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Sustainable Biofuels. Strategy for Growth and Energy Security

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Abstract

In Mexico, the goal of economic growth, sustainability, decrease consumption of imported oil fuels and additives meeting the climate change commitments with ethanol biofuel is a development goal not yet resolved. This work is based on the premise that feedstock, the use of agricultural lands as a function of economic, ecological and social aspects, inefficient public policies, disinformation and lack of knowledge, culture and attitude of the population and stakeholders towards biofuels has been identified as critical success factors for the transition of conventional sugar mill to an agro-industrial complex. Therefore, a systematic review of academic and technological research was carried out on the recent innovations and scope for future endeavours in ethanol biofuel. Ethanol can gain importance in developing countries as Mexico, producers, and exporters of oil without refining capacity for environmental, climatic and financial benefits. In such a scenario, investments, and public policies in the sector for increasing production efficiency and crop yields as sugarcane will play a critical role in bioethanol value chain.

JEL Classification: O130, Q420, Q480, Q510, O210, O320.

Keywords: Ethanol fuel, feedstocks, public policy, technological innovations, barriers.

Biocombustibles sostenibles. Estrategia para el crecimiento y la seguridad energética

Resumen

En México, la meta de crecimiento económico, sustentabilidad, disminución del consumo de combustibles petroleros importados y aditivos que cumplan con los compromisos de cambio climático con biocombustible de etanol es una meta de desarrollo aún no resuelta. Este trabajo se basa en la premisa de que la materia prima, el uso de las tierras agrícolas en función de los aspectos económicos, ecológicos y sociales, las políticas públicas ineficientes, la desinformación y la falta de conocimiento, la cultura y la actitud de la población y los actores hacia los biocombustibles se han identificado como factores críticos de éxito para la transición de un ingenio azucarero convencional a un complejo agroindustrial. Por lo tanto, se llevó a cabo una revisión sistemática de la investigación académica y tecnológica sobre las innovaciones recientes y el alcance de los esfuerzos futuros en biocombustible de etanol. El etanol puede ganar importancia en países en desarrollo como México, productores y exportadores de petróleo sin capacidad de refinación para beneficios ambientales, climáticos y financieros. En tal escenario, las inversiones y las políticas públicas en el sector para aumentar la eficiencia de la producción y los rendimientos de los cultivos como la caña de azúcar jugarán un papel crítico en la cadena de valor del bioetanol.

Clasificación JEL: O130, Q420, Q480, Q510, O210, O320.

Palabras clave: Combustible de etanol, materias primas, políticas públicas, innovaciones tecnológicas, barreras.

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1. Introduction

In recent years, bioenergy has become a sustainable power source for modern industrial economies, domestic energy security, concerns over global warming from greenhouse gases (GHG) emissions and instability of fuel prices, provide income to poor farmers and rural communities, create jobs and additional markets for agricultural commodities and waste biomass around the globe, besides growing energy demand, and increased openness to renewable energy resources, and the push for expansion into new markets for plantation crops, wastes and biomass are all factors driving interest in expanding biofuels, bioenergy and biorefineries (Koutinas et al. 2014).

The novel processes of biofuels production have been oriented towards the use of biomass (carbohydrates, fats, and lignin); all of them are found in roots, stems, leaves, seeds and waste fruits and vegetables. They can be exploited directly by being the plant cultivated or indirectly using the residues of agro-industrial or forestry processes. Besides, livestock residues or even organic matter from sewage treatment plants can also be used as a source in agro-industrial facilities (Abdulkareem-Alsultan et al. 2020).

In this regard, it is necessary adequate political and regulatory conditions that allow in a general way the use of wastes towards biofuels evolution. Most of countries that are involved in obtaining biofuels have established regulations that guide their production processes considering technological and socioeconomic aspects that permit generating the necessary infrastructure and optimal comparative and competitive advantages for the production of biofuel and bioenergy. At the global level, there are countries that have established laws to encourage the generation of internal markets that allow the production of biofuels in an integral manner, considering incentives for the establishment of crops or the use of waste to generate the raw material (Arnold et al. 2019; Gregg et al. 2017)

Lin et al. (2014) and Arancon et al. (2013) discuss various approaches related to current valorization strategies and alternatives for wastes from food production to be developed to maximize the value as source for biofuels and biochemical.

There is a growing multidisciplinary campaign related to biofuels, which has been primarily addressed with issues as public policy instruments, environmental impact and greenhouse gas emission reductions, food and poverty interactions and countless scientific papers on technological advances in ethanol manufacturing (Gaurav et al. 2017; Ji et al. 2016).

Sukumara et al. (2014) and Pérez et al (2017) presented overall frameworks and multidisciplinary methodologies to estimate various factors for sustainable biorefining encompassing feedstock assessment, supply chain optimization, and process systems engineering can be implemented to estimate the total production cost of energy, fuel, and inputs from various renewable resources in a specific geographic region.

