacity from such areas. Sugarcane cultivation is integrated and optimized into an established production system in Jalisco, Michoacán, Puebla, and Morelos, which allows competitive yields from very small farms, even if optimal environmental conditions are not available. In rest of the country, the potential yield can only be reached if optimal environmental conditions are identified based on edaphic and environmental requirements.

We used agroecological zoning to construct a distribution modeling for the sugarcane crop using Maximum Entropy Species Distribution Modeling (MAXENT®), which produces a continuous binomial probability distribution representing habitat suitability according to the climate variables (Phillips et al. 2006, 2017). Firstly, a cane polygon was developed using ILWIS 3.1 software (Integrated Land and Water Information System) and GIS tools ESRI ArcGIS 10.1 (Fig. 10.29). Secondly, the soil and climate conditions prevalent for modelling, and various climate variables including one topographical variable with a resolution of 30 arcseconds or around 1 km^2, were applied. Finally, we used nine layers related to the Mexican soil properties at a scale of 1:1000000 (Cruz-Cárdenas et al. 2014; Merow et al. 2013) (Tables 10.2, 10.3 and Fig. 10.30).

From the analysis, it was determined that current sugarcane regions, Jalisco, Veracruz, and Sinaloa, have the largest acreage available with exceptional suitability for growing sugarcane and harvesting maximum yields. However, the states of Morelos, Sinaloa, and Nayarit have the greatest potential in terms of land suitable

