



# Is Sugarcane a Convenient Feedstock to Provide Ethanol to Oxygenate Gasolines in Mexico? A Process Simulation and Techno-Economic-Based Analysis

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Sugarcane is a major crop produced in many tropical countries including Mexico and has been the basis of a well-established agroindustry. However, the variation in market prices and health concerns over the consumption of sugar are challenging the economics and sustainability of sugarcane growers and mills. This paper presents a techno-economic assessment of using existing production capacity of sugarcane in Mexico and the correspondent Mexican sugarcane mills for producing ethanol as gasoline oxygenate, in comparison to the export of excess sugar production. Using the most recent statistics, we found out that the bioethanol potential is of 849,260,499 L/year which can cover for 100% of the premium and magna gasoline demand in metropolitan area (MA) and 48% of premium gasoline in rest of the country areas (RoCAs) at 5.8% w/v blending (2.7% O<sub>2</sub> w/v). This can be done by diverting the 20% sugar production excess to ethanol with the benefit of a higher gross netback of 308.3 USD/ton of sugarcane in comparison to 222.5 USD/ton of sugarcane when it is exported. Furthermore, a minimum ethanol-selling price (MESP) of 0.5211 USD/L was estimated, showing that ethanol might be competitive against methyl tert-butyl ether (0.50 USD/L FOB Gulf price) as gasoline oxygenate agent. Decarbonizing gasoline in Mexico through the use of ethanol might allow the abatement of 5,766.8 kg CO<sub>2</sub>/day when 20% sugar is used. Concerning the underconstruction Dos Bocas refinery in Tabasco State, southern Mexico, ethanol blend at 5.8% in gasolines might but also contribute to the abatement of 6.1% of CO<sub>2</sub> emissions and the required sugarcane was estimated at 1 million tons per year. All these indicate that sugarcane has a great potential as a feedstock to produce first-generation ethanol as a gasoline oxygenate agent in Mexico.

**Keywords:** sugar to ethanol, sugar to exports, ethanol as oxygenate agent of gasolines, techno-economic analysis, decarbonization

## INTRODUCTION

The use of ethanol as oxygenate agent in gasolines is currently worldwide spread but at different penetration rates in national and subnational economies. Its use has even diversified and became a gasoline component in countries such as the United States and Brazil, where a major ethanol volume may be blended from 10, 15, and 27% and even hydrous ethanol as 96% is allowed for use in Brazil. Yellow corn and sugarcane are the most used feedstock in first-generation technology for sugar fermentation to ethanol. The latter may utilize different grade molasses, but sugar juice and standard sugar are also usually used. There are other less common sugar or starch crops as feedstocks such as sweet sorghum, sugar beet, potato and cassava, and cereals such as sorghum grains and wheat, among others.

Mexico has issued some laws and regulations in order to afford the use of ethanol as oxygenate agent, but legal, economic, social, and environmental issues have constrained its production and blending with gasolines. Even pharmaceutical, cosmetic, and beverage industries that use ethanol need to import such commodity since the national market is insufficient and has reduced constantly in last years, from a top of 50 to ca 9 ML from 2005 to 2018 (UNC, 2020). The coronavirus outbreak in 2020 completely exhausted ethanol reserves and some distilleries and sugar mills committed to furnish this ethanol for 70% liquid and gel products to the Mexican Health Service and general public. Besides, Mexico is completely self-sufficient in sugar production and usually exports its surplus to the international market, mainly the United States, at a lower price (around two-thirds of national price). Moreover, sugar consumption as sweetener has been associated with public health issues as obesity and diabetes which has raised public concerns about its use and contents in processed foods that may modify the conventional market of sugar products (Marrón-Ponce et al., 2019; Braverman-Bronstein et al., 2020). In fact, the Mexican government recently published modifications to the standard of food and nonalcoholic beverage labeling where a frontal label must be printed in such products indicating excess of calories and sugar content (NOM-051, 2020). This has raised concerns about the consumption of sugar along the chain value, and alternative markets for sugar are needed. Even if national consumption of sugar might diminish, the international prices are not always an economically attractive option for sugarcane mills.

Therefore, distilleries and sugar mills are eager to diversify their products and ethanol might now have its opportunity for steady production and blending with gasolines, among other technological options. Indeed, such sugar mills already use sugarcane bagasse in their energy-generation processes in order to diminish fossil fuel consumption, CO<sub>2</sub> emissions, and OPEX but also as an energy-transition programme where efficiency of steam and power generation is still under current study and development (Amezcuca-Allieri et al., 2019). Moreover, the sustainability of ethanol production resulted in the higher sustainability index when direct juice is used to produce ethanol with respect to molasses (García et al., 2017). Also, the Mexican Agriculture and Energy Secretariats are looking for strategies to empower sugar growers and ethanol producers to a national

ethanol agenda that could diversify industry with strong social and environmental commitments aligned to a Penta Helix innovation strategy.

In this work, we are interested to answer the question if sugarcane might be an affordable source for the production of ethanol and its blending to Mexican gasolines at 5.8% (2.7% O<sub>2</sub> w/v). This is in line with Mexican policy of energy independence and diminution of fuel imports but also in the reduction of CO<sub>2</sub> emissions from fossil sources. Therefore, we have simulated the potential production of sugar, molasses, and ethanol from sugar juice using 1st generation technology and techno-economic analysis were done according to the scenarios (1) sugar to exports against (2) sugar to ethanol. Moreover, we have analysed gasoline consumption in Mexico and estimated the fraction of gasoline market that ethanol production can cover along with the MESP and abatement of CO<sub>2</sub> combustion emissions due to the use of ethanol as oxygenate agent of gasolines.

## PROCESS SIMULATION AND TECHNO-ECONOMIC ANALYSIS

We have undertaken two scenarios for sugar markets. The first one considers the process simulation and techno-economic analysis of an actual sugarcane mill where sugarcane is processed into standard sugar for national and export markets as well as molasses mainly used for cattle feed and in some factories to diverse grade ethanol. Besides, we carried out the process simulation where we considered 5–50% of sugar for ethanol production instead of sugar exporting and the techno-economic analysis for both scenarios.