Several studies indicate that biofuels have the capacity to reduce GHG; nevertheless, the environmental impact analysis in the production of biofuels production, the development of different production technologies and potential impacts has become controversial. Indicators should be developed to evaluate the effects of each of the processes and steps carried out to produce biofuels from the generation of crops or their biomass sources, the production or refining processes, the cogeneration systems, the conversion of their waste and the compounds that are released into the atmosphere according to each geographic region (Callegari et al. 2020; Venturini et al. 2020; Ziolkowska, 2014)

On the one hand, there is uncertainty about the current and future availability of suitable biomass for bioenergy use with dynamic physical, technological, economic, politics and social constraints because they are strongly interrelated with other economic sectors and sustainability, and ultimately depend of political-normative decisions (Leibensperger et al., 2021).

The main barriers to bioenergy and biofuels deployment are:

- Lack of awareness and understanding of bioenergy
- Perception that bioenergy and biofuel are unsustainable
- Lack of policy stability
- Lack of catalytic finance
- Lack of sustainable supply chains
- Poor yields, dad roads, infraestucture etc

Ziolkowska, (2014) concluded the design of biofuels policy, multiple economic, environmental and social goals and stakeholders perceptions need to be considered to be sustainable in three ways simultaneously:

1) Economic objectives: Reducing feedstock and biofuels production costs, increasing profitability (biofuel productivity/acreage), insuring domestic food and energy security, stable economic income for growers and rural development
2) Environmental objectives: Reducing greenhouse gas emissions, water, land, and inputs use preserved to the maximum the biodiversity and landscapes
3) Social objectives: Achieve common goals of well-being, health, food and energy safety, for communities and growers and the creation of job opportunities.

The objective of this review is to analyze the Mexican context, opportunities, barriers and political, socioeconomic and technological challenges for the establishment of a national sugar cane ethanol program based in sugarcane

2. Literature Review

2.1 Worldwide biofuel production and management

The 1G (first-generation biofuels) are largely associated to ethanol produced from sugar- and starch-based feedstocks derived from food crops such as sugarcane (*Saccharum spp.),* sugar beet (*Beta vulgaris subsp. vulgaris*), cassava (*Manihot esculanta*), corn (*Zea mays*) and other food grains.

Kumar et al (2020); Meneghin (2016) and Organization for Economic Co-operation and Development (OECD) - FAO (2020) reported that forty-five countries are ethanol producers. As the main biofuel, ethanol production is undergoing exponential growth and is a mature market with three large geographic areas currently dominating the value chain: the United States, Brazil and European Union. Demand for fuel ethanol in the United States is expected to remain strong. The world leaders in ethanol production in 2020 were United States produced from corn (53 %), followed by Brazil from sugarcane (molasses, juice and syrup) (30 %), European Union (5 %), China (3 %), India (2 %), Canada (2 %), Thailand (2 %), Argentina (1 %) and accounting for the rest of world production (2 %) using wheat or sugar beet.

Beet or cane molasses are the most established carbon source for ethanol production, equivalent to around 70% of world production. Other countries, growers of maize, cane or beet, are planning to implement competitive domestic biofuel programs (https://ethanolrfa.org/statistics/annual-ethanol-production/) Biofuel ethanol as a mixture with gasoline vary between regions depending on the geopolitics of oil and the availability of raw materials from agroindustries, public policies, industrialists and automobile companies and at 2020 because of COVID-19 pandemic (Figure 1 and 2).