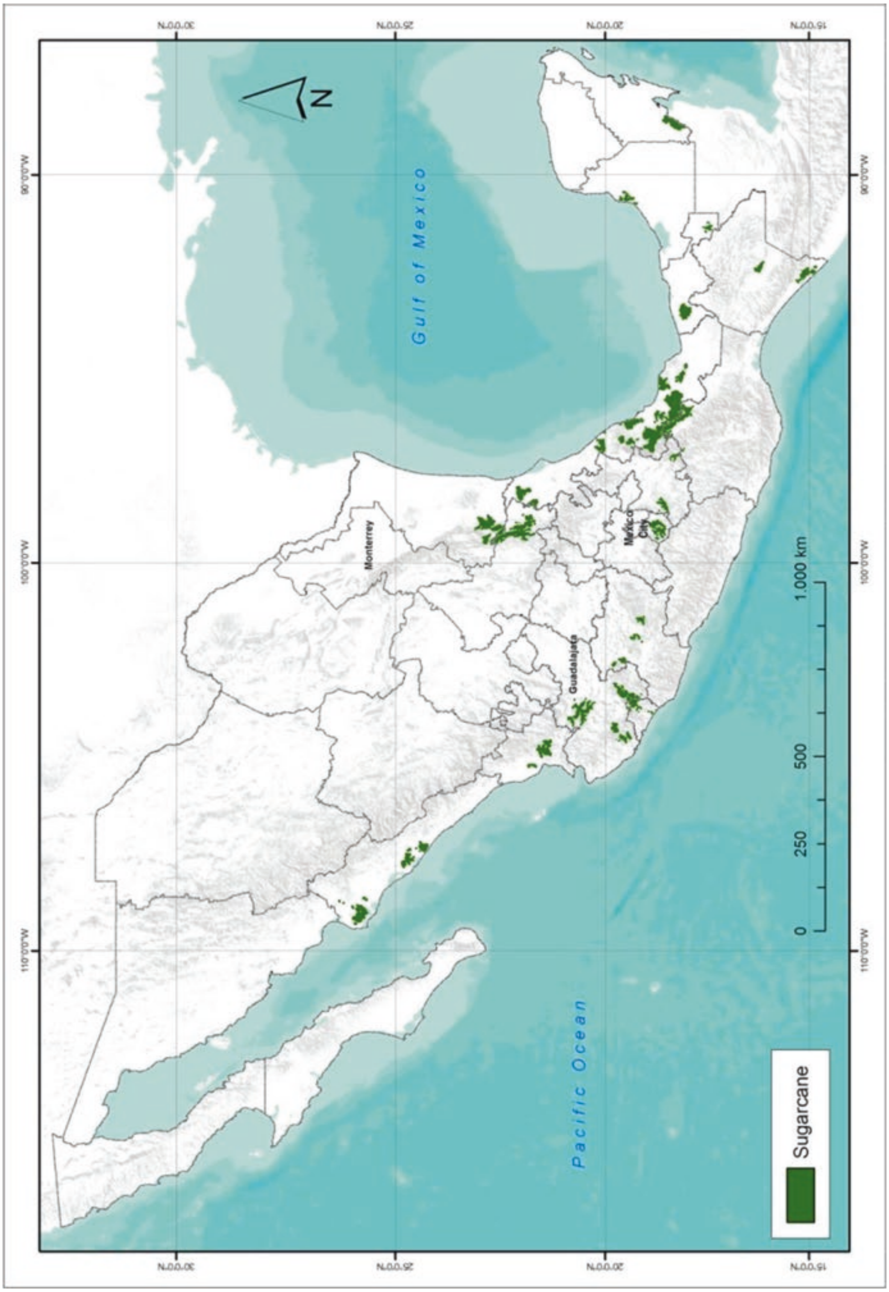


Fig. 10.29 Sugarcane supply zones in Mexico and Mexico City, Guadalajara, and Monterrey. (Aguilar-Rivera et al. 2017)

Table 10.2 Agroecological suitability (ha) for sugarcane crop fields in Mexico

State	Very low	Low	Medium	High	Total
Morelos	569.84	852.31	447.06	3001.98	4871.19
Sinaloa	7933.96	3747.02	12101.31	31646.99	55429.29
Nayarit	2368.99	1756.13	8050.81	15516.19	27692.12
Colima	36.46	1748.17	1087.43	2711.49	5583.54
Jalisco	33597.62	3217.22	4712.41	36803.38	78330.64
Veracruz	10100.01	18922.96	10055.41	31805.88	70884.26
Campeche	1875.99	29314.32	9284.74	15587.25	56062.30
Chiapas	20573.54	26697.86	12398.70	13499.60	73169.70
San Luis Potosí	36245.23	5499.94	8486.97	10616.60	60848.73
Oaxaca	35404.91	27805.21	15244.40	15215.62	93670.14
Michoacán	33429.20	12544.30	4049.53	8445.33	58468.37
Tamaulipas	45759.95	11387.55	9653.53	11102.85	77903.87
Tabasco	2981.19	7910.69	10382.15	3236.60	24510.62
Puebla	17970.94	4341.55	8295.73	3611.52	34219.75
Quintana Roo	22437.39	19666.90	0	0	42104.29
National	271285.22	175412.13	114250.16	202801.28	763748.80

Table 10.3 Agroecological suitability (% of land) for sugarcane crop fields in Mexico

State	Very low	Low	Medium	High
Morelos	11.70	17.50	9.18	61.63
Sinaloa	14.31	6.76	21.83	57.09
Nayarit	8.55	6.34	29.07	56.03
Colima	0.65	31.31	19.48	48.56
Jalisco	42.89	4.11	6.02	46.98
Veracruz	14.25	26.70	14.19	44.87
Campeche	3.35	52.29	16.56	27.80
Chiapas	28.12	36.49	16.95	18.45
San Luis Potosí	59.57	9.04	13.95	17.45
Oaxaca	37.80	29.68	16.27	16.24
Michoacán	57.17	21.45	6.93	14.44
Tamaulipas	58.74	14.62	12.39	14.25
Tabasco	12.16	32.27	42.36	13.20
Puebla	52.52	12.69	24.24	10.55
Quintana Roo	53.29	46.71	0.00	0.00
National	30.34	23.20	16.63	29.84

for the cultivation of sugarcane in relation to current acreage (ha). At the national level, less than a third of the agricultural land presented a high level of suitability for cultivation of sugarcane (29.84%).

Mexico produces sugar with lower environmental impact than other countries because it has a good agroclimatic suitability for the crop. Therefore, if properly planned, the production of sugarcane, sugar, and ethanol could be carried out with less water and fertilizer use and fewer emissions. Crop production in the regions