### Sugar Production to National and Export Markets

The sugar and molasses production process was simulated in SuperPro Designer<sup>®</sup> v. 7 as shown in **Figure 1**. The flowsheet consists of two main sections: 1) sugarcane fractionation and 2) sugar and molasses purification. Sugarcane main processing units comprise the following steps: reception, grinding, shredding, clarification with lime, solid filtration and bagasse separation, evaporation, crystallization, centrifugation, standard sugar drying, and packing. Sugarcane composition and sugar process simulation parameters are shown in **Table 1**. Stoichiometric along the process considers a global 86.76% mill efficiency in sugar fractionation according to reported data (UNC, 2020) and obtention of standard sugar and molasses known as utility blackstrap since the sugar contents are 47%.

### Ethanol Production

The ethanol production process was built based on a common sugarcane process and simulated in SuperPro Designer<sup>®</sup> as shown in **Figure 2**. The flowsheet consists now of five main sections: 1) sugarcane fractionation, 2) sugar juice separation to sugar or ethanol process, 3) sugar purification, 4) sugar fermentation to ethanol, and 5) anhydrous ethanol obtention (99.9%). Sugar juice

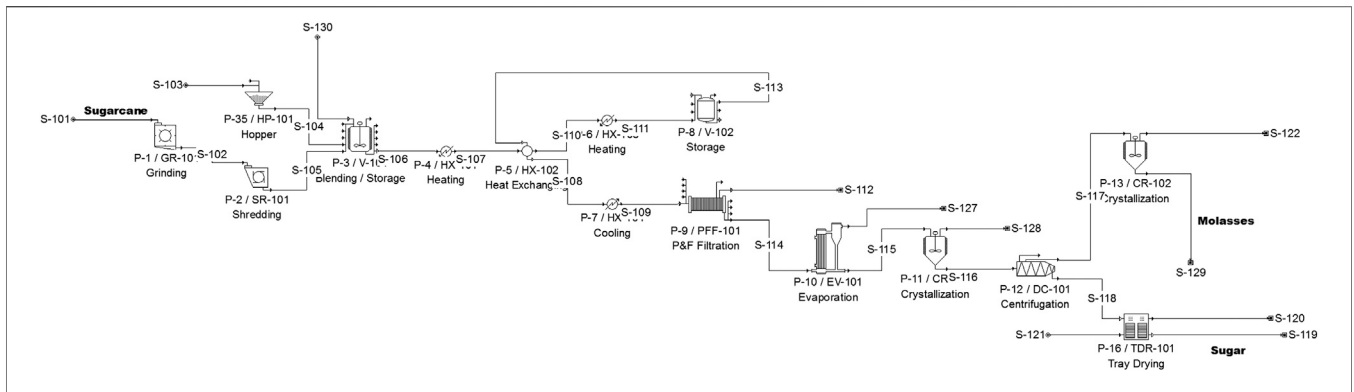


FIGURE 1 | Simulation flowsheet of the sugar and molasses production process in SuperPro Designer®.

TABLE 1 | Sugarcane composition and simulation parameters for sugar, molasses, and ethanol production.

Sugarcane composition	% weight		
Cellulose	8.4		
Hemicellulose	4.2		
Lignin	1.12		
Saccharose	13		
Glucose	0.3		
Fructose	0.3		
Water	71.8		
Ash	0.28		
<b>Sugar and molasses production</b>			
Sugarcane	12,168.9 tons/h	Factory time (zafra)	6 months
Sugarcane price to growers	35.69 USD/ton	Crystallization yield	
Solid filter section		First and second crystallizer	40 and 87.5%
Solid removal	95%	Centrifugation	87.5%
Loss on drying (LOD)	20%	Sugar to exports	0–50% sugar production
Separation efficiency		<0.06% water content	
Sugar	0.0868 kg sugar/kg sugarcane	85% brix	
Molasses (utility blackstrap)	0.026 kg molasses/kg sugarcane		
<b>Ethanol production section</b>			
Sugar to ethanol	0–50% sugar production	Distillery time	365 days
Sugar juice to fermentation	15% sugar		
Fermentation efficiency	95%		
Ethanol distillation			
First- and second-stage stage efficiency	80%		
Column pressure	1.013 bar	Ethanol in distillate	99%
Ethanol incentive credit	2 and 4 USD/ton of sugarcane	Horizon credit	10 years at lost fund

with 15% saccharose is sent to the ethanol production section (Table 1). Sugarcane main processing units to ethanol comprise the additional steps: sugar juice conditioning, fermentation, broth distillation, and ethanol drying to 99.9%. Stoichiometric along the process considers 95 and 80% efficiency in sugar fermentation and distillation, respectively. Main data consider from 0 to 50% sugar sent to this section. In Mexico, there are 51 sugarcane mills but only eight sugar mills and one distillery have already installed capacity for sugar fermentation and ethanol production (566,000 L/day; Table 2) and the installations are already depreciated. We also considered only the sugarcane cost to the mill as discussed earlier, but

we defined here three subscenarios for ethanol production: actual sugarcane cost (35.69 USD/ton; case 1), and a 2 and 4 USD/ton incentive credit to the sugarcane mill (33.59 USD/ton in case 2 and 31.39 USD/ton in case 3). Such incentive credit called the ethanol incentive credit may be available to sugarcane mills if they conserve and create jobs as well as promote the technification of agriculture and industrial procedures for a period of 10 years (Table 1). There is today a federal incentive for sugarcane growers known as the Wellness Production Programme (CONADESUCA, 2020) that affords 0.8950 USD/ton for technical assistance and operational expenses (OPEX).