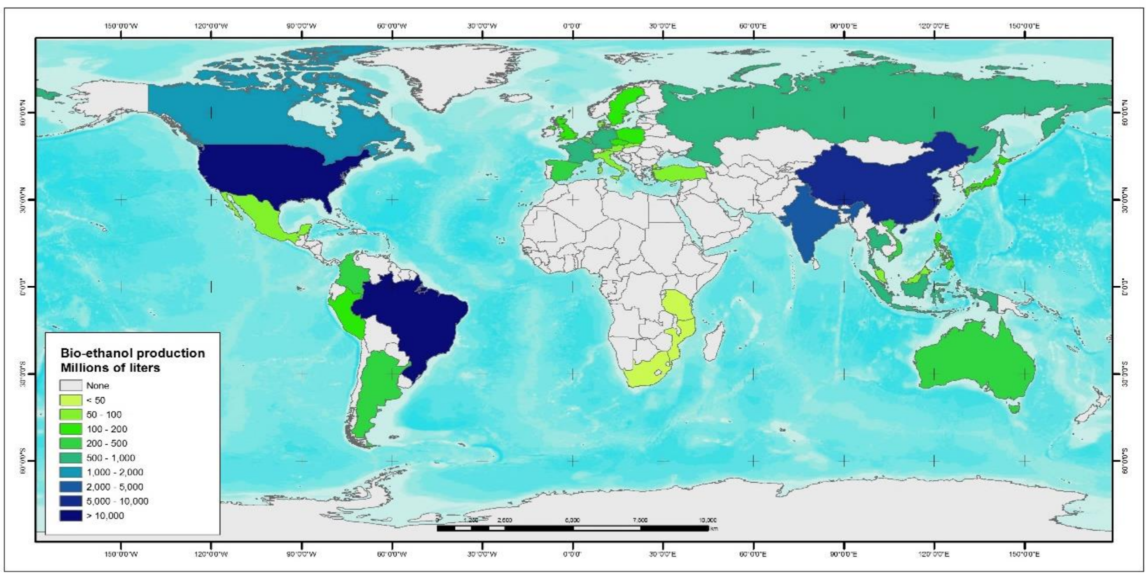

Figure 1. Ethanol producing countries (OECD-FAO, 2020

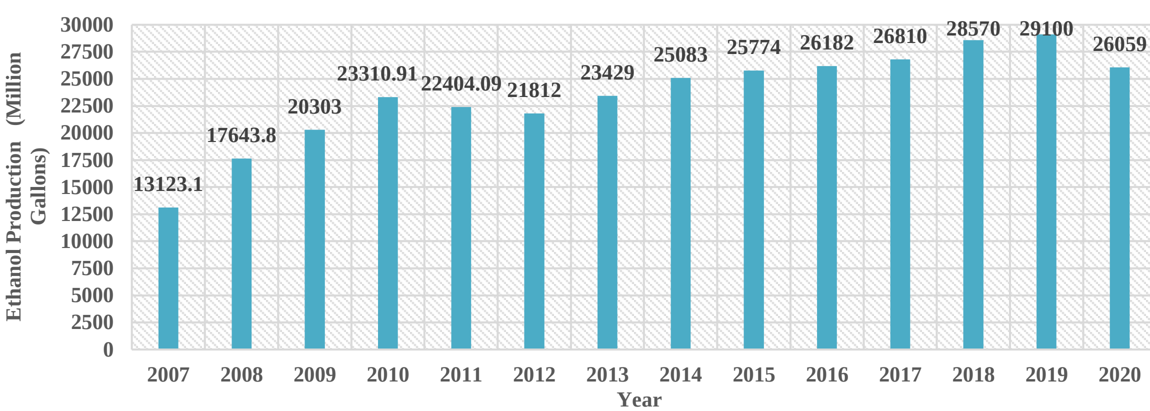

Figure 2. World ethanol production

Source: Data from https://ethanolrfa.org/statistics/annual-ethanol-production/

The bioethanol-based motor biofuels and programs most popular are E5 (UK), E10 (EU), E15 (United States of America), and E25-100 (Brazil). Meneghin (2016) reported that the main blend mandates of ethanol are Brazil (27 %), Paraguay (24 %), Argentina (12 %), the United States, China, and India (10 %), whereas for the rest of the world (approximately 60 countries) it ranges from 2 to 10%.

The biofuel ethanol value chain is generically divided into three different stages: Processing of carbon sources (sugarcane, cereals, beet, agro-industrial by-products or energy plantations), anhydrous ethanol production technology, and transportation logistics, distribution, mixed and retail to users. Derived from these stages, there are three forces that shape the evolution of the biofuel ethanol chain structure: (i) permeable industrial borders, (ii) security in the supply of inputs, and (iii) access to the retail market. These forces structure vertical integration in the development of the biofuels biorefinery (Banerjee et al. 2019).

Therefore, worldwide some countries and regions have introduced ethanol biofuel programs and mandates over the last 30 years, the main goals are:

1. Rising or decreasing oil, petrochemical, fuel (gasoline and diesel) and fuel additive prices (MTBE etc)
2. Concern about fuel emissions (COx, SOx, NOx, ozone) and other potentially carcinogenic chemicals, etc.
3. The Kyoto Protocol of industrialized nations and Paris Agreement about carbon emissions (GHGs)
4. The generation of alternative jobs and income for growers and industrialization in developing countries (Chen and Chao 2020; Azad et al. 2016).

Thus, the increasing use of bioethanol, as a replacement for fossil fuels, has already been pushed for years, based on competitive core technology models from Brazil and the USA, which, despite being competitive and sustainable, consist of several controversial issues such as: anhydrous and hydrous ethanol prices and end uses, taxes, bioethanol policies and regulatory framework, world markets and drivers, use of different feedstocks, trade policies, flex-fuel vehicle production, market prospects, economic and energetic ethanol balances (inputs/outputs) shares of fuel and energetic balance & gasoline, industrial and beverage ethanol production, byproduct output of wet and dry milling from corn and sugarcane vinasses and development of ethanol byproduct value chain, future ethanol plants and projects as ethanolchemistry, impacts of the gasoline price and additives such as MTBE (Methyl-Tert Butyl Ether), ETBE (Ethyl-Tert Butyl Ether), or TAME (*tert*-Amyl methyl ether) etc, the total cost of producing ethanol biofuel (capital-related or fixed, variable operating, feedstock costs and byproduct and wastes prices), change of agricultural land use for food, feed, destruction of native vegetation, pollution by additional agricultural practices, methodological frameworks and approaches to evaluate the sustainability and environmental impacts such as life cycle assessment (LCA), eMergy, ecological footprint (carbon and water), and Energy Return on Investment (EROI), among many other socio-economic, political, technological and environmental issues (Yang et al. 2020).