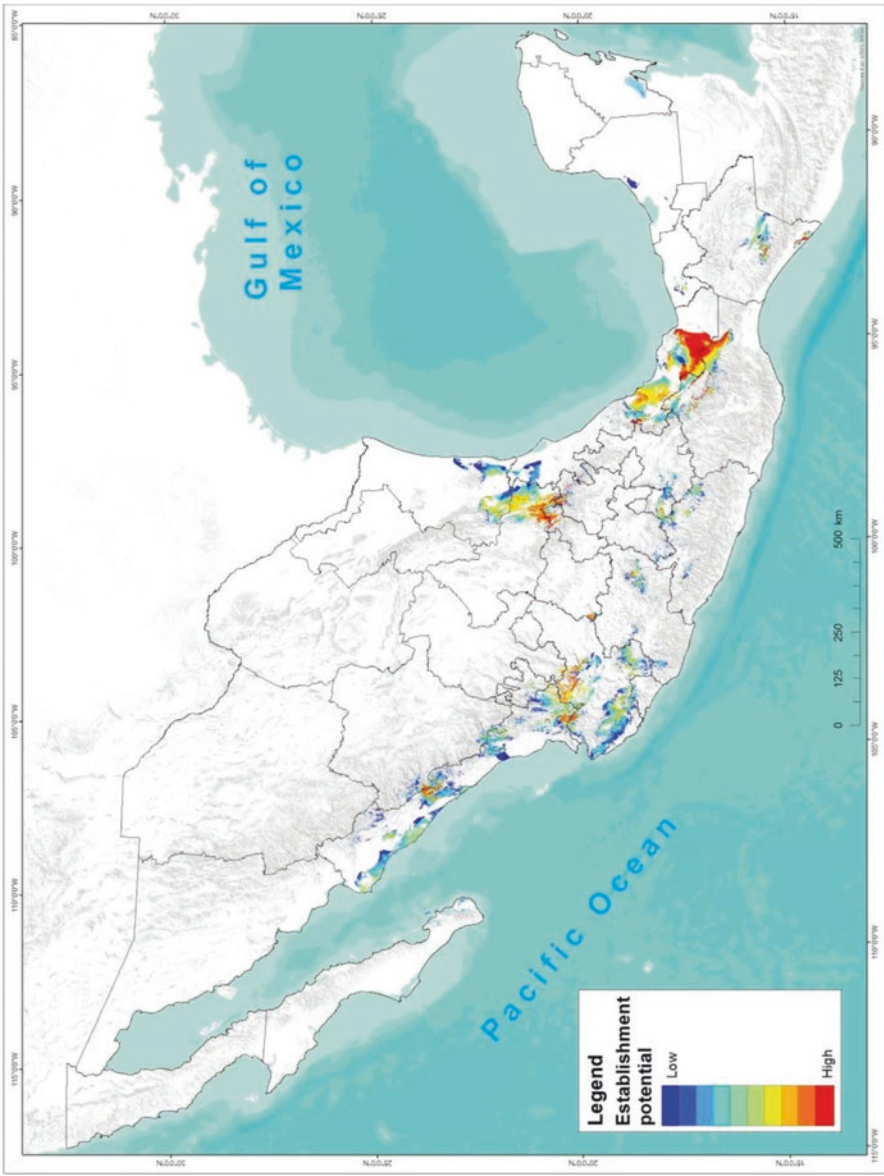


Fig. 10.30 Agroecological suitability in Mexican sugarcane regions. (Aguilar-Rivera et al. 2019)

identified through AEZ analysis can help enhance sugarcane cropping in Mexico. According to Garcia-Chavez (2015), the production of anhydrous and hydrated ethanol in Mexico is economically viable and has domestic and international market potential; however, it requires concrete efforts by stakeholders to stimulate investments in sugarcane fields and sugar mills to increase productivity, diversify the uses of sugarcane, and increase its sustainability and competitiveness.

10.9 Enhancing the Sugarcane Biofuel Production in Mexico

Keeping in view the current status of biofuels in Mexico, it is necessary to reshape the sugar industry for enhancing ethanol production considering the 2030 Agenda for Sustainable Development, goals of BONSUCRO, FSSC 22000 Food Safety System Certification, and other frameworks. One of the major factors is the incorporation of scientific research, technological developments, and innovations carried out by Mexican researchers in industry and crop production (Gracida Rodríguez and Pérez-Díaz 2014; Ramos-Hernández et al. 2016), which can help in modernizing the value chain involving sugarcane agronomy, transport, distillation, and marketing system.

Rendon-Sagardi et al. (2014) mentioned that Mexico is a country with fuel ethanol production capacities, but no policy programs to support the same. Thus, the cane millers in the region follow an opportunistic strategy: the syrup is crystallized into the maximum amounts of sugar for domestic consumption and exports, and most of the remainder is exported as feedstock molasses, decreasing its use as raw material for ethanol production. Even though this means that their investment in fuel ethanol production capacity remains underutilized, the strategy still provides the best returns in an environment characterized by fairly weak biofuel legislation (Castañeda-Ayarza and Cortez 2017).