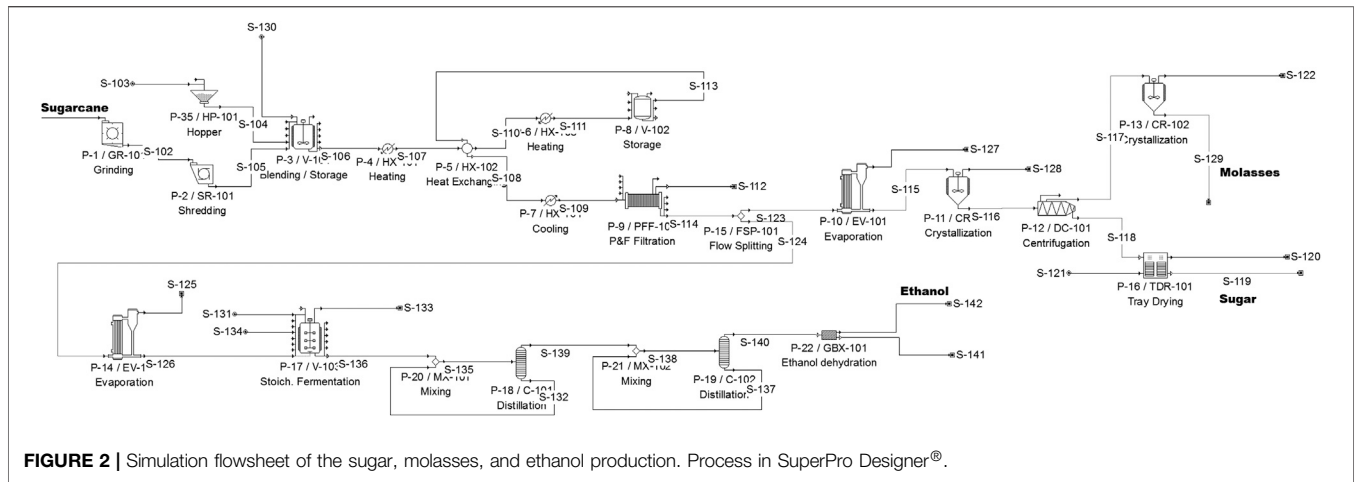


FIGURE 2 | Simulation flowsheet of the sugar, molasses, and ethanol production. Process in SuperPro Designer®.

TABLE 2 | Factories with ethanol capacity (CONADESUCA, 2020).

ZIP code	Factory	Capacity (L/day)	Capacity (kton/year)
68300	Destiladora del Papaloapan	250,000	71.9
91633	Ingenio La Gloria	100,000	28.8
30310	Cia. Azucarera La Fe	60,000	17.3
94920	San Nicolás	40,000	11.5
95096	Ingenio Constancia	30,000	8.7
94929	Ingenio La Providencia	25,000	7.2
95285	Ingenio San Pedro	25,000	7.2
94965	Ingenio El Potrero	18,000	5.2
94910	Ingenio San José de Abajo	18,000	5.2
	Total	566,000	163

### Techno-Economic Analysis

The mass balance analysis was performed using the feature of SuperPro Designer® while economic analysis was done in a spreadsheet. The revenue streams were the sugar to national and export markets, molasses, and ethanol in the respective scenario. The capital costs were not considered since we assume that sugarcane mill installations in Table 2 are already depreciated due to the operational period larger than 20 years and obsolescence. The techno-economic analysis only considers feedstock cost as OPEX to the sugarcane mill. It is very well documented that such cost accounts for 60–80% of all OPEX (CONADESUCA, 2019). The main parameters used for techno-economic analysis are presented in Table 3.

The following analyses were carried out:

- a) Product generation in scenarios 1) sugar to exports and 2) sugar to ethanol.

Mass balances were obtained from SuperPro Designer® according to the scenarios where sugar was used for exports or to ethanol production in a range of 0–50% w/w.

- b) Gross netback on sugar to exports or sugar to ethanol.

$$GNB = \left( \sum_i^n income_i - \sum_i^m expense_i \right) / SGP, \quad [1]$$

where *GNB* is the gross netback since it is before any tax or credit; *income* is the sum of *n* selling units: national sugar, sugar to exports, molasses, and ethanol in USD/ton; *expense* is *m* costing units of feedstock in USD/ton; and *SGP* is the total sugar production for 2019 in tons.

- c) Annual return of investment (ARO), payback time (Pbt), and internal return rate (IRR) on sugar to exports and sugar to ethanol.

First, we calculated the return of investment (ROI in %) in a 10-year lifetime project followed by the ARO by

$$ROI = \frac{total\ income - IVI}{total\ expenses} * 100, \quad [2]$$

where total income and total expenses correspond to the sum of all earning and costs in a 10-year lifetime project and *IVI* is the initial value of investment and corresponds to the purchased sugarcane in year zero for factory start-up. The ARO is

$$ARO = \left[ (1 + ROI)^{1/n} - 1 \right] * 100, \quad [3]$$

where *n* is the lifetime project of 10 years.

Pbt is the inverse of ARO in years.

The IRR was calculated using the build-up function in Excel for a 10-year lifetime project and a discount rate of 10%.

- d) Minimum ethanol selling price (MESP).

Since the average amount of sugar yearly exported to the United States is around 20% (1,383,513 ton/year for 2019), we

**TABLE 3 |** Parameters for the techno-economic analysis of the sugar to exports vs. sugar to ethanol.

Parameter	Value
General	
Annual operating time	3,960 h for sugar production 7920 h for ethanol production
Total annual sugar production in Mexico (UNC, 2020)	5,827,504.6 tons
Dollar exchange rate	1 US\$ = 24 Mexico pesos
Discount rate	10%
Project lifetime	10 years
Sugarcane cost	Scenario: sugar to exports Case 0: 35.69 USD/ton Scenario 2: sugar to ethanol Case 1: 35.69 USD/ton Case 2: 33.69 USD/ton Case 3: 31.69 USD/ton
Product selling prices	
National sugar price	529.65 USD/ton
Sugar price to export	
United States	430.62 USD/ton
Rest of the world	237.15 USD/ton
Molasses price	0.1210 US\$/kg
Ethanol price	0.4–0.7 USD/L for sensitivity analysis

iterate the ethanol selling price from 0.39 to 0.60 USD/L in order to get an MESP with an IRR of 10% for scenario 2 and cases 1 to 3.

The objective function is

$$MESP = B_0 + B_1 * IRR + B_2 * IRR^2 \quad [4]$$

and is set up by iteration to minimize

$$\sum_i^n (ESP_{set, i} - ESP_{calc, i})^2, \quad [5]$$

where  $n$  is every set ethanol selling price ranging from 0.39 to 0.60 USD/L,  $ESP_{set}$  is the ethanol selling price set at each iteration, and  $ESP_{calc}$  is the value found by iteration that minimizes the quadratic error.  $B_0$ ,  $B_1$ , and  $B_2$  are correlation parameters and shown in **Table 4**.

e) Ethanol coverage of gasoline demand in the three larger metropolitan areas (MAs): Mexico City (ZMVM), Monterrey, Nuevo León (ZMM), and Guadalajara, Jalisco (ZMG), and rest of the country area (RoCA).