Besides, there are other key economic factors:

- Ethanol is more expensive than gasoline and additives mainly in developing countries oil producers, except for Brazil, due to multiple factors influence the biofuels final costs such as the carbon source, crop type, production efficiency, technology among others
- Faces an unfavorable opportunity cost structure in relation to the replacement of gasoline and additives without a holistic program with stakeholder agreements.
- Feedstock price support by government with investments, tax incentives, infrastructure and research available land with high suitability to increase the productivity of current or energy crops such as sugar cane, maize etc. and increase the current agricultural frontier.
- Capital cost support.
- Income tax concessions.
- Excise tax concessions.
- Diversify markets and move gradually towards a flexible sugar mill or integrated biorefinery.
- Guaranteed (captive) markets, such as late model car owners.
- Price guarantees.
- Direct price support from government.
- The recent worldwide increase in flex-fuel automobiles, which that can use gasoline, ethanol fuel or any mixture of them

About 46% of the world's sugar (beet or cane) producing countries and 40% of the corn producers are also ethanol producers. In this regard, Balat and Balat (2009), Sorda et al. (2010); Ji et al (2016); and Ghoddusi, (2017) reviewed the world's fuel ethanol programs, public policies, and mandates. Manochio et al. (2017) provided an extensive overview of ethanol biofuel production processes as 1G and 2G from cane, corn and beet related to energy, carbon emissions and economic indicators.

Moreover, the possibility to increase production capacity in starch- and sugar-based ethanol (first generation, 1 G) and lignocelulosic ethanol (second generation, 2G) through the use of agro-industrial residues, wastes and byproducts as feedstocks in developing countries is a sustainable option because the materials are abundant and have negligible production costs, and labor is qualified and inexpensive. As a result, these regions have great comparative advantages and great potential for competitive advantages for ethanol biofuel and non-fuel production (Alalwan et al. 2019; Chang et al 2017)

The technologies used in current ethanol biofuel production are fairly mature and new advances are coming with the promise of sustainability and competitiveness, because biofuel use can provide air quality benefits in terms of lower emissions of key pollutants, such as carbon monoxide and sulfur dioxide, which leads to several questions: How "Green" is ethanol biofuel?, How large is the world and domestic potential for production?, With ethanol, is there a new future for rural communities as suppliers of raw materials?, What will be the impact on energy security and trade? These questions have been answered by stakeholders in several articles, publications and reports with three fundamental aspects of ethanol fuel (Bian & Liu, 2021; Berchi et al. 2018)

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Moreover, the key components of future success for ethanol biofuel are:

1. Feedstocks (ethanol yields per ha, ethanol yields per ton of feedstock, gross feedstock costs per liter of ethanol, energy balance by feedstock)
2. Technology
3. Policy
4. World production will continue to grow strongly

Based in advantages and disadvantages the conclusions drawn by Goldstein, (2016) are:

1. Ethanol produced by biological means is commercially viable and profitable for farmers and producers.
2. Ethanol is another valued entity in the mix of viable energy alternatives, any of which can apply depending on specific circumstances of countries.
3. The ethanol industry is *de facto* a valued partner of the petroleum industry by helping to preserve our energy supply that provides fuel for automobiles.
4. The ethanol industry can be a primary pathfinder, seeking ways via research to show how fuel blends can be more efficient.
5. The industry can serve as a primary resource to lead research to improve the environment based on its actions and the products it can develop and refine.
6. The ethanol industry can provide ways to introduce health benefits to the animal feed industry using byproducts.
7. The industry covers all facets involving the production and use of ethanol.
8. Topics include the optimization of raw materials, energy, capital, software, and human resources to produce ethanol.

2.2. Ethanol fuel facts

There are several reviews published recently concerning first, second, third and fourth generation (1G, 2G, 3G and 4G) ethanol technologies (Khan and Usmani 2016; Aditiya et al. 2016; Jambo et al. 2016; Kumar et al. 2019; Callegari et al. 2020)

These are related to cost-benefit of novel processes and technologies to convert different feedstocks into biofuels and bioproducts (ethanol biorefinery), aiming at the integrated use of these feedstock for value-added biochemicals production with multidisciplinary approaches for sustainability. Likewise, Küüt et al. (2019) reviewed several issues related to ethanol profitability, covering both 1G and 2G ethanol processes, characteristics and advantages as a biofuel, economics, energy and environmental aspects. The issues discussed are: ethanol fermentation systems, yeast physiology to optimize ethanol production and enzymes as processing aids, energy balances of ethanol production, processing and supply chain of feedstocks, physical, chemical and biological pre-treatment of lignocellulosic biomass, liquefaction, fermentation, distillation, anhydrous (water-free) ethanol production with molecular sieves and solvents, analyzing distillation energy consumption and fuel alcohol formulations and blends, co-products from ethanol production with a focus on current challenges and future opportunities of lignocellulose.