Regarding crop production, it is necessary to move toward precision agriculture (PA) for yield prediction and growth monitoring for enhancing the sustainable cultivation of sugarcane under rainfed and irrigated conditions. Moreover, modernization of sugarcane fields based on agroecological zoning will also help. An emphasis on crop grower throughout the value chain should also be placed. Further, a differential pricing mechanism should be established based on the final use of the crop for ethanol, or sugar production. For crop improvement, transgenic sugarcane can also reduce the costs involved in sugarcane cropping, making it far more profitable.

At the milling levels, there is need to enhance ethanol engenderment efficiency. Also, second-generation ethanol production should be adopted apart from installation of novel pretreatment options which would make the process more profitable and feasible. Additionally, employing cane-generated electric power in milling operations will decrease the fossil fuel consumption. Economic incentives are also necessary to help the construction and modernization of milling and distillation operations. Furthermore, it is necessary to implement biotechnological approaches in the fermentation process, which could revolutionize the cost-benefit ratio of this phenomenon once established.

10.10 Prospects of Cane Bioenergy in Mexico

Elizondo and Boyd (2017) proposed that policymakers made the decision to foster the use of ethanol because of its potential environmental advantages along with its possible benefits to energy security and rural development. According to Alemán-Nava et al. (2015) and Rios and Kaltschmitt (2013), Mexico's energy needs are expected to increase due to population growth in the years to come. Thus, if adopted, the overall potential of biomass for energy production in Mexico will account for only 39% and 31% on average of the final energy demand in Mexico for the years 2020 and 2030, respectively. Therefore, it is likely that in the future bioenergy will play a role, but with decreasing importance in Mexican energy system because of the potential effects of the Mexican energy sector's reformation targeting possible exploitation of new oil and natural gas deposits (Elizondo et al. 2017). On the other hand, the land available for energy crop production and the provision of forestry wood residues are expected to decline; it is therefore essential to develop strategies and scenarios for increased use of different biomass sources and improve the technical aspects of first- as well as second-generation ethanol production.

Mexican government and the Energy Regulatory Commission recently published and approved Mexican official standard "NOM-016-CRE-2016," which allows the mixing and sale of up to 5.8% (v/v) blend of ethanol anhydrous oxygenate in regular and premium gasoline sold by PEMEX. The official standard does not, however, include the three major metropolitan areas: Mexico City, Guadalajara, and Monterrey. Moreover, there are still several technological barriers that limit the full potential of this approach and that are the topics of active research by Mexican researchers (Chavez-Baeza and Sheinbaum-Pardo 2014).

In spite of all the hurdles, keeping in view current production capacity and distilling technologies available, only sugarcane industry can generate enough supplies to target ethanol blending in Mexico. If new energy supplies and biofuels such as ethanol or biodiesel are not incorporated, prioritizing the renewable fuels to diversify the energy sources in the Mexican energy market, the country may face a fuel shortage in future. Rendon-Sagardi et al. (2014) commented that based on international experiences, the use of ethanol to produce biofuel in Mexico represents the beginning of a transition process leading to sustainable transportation systems.

10.11 Conclusion

Mexico has good agroclimatic conditions for growing and thriving sugarcane crop. However, currently, use of sugarcane ethanol as a biofuel in Mexico is hindered by many factors, which mainly include Mexico's own oil reserves limiting the need to move toward novel options, absence of a multidimensional national policy for biofuel adoption, unavailability of efficient technologies in sugar mills and distilleries, and use of ethanol in other industries. In the future, cane ethanol can gain importance in Mexico for environmental and climatic benefits rather than financial ones. In such a scenario, investments in the sector for increasing production efficiency and crop yields will play a critical role. Moreover, a national policy will indeed be required for launching a multidimensional approach to make the ethanol blending market competitive. Since sugarcane, as a crop, has good prospects in Mexico, the biorefinery concept at the sugar mills for producing first- and second-generation ethanol along with sugar production can benefit the stakeholders involved in sugarcane milling and cropping, apart from meeting the climate change commitments. Commencing from lower blending levels will be a good start as it won't demand major investments or changes in the vehicles.

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