Gasoline distribution and consumption in Mexico is classified in metropolitan areas (Mexico City, Monterrey, and Guadalajara areas) and rest of the country area (RoCA). Volume demand for every area and kind of gasoline were obtained from the Energy Information System of the Energy Secretariat (SENER, 2020). Mexico has two gasoline grades, magna (antiknock index, AKI = 87) and premium (AKI = 91). The ethanol coverage was calculated in kg ethanol per liter of gasoline to obtain 2.7% w/v of oxygen, i.e., 5.8% w/v ethanol according to current Mexican standard (NOM-016-Comisión Reguladora de Energía (CRE), 2016).

## Decarbonization of Gasolines and Calculation of CO<sub>2</sub> Combustion Emission Abatement

The use of sustainable ethanol produced from sugarcane juice might allow the decarbonization of gasolines in Mexico. We present here the potential abatement of CO<sub>2</sub> combustion emissions according to the following formula:

$$Q_{CO_2} = (Q_{Gasoline} * NCV_{gasoline} * CO_2 EF_{gasoline}). \quad [6]$$

Here, we considered that the use of ethanol as oxygenate agent of gasolines in Mexico might diminish the CO<sub>2</sub> combustion emissions since less gasoline is burned in engines but also because of the neutral CO<sub>2</sub> emissions from ethanol. Therefore,  $Q_{CO_2}$  is the abatement of CO<sub>2</sub> combustion emissions (tons CO<sub>2</sub>/day) by the use of ethanol as oxygenate agent of gasolines at 5.8% w/v (2.7% O<sub>2</sub> w/v).  $Q_{gasoline}$  is the quantity of premium or magna gasoline in tons per day that has been substituted by ethanol.  $NCV_{gasoline}$  is the net calorific value in MJ per kg of gasoline (42.57 MJ/kg; Rodríguez-Lara et al., 2014).  $CO_2 EF_{gasoline}$  is the CO<sub>2</sub> emission factor of gasoline in Mexico (0.0738 kg CO<sub>2</sub>/MJ; Rodríguez-Lara et al., 2014).

## RESULTS AND DISCUSSION

### Simulation Process of Sugar, Molasses, and Ethanol Production

Main data consider a sugarcane annual harvesting of 53.3 million tons (Mtons) per annual cycle, called zafra, which lasts normally from September to March every year. The production in 51 Mexican sugarcane mills was around 5.8 Mtons of standard base sugar and 1.76 Mtons of molasses with 85% Brix in 2018 (UNC, 2020). Mexico is self-sufficient in sugar production according to consumption patterns, and around 1–2 Mtons per zafra is yearly exported, mainly to the United States. If we consider case 0, around 20% of sugar production (1.17 Mtons/year) is exported mainly to the United States (85%) and the rest to world markets (**Figure 3** left). In this scenario, we observed a steady diminution of sugar to national market depending on sugar to exports, but molasses production remains the same since all sugarcane juice is processed into standard sugar and the latter. The obtained sugar is sold at 529.65, 430.62, and 237.15 USD/ton in Mexico, United States, and world market (CONADESUCA, 2019). Since sugarcane growers obtain a fixed price of 35.69 USD/ton (case 0) regardless of sugar selling prices according to law, sugarcane refiners are eager to find new markets or products such as ethanol that help them to improve profits and business factibility.

Considering scenario 2, the exported sugar (291.4–2,913.8 ktons/year) is instead sent to ethanol production with a potential of 169.1 to 1,517.6 ktons/year of ethanol (**Figure 3** right). The potential ethanol production is 670.1 ktons/year in case 0 where actual sugar exports correspond to 20% sugar production (1,165.5 ktons/year). With respect to molasses production, the scenario 1 considers 1,755.9 ktons/zafra

**TABLE 4 |** Correlation parameters for minimum ethanol selling.

Scenario 2: 20% sugar to ethanol	Case 1: actual sugarcane cost	Case 2: 2 USD/ton incentive credit	Case 3: 4 USD/ton incentive credit
$B_0$	0.4979	0.4659	0.4466
$B_1$	0.0023	0.0022	0.0025
$B_2$	2.88e-5	2.95e-5	2.64e-5

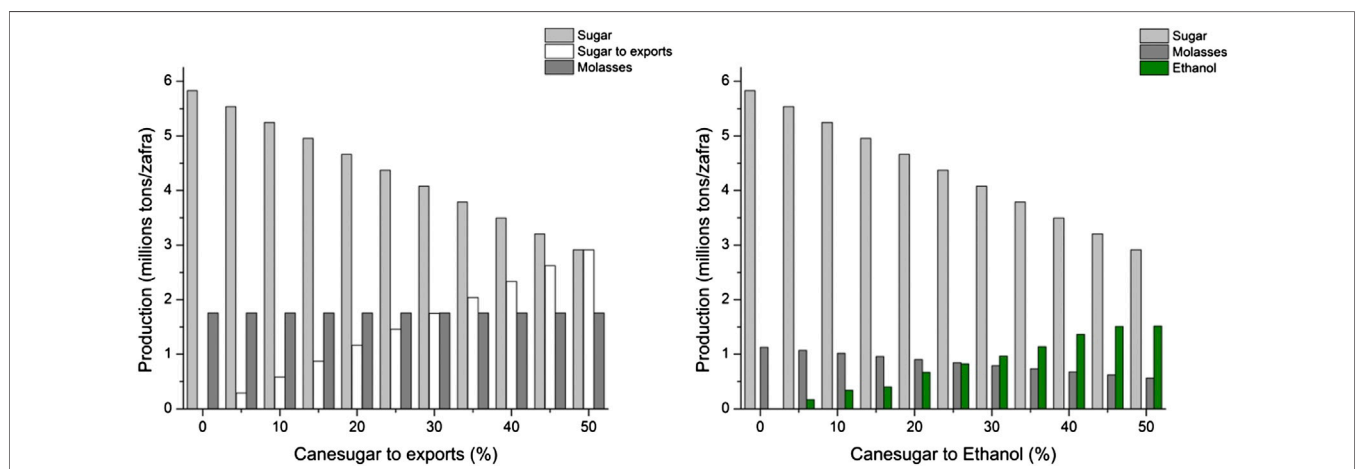
and it is unaffected in scenario 1 whilst it diminishes in scenario 2 from the initial 1,755.9 to 876.2 ktons/zafra at 50% sugar to ethanol (Figure 3 right). Indeed, such diminution is attributed to the less sugarcane juice processed through evaporation and crystallization since we use different sugarcane juice percentages to produce ethanol.