It has been fully demonstrated that 1G and 2G ethanol bioethanol have advantages because they are cheaper than fossil fuels, because are obtained through simpler processing, and they offer technical advantages (Balat and Balat, 2009). and competiveness because the ethanolchemistry (Dagle et al. 2020; Rosales-Calderon and Arantes, 2019).

Therefore, analysis of the advantages or disadvantages of ethanol production should be carried out from different perspectives:

1. Technological. Ethanol is used as a gasoline improver, with the property of boosting octane and reducing engine gas emissions (up to 108 octane). It also has higher flammability limits, higher flame velocity and greater heat of vaporization, In comparison with petroleum gasoline; ethanol is less toxic, biodegradable and generally releases fewer pollutants into the atmosphere (Mohd-Azhar et al. 2017).
2. Environmental. Studies indicate that biofuels can reduce emissions to the atmosphere. The indicators will depend on the type of biomass used and especially the agricultural land from which it is obtained (Palandri et al. 2019; Lewandrowski et al. 2020).
3. Geographical. Research is being carried out by means of simulation models using information from Geographic Information Systems (GIS); data such as agricultural land availability, input costs and environmental factors such as climate and soil are used to predict the productive potential for agro-ecological zones that can be used to increase current productivity and to have a surplus of plantation crops and the cultivation of plant species without food potential or to define low quality soils without a food vocation but with the capacity to nurture alternative plant species for ethanol biofuel production (Avtar et al. 2019).
4. Conversion of marginal lands into productive biomass lands is a subject of vigorous debate related to carbon sequestration and GHG generation; large-scale agricultural system planning should take into account that monocultures focused on the production of ethanol will inevitably have a significant negative impact on biodiversity (Muscat et al. 2019; Pancaldi et al. 2020).

Vanholme et al. (2013) and Tylecote, (2019) reviewed the fundamental aspects of sustainability considering seven major domestic and world issues: (1) integral sustainability, (2) global climate change, (3) biodegradability, (4) urban air pollution, (5) carbon sequestration, (6) national security, and (7) the farm economy.

2.3 Biofuels sustainability

Nunes et al. (2020); Eckert et al. (2018) and Martinez-Hernandez and Samsatli, (2017) concluded with reference to environmental and socioeconomic goals the following elements must be considered: (1) ethanol plants should use biomass as energetic (bagasse, sugarcane trash, straws, husks, shells, forest residues, corn waste) and not fossil fuels as fuel oil or natural gas, (2) cultivation of annual feedstock and energy crops should be avoided on land rich in organic carbon, prioritizing marginal lands (3) ethanol production by-products (mainly vinasses, dried distillers grains and yeast) should be utilized efficiently in irrigation, composting and feed in order to maximize their energy, nutrients, fiber and GHG benefits, (4) nitrous oxide emissions should be kept to a minimum by means of efficient fertilization strategies, usage of manures and agroecological energy crop management and (5) appropriate methodological frameworks should be implemented to evaluate the ethanol biofuel value chain and sustainability.

If ethanol biofuel is projected to be used in developing countries with a complex number of vehicles of different ages and models, it seems clear that combustion characteristics will need to be evaluated, and adjusted with emission controls devised that will allow ethanol biofuel to meet these environmental standards according the performance of combustion in vehicles. Therefore, it will be desirable to use a low percentage of biofuels in the blends, to allow increasing use in the future according to the climate, elevation and type of vehicles in circulation, and to adapt to changing costs and availability of the ethanol biofuel and fossil fuel components (Tibaquiráet al. 2018).

In relation to the above, the Mexican automobile production industry has no flexible-fuel capability to use an anhydrous bioethanol/gasoline blend and the authorized company to blend ethanol with gasoline in Mexico is *Petróleos Mexicanos* (PEMEX).

3. Data and Methodology

This review was carried out to study the challenges and potential to produce ethanol from sugarcane in Mexico with the analysis of scientific literature proposed by Koutsos et al. (2019) during the last years and to understand their impact on the overall performance of the Mexican sugar mills before the objective of the productive reconversion to ethanol and electric cogeneration plants. These primary data along with secondary data from the sugar industry (technological and socioeconomic statistics) formed the basis for the analysis.

4. Mexican ethanol biorefinery from sugarcane

Sugarcane in Mexico is an agroindustry with 500 years of history that has created producing regions, popular culture and traditions related to sugarcane plantations, trapiches and sugar mills which have been studied by various disciplines such as chemical and agronomic engineering, economy, anthropology, sociology, geography, history, and others by Mexican and foreign researchers.

However, although there are various technological developments and management practices that would increase productivity by reducing pollution, production costs and expanding the value chain beyond the production of sucrose (raw, standard, refined, muscovado etc.), the low level of coordination and holistic solutions among stakeholders mainly farmers, ethanol producers, traders, sugar mill owners, technology and agrochemical companies, government, universities, researchers, shipping firms, logistics companies, PEMEX, CFE, and users of cane derivatives, industrial and beverage ethanol is the main characteristic of this agribusiness.

Furthermore, the political, socio-economic, environmental, business and academic debate of stakeholders, as well as the technologies employed for cogeneration, as a necessary complement for the joint production of ethanol, sugar, steam and electric energy under the concept of biorefining in sugar mills, remain largely unchanged since the establishing of last Decretos cañeros (1991) and the current legislation of 2005 (Law of sustainable development of sugar cane) and the national program of sugar agroindustry (PRONAC) of each presidential sexennium by the National Sustainable Development Commission of Sugarcane (CONADESUCA).

In this regard, only the production of ethanol derived from molasses is considered in the annual statistical reports. Moreover, the ethanol in turn is imported, for the needs of the domestic food, beverages, chemical and pharmaceutical industries, as non-fuel ethanol or denatured and undenatured ethanol, of at least 80 degrees GL, from countries such as Brazil, the United States, Canada, the United Kingdom, Colombia, Guatemala, and Australia, among others (García-Chávez, 2014).

In the entire sugarcane value chain: raw material production, industrial processes, fermentations, distillation, vinasses uses and several environmental and socioeconomic impacts of the current low production of ethanol (as bioproduct) and low sugarcane yield (t ha^{-1}) (as raw material) with a high harvested area and sucrose monoproduction (Figures 3 and 4) are constraints of high controversy among stakeholders for future prospects in the use of this renewable feedstock to biofuel and its integration with sugar production in Mexico that have not been resolved.

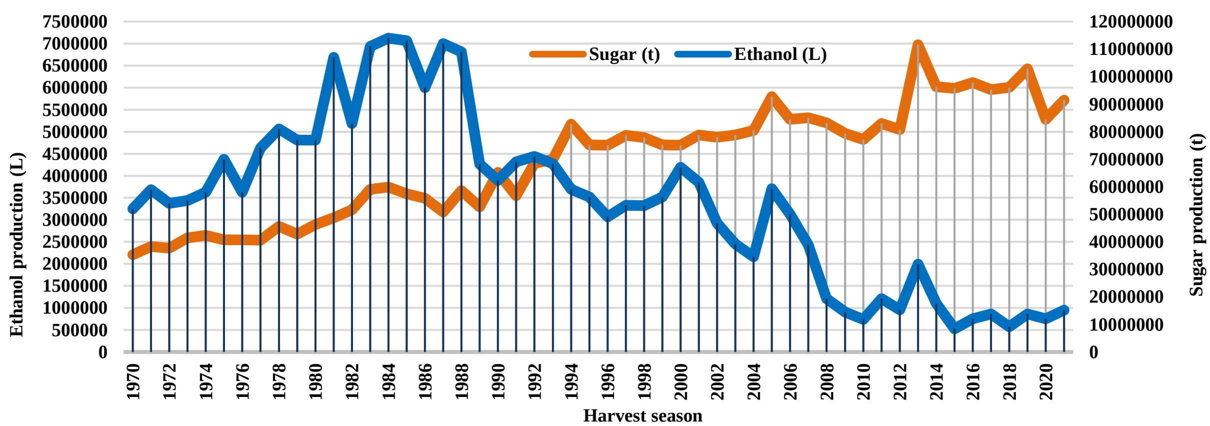

Figure 3. Ethanol and sugar production 1970-2021
Source: Data from CONADESUCA, 2021 and INEGI, 1994