### Techno-Economic Analysis: Sensitivity to Sugar to Exports or Sugar to Ethanol

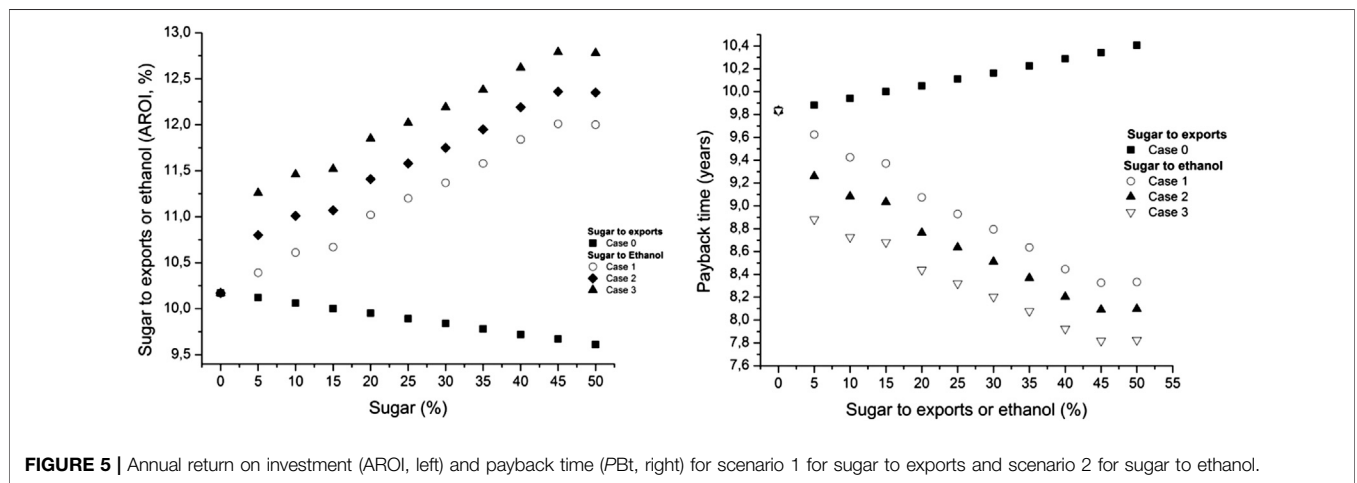
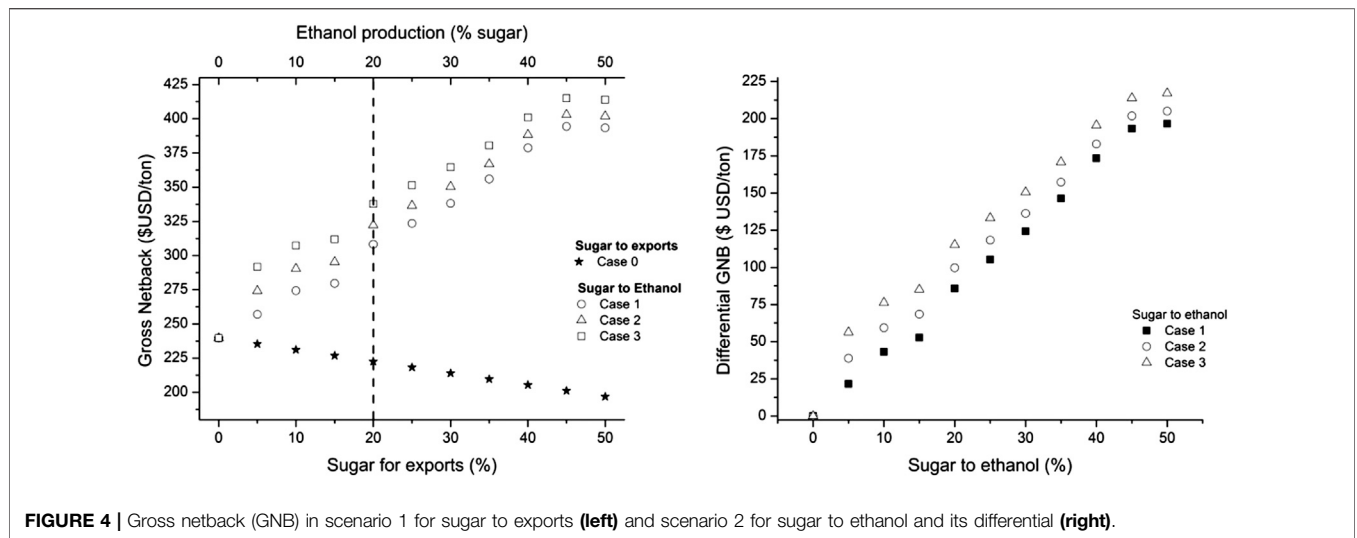
Considering scenarios 1 and 2, the gross netback (GNB) gives a first-year outlook of cash flow of sugar exports vs. sugar to ethanol with respect to the total sugar production. The GNB diminishes sharply from 239.7 to 196.8 USD/ton at 50% sugar to exports when compared to the case where all sugar production is nationally commercialized (Figure 4 left). The GNB is 222.5 USD/ton at 20% sugar to exports. This is clearly due to the more attractive national market where sugar is sold 1.23 and 2.23 times higher than in the United States and rest of the world, respectively. The national sugarcane price paid to growers (35.69 USD/ton in 2019) is calculated based on a ponderation of the recovered kilograms of standard-based sugar (KARBE in Spanish), i.e., attributed to sugar content in sugarcane and factory efficiency, national and international prices, and volume of sugar to exports. Since the GNB represents the cash flow of selling minus expenses of sugar production, then both the sugarcane growers and the sugarcane mills lose value when the standard sugar is exported.