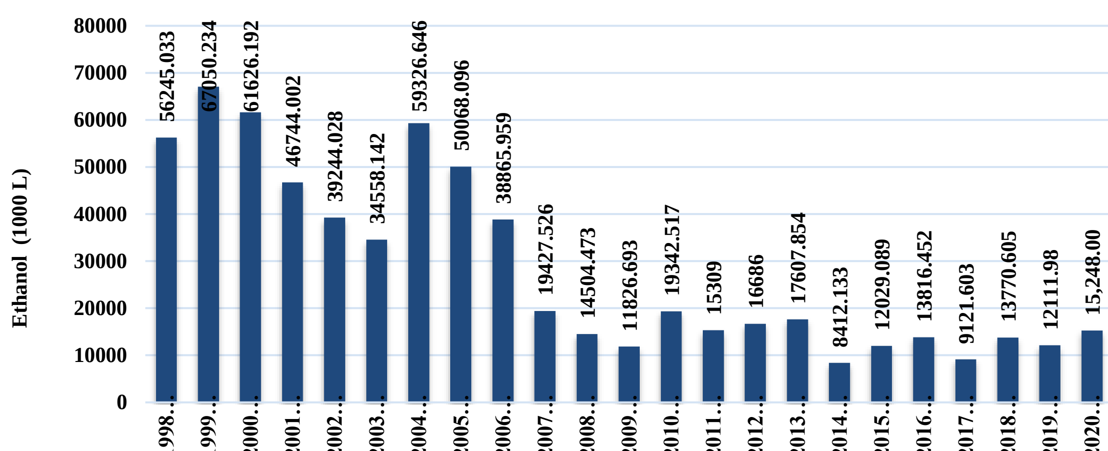

Figure 4. Historical ethanol production from sugarcane
Source: Data from CNPR, 2021 and CONADESUCA, 2021

The indicators show that the sugar industry has displaced ethanol production for several decades, and the sugar mills have a productive structure based on producing exclusively sugar with the increase in the area planted with stagnant or low yields, consequently an underutilization of the technological potential of sugarcane (Figures 5 and 6)

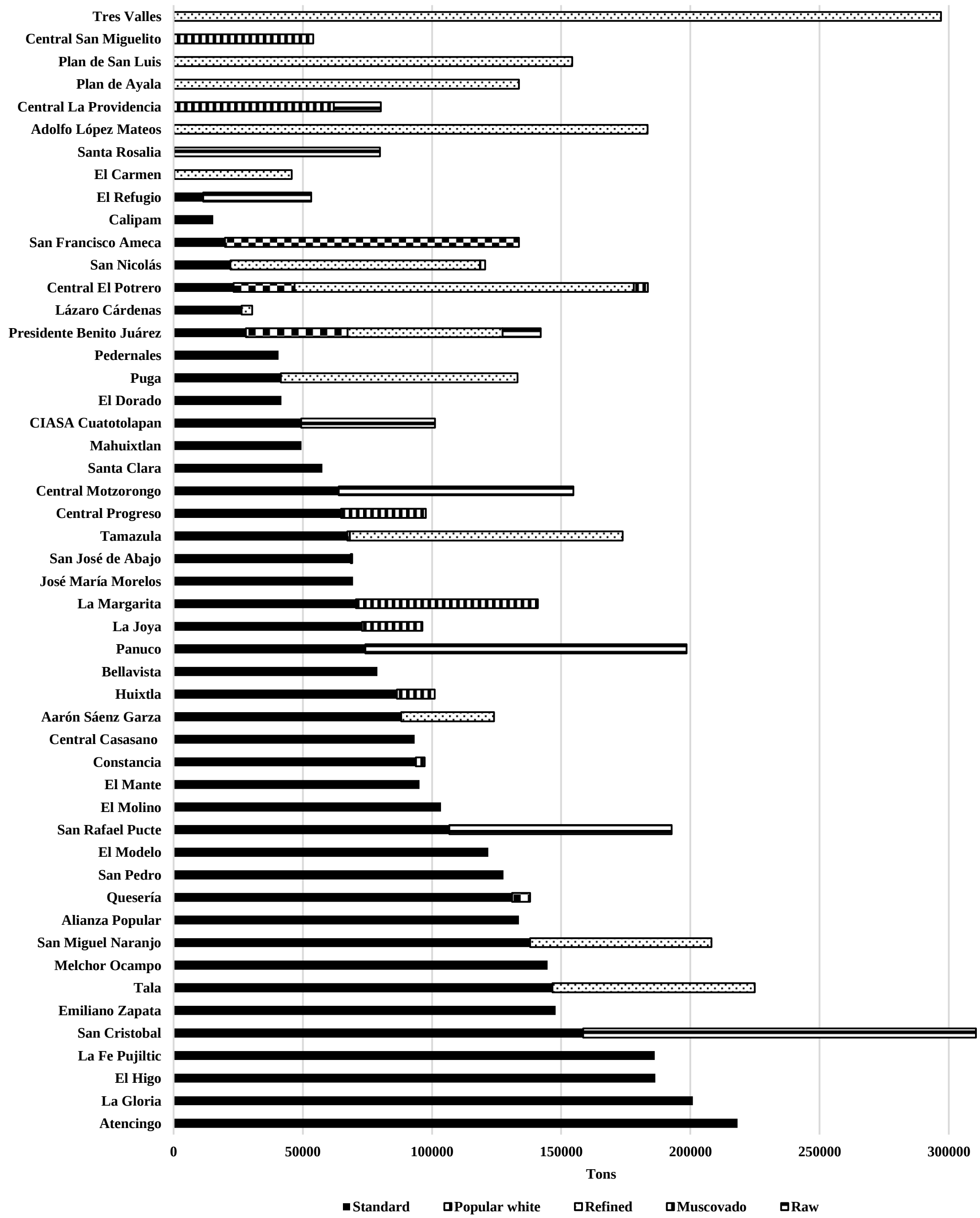

Figure 5. sugar production harvest season 2019/2020
Source: Data from CONADESUCA, 2021