On the contrary, the GNB increases steadily from 239.7 to 393.4 USD/ton in case 1 that considers ethanol production instead of sugar to exports and 35.69 USD/ton paid to sugarcane growers (Figure 4 left). The GNB is 308.3 USD/ton at 20% sugar to ethanol in case 1 with a differential GNB of 85.7 USD/ton with respect to scenario 1 and case 0 (Figure 4 right). Here, we get a better GNB with respect to scenario 1 because of a higher income from ethanol selling since we considered a calculated MESP of 0.5211 USD/L (0.6604 USD/kg) as we will discuss further. In scenario 2 and cases 2 and 3, we have considered an ethanol incentive credit of 2 and 4 USD per ton of sugar and the GNB at 50% sugar to ethanol reached a value of 401.91 and 413.87 USD/ton, respectively. In the actual market situation of 20% sugar to exports, the GNB is 322.3 and 337.8 USD/ton if this sugar is nationally converted to ethanol with a differential GNB of 99.7 and 115.2 USD/ton in cases 2 and 3. We see that the incorporation of such an ethanol incentive credit is somehow relevant since the GNB value in scenario 1 and case 0 is 222.5 USD/ton. Therefore, sugarcane growers and mills might perceive a higher GNB by producing ethanol instead of sugar to exports. We might also consider other incentives such as a carbon tax to gasolines or reduction of the special product and service tax (IEPS in Spanish) to ethanol production and commercialization as oxygenate agent for Mexico’s gasolines that in the case of nonfossil fuels accounted for 4.18 MXN/L (220.7 USD/ton; Diario Oficial de la Federación (DOF), 2019). IEPS tax is charged to final users by fuel producers.

Since GNB is just a snapshot of cash flow per processed sugarcane, we calculated the corresponding AROI and PBt for scenarios 1 and 2 (Figure 5). We observed again that sugar to ethanol in scenario 2 allows a higher AROI and lower PBt in all three cases when compared to scenario 1 of sugar to exports. These calculations relied only on sugar to exports or sugar to ethanol sellings and corresponding feedstock expenses. We clearly observed that a major AROI and a shorter PBt are reached when more sugar is converted to ethanol instead of sugar to exports as well as for cases 2 and 3 where an ethanol incentive is applied to sugarcane price as explained earlier.



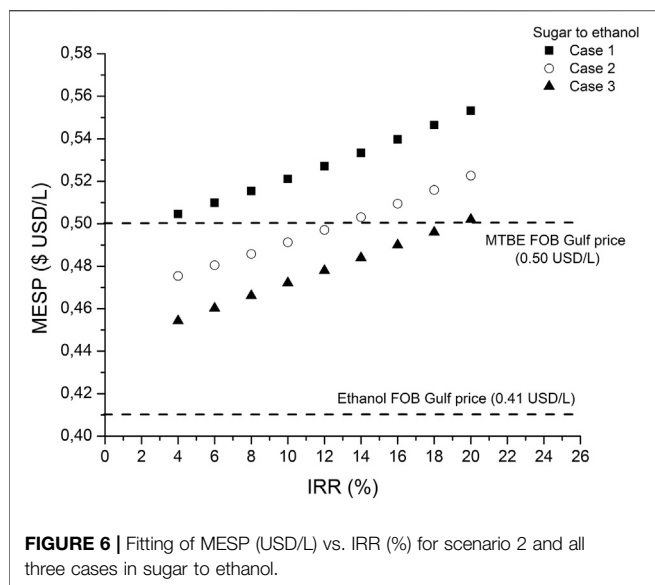
**FIGURE 3 |** Sugarcane products in scenario 1 for sugar to exports (left) and scenario 2 for sugar to ethanol (right).



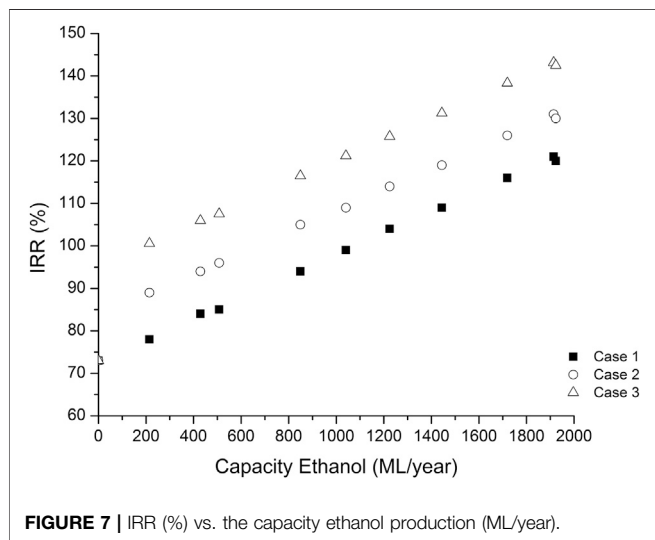
Since sugar to ethanol seems to be more profitable than sugar to exports, we calculated by iteration the MESP with respect to IRR in scenario 2 and all three cases departing from a 10% IRR since this is the usual discount rate (Figure 6). All iterated MESP are higher than the ethanol FOB Gulf price. This is expected since sugar price is higher in Mexico when compared to sugar from maize and sugarbeet, which have more incentives and a consolidated market in the United States when compared to Mexico (US Grain Council, 2019). Nevertheless, we observed that the sugar to ethanol scenario presents opportunities against the importation of methyl tert-butyl ether (MTBE) for the oxygenation of Mexican gasolines in cases 2 and 3. Here, it becomes relevant the existence of an energy policy such as the ethanol incentive credit of 2 or 4 USD per ton of sugarcane for the diversification of sugarcane products for the self-sufficiency of sugarcane growers and mills, as well as Sovereign production of fuels, components, and additives as ethanol.

With respect to ethanol capacity production, we observed that the IRR (%) augmented with the latter which indicates that

feedstock cost is financially relevant for increasing capacities of ethanol but that other capital (CAPEX) and operational expenses (OPEX) might become relevant at larger ethanol production capacities Figure 7. Since all 51 operating sugarcane mills have different starting operational dates and production efficiencies, we can just give a general outcome of the decision to sugar to exports (scenario 1) or sugar to ethanol (scenario 2). The total national installed ethanol capacity accounts for 163 ktons/year according to Table 2. This is almost 4-fold less the needed capacity in eight sugar mills and one distillery. This indicates that the ethanol production capacity in Mexico must be substantially incremented in order to give a business as usual financial sense to such industrial decision. Nevertheless, externalities such as social impact, industrial sugarcane strengthening, energy independency, environmental benefices, and sugar diversification market, among others, have not been considered and are out of scope of present work. The impact of oxygenate agent coverage of ethanol on national gasolines is discussed further.



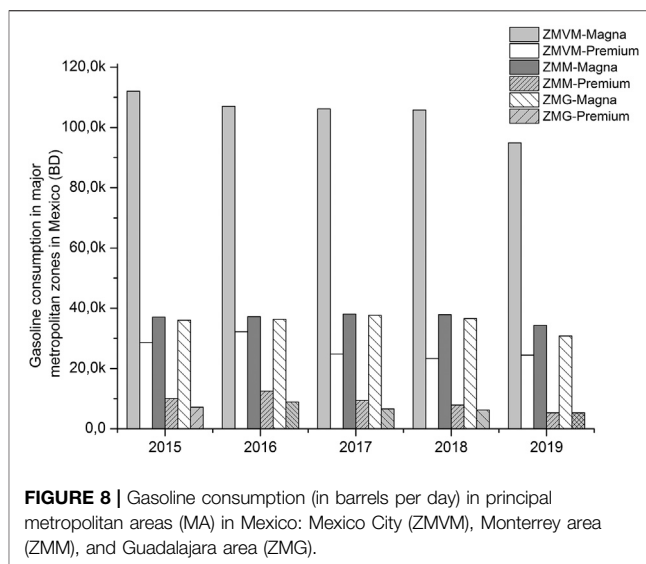
**FIGURE 6 |** Fitting of MESP (USD/L) vs. IRR (%) for scenario 2 and all three cases in sugar to ethanol.



**FIGURE 7 |** IRR (%) vs. the capacity ethanol production (ML/year).

### Ethanol Coverage of Gasoline Consumption in Mexico

ZMVM is the largest metropolitan area in Mexico with the highest consumption of gasoline, both magna and premium, followed by Monterrey and Guadalajara areas (Figure 8). ZMVM’s total gasoline demand accounts for two-thirds of consumption in metropolitan areas, and magna gasoline represents the 82% with respect to premium (SENER, 2020). Moreover, we observed a steady decrease on consumption in the 2015–2019 period that might come for a major fuel and engine efficiency, the renewal of vehicle fleet, the presence of hybrid and electric cars, and the limitation of one-day vehicle circulation but also to fuel robbery that is not considered in official statistics.



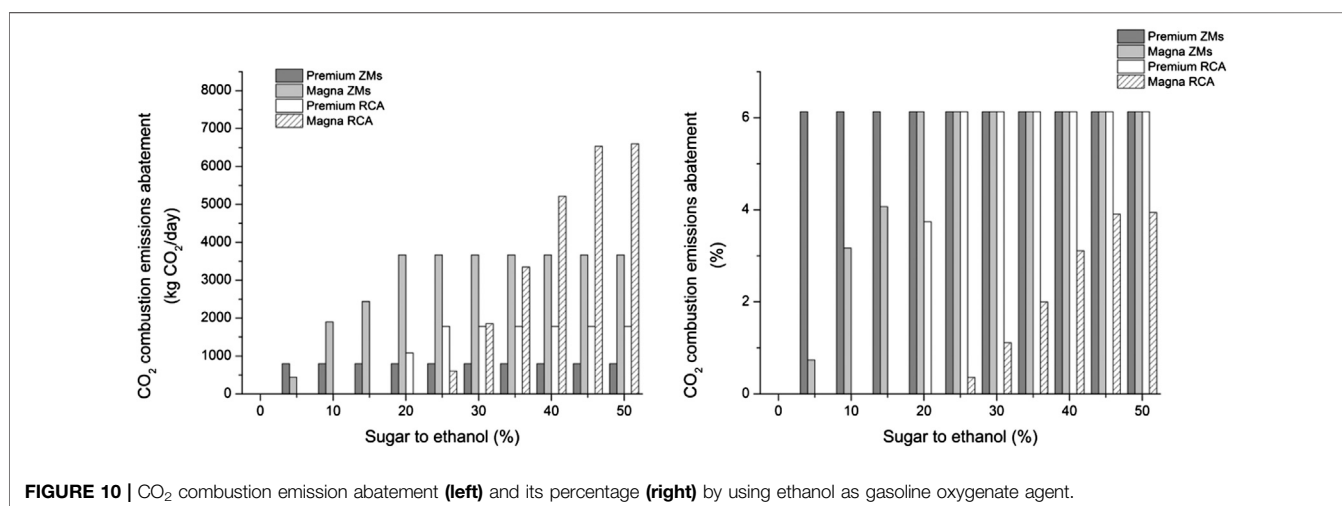
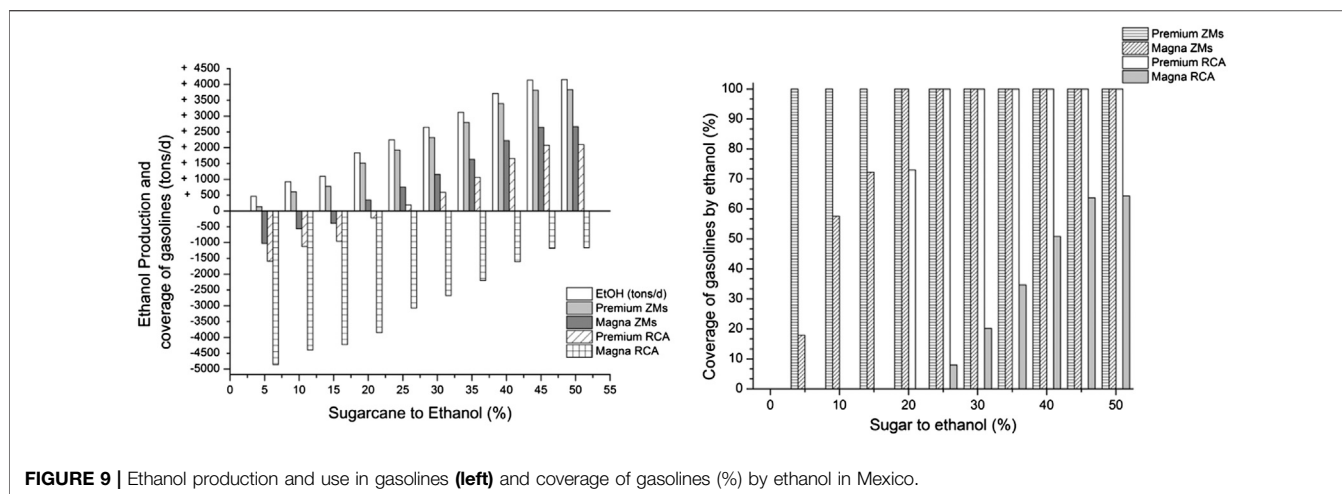
**FIGURE 8 |** Gasoline consumption (in barrels per day) in principal metropolitan areas (MA) in Mexico: Mexico City (ZMVM), Monterrey area (ZMM), and Guadalajara area (ZMG).

Sugar to ethanol production might afford the demand of oxygenate agent in gasoline consumption in metropolitan areas and a high proportion in rest of the country area (RoCA; Figure 9). The 20% of sugar to ethanol would provide the needed oxygenate agent for both magna and premium gasolines in metropolitan zones but just the 48% of premium in RoCA. The 50% of sugar to ethanol may comply almost all need of oxygenate agent for gasoline in Mexico since all metropolitan zones are already covered and also premium in RoCA, but just the 50.7% of magna gasoline might be covered with such ethanol production. Therefore, other feedstock options for ethanol production must be defined, i.e., lignocellulosic biomass from agricultural, agroindustrial, and forest industries, among others. Here, sorghum might also be an option as studied earlier (García et al., 2017). All eight sugar mills and one distillery have a joint production capacity of 206,590 kl per year, but if 20% sugar is diverted to ethanol production, we would need a production capacity of 849,267 kl per year; i.e., we need four-fold the actual production capacity. Here, the retrofit of existing sugarcane mills as well as the construction of new ones and distilleries is essential to be able to produce the required ethanol in Mexico for energy independence and diminution of fuel imports.

### Decarbonization of Gasolines by the Incorporation of Ethanol as Oxygenate Agent

Since ethanol production in Mexico might cover metropolitan areas (MAs) but also some gasoline demand in the rest of the country (RoCA) as discussed above, we have calculated the CO<sub>2</sub> combustion emission abatement for the oxygenation of fossil gasoline for national production of ethanol (Figure 10). Such blending of ethanol in gasolines might afford for their decarbonization only if the ethanol is sustainably produced





along all the chain values. We have done these calculations assuming then the sustainable production of ethanol that accounts for neutral CO<sub>2</sub> combustion emissions. The sugar to exports is usually 20% of the production, but if instead we produced ethanol, then we could cover the oxygenation of gasolines in metropolitan areas and some of premium in RoCA as discussed earlier. In this case, we could abate 799, 3,669 and 1,298 kg CO<sub>2</sub> per day in premium and magna’s MA and premium’s RoCA, respectively (Figure 10 left). These represent the 6.1% CO<sub>2</sub> combustion emission abatement in MA and just 4.5% in RoCA (Figure 10 right).

Finally, we have estimated the required ethanol to blend at 5.8% w/v in gasolines of the underconstruction Dos Bocas refinery in Tabasco State, southern Mexico, with a gasoline capacity of 190,000 B/d (Table 5). Indeed, we need to process nearly 1 million tons per year of sugarcane to ethanol in order to obtain 1.4 ktons per day of ethanol and a potential CO<sub>2</sub> emission abatement of 4.4 ktons per day.

## CONCLUSION

This paper presents a techno-economic assessment of using existing sugarcane production capacity in Mexico as well as in sugarcane mills and distilleries for producing ethanol as gasoline oxygenate, as an alternative to the export of excess sugar at low prices and the import of fuels or oxygenate agents. Results showed that it is possible to cover up to 100% of the ethanol demand as gasoline oxygenate in premium and magna gasolines in MA but just 48% of premium gasoline in RoCA at 5.8% w/v ethanol blending and by processing 20% of sugar to ethanol, i.e., 1.6 million tons of sugar per zafrá. This can be beneficial for Mexican sugarcane mills as producing ethanol has a higher gross netback than sugar export. Furthermore, estimation of the MESP showed that ethanol can be competitive against importation of MTBE. The ethanol production capacity needs to be reinforced in order to comply with the oxygenate agent needs. This means that sugarcane has a great potential as a feedstock to produce first generation ethanol as a gasoline oxygenate in Mexico.

**TABLE 5 |** Gasoline capacity, required sugarcane and ethanol, and CO<sub>2</sub> abatement emissions for Dos Bocas refinery in Tabasco State.

Petroleum processing capacity	340,000 B/day
Gasoline production	190,000 B/day
Sugarcane requirement	1,029,768.4 tons/year
Ethanol requirement of 5.8% w/v blend	1,386.2 tons/day
CO <sub>2</sub> emission abatement	4,354.5 kg CO <sub>2</sub> /day (6.12%)

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## AUTHOR CONTRIBUTIONS

JA elaborated the framework and scope of this research dealing with the question if ethanol obtained from sugarcane might be able to blend with gasolines in Mexico in order to diversify

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sugarcane industry and allow the decarbonization of fuels and diminution of gasoline imports. We have done process simulations where direct sugarcane juice is transformed to ethanol as well as calculation of financial parameters to answer the question. JA and EM-H elaborated the process simulations and calculations of financial parameters. JA wrote and reviewed the research article. EM-H reviewed the research article and gave insights and recommendations.

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**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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