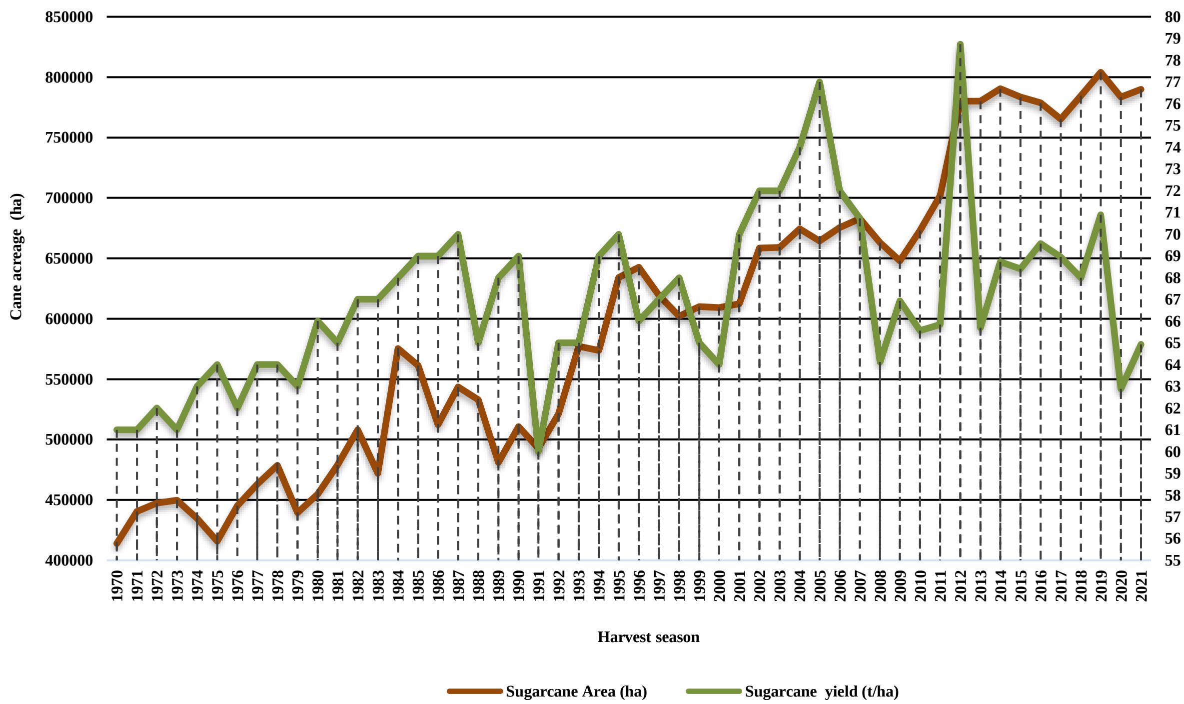

Figure 6. Harvested area and cane yield 1970-2021
Source: Data from CONADESUCA, 2021 and INEGI, 1994

This situation was seen directly during the harvest season 2020/2021 an area of 789,996 ha was industrialized with a cane production of 51,292,545 t with a field yield of 64,93 t ha^{-1}. The sugar production was 5'715,448 t, factory yield 11.14% and agroindustrial yield 7,23 t/ sucrose/ha. The sucrose production was classified by sugar qualities: Refined sugar 1'348,267 t, standard sugar 3'410,438 t, special white sugar 182,721 t, muscovado 35,876 t and raw 738,146 t. and ethanol production of 15'248.167,00 L.

Therefore, the production of ethanol under current conditions is not viable, mainly due to the lack of demand for automobiles, the low productivity of the field without determining a differentiated price of the sugarcane destined for this purpose. There is no program or public policy that allows directing the sugar agribusiness towards improving productivity and/or taking advantage of the opportunities that ethanol represents (Carrillo-Nieves et al. 2019).

Changes are required in the policies that currently support the sugar industry such as the establishment of a free market for sugar cane outside the context of the Sustainable Development Law of Sugar Cane (LDSCA), or linking the price of ethanol to the payment of cane. Encourage investment projects related to the diversification of the uses of sugarcane to transfer technology and capital. The labor-management relations, outside the contract, the related Sugar Industry Laws, and the Sugarcane Production Committee.

The attainment of these targets, to move to a new competitive model of the sugar industry and use of byproducts such as biorefineries and ethanol biofuel, requires major policy decisions which should be taken as soon as possible.

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In relation to the above,

1. In Mexico 178 000 growers of sugarcane sell sugar mills
2. Zero child labor achieved in all sugar factories
3. Commitments of zero child labor in field (OIT program) and sugarcane cutter certification
4. Education provided to elderly people working in sugar mills
5. Bonsucro and other certifications in progress in some sugar mills
6. Numerous sugar cane producing regions are agroecologically suitable and have comparative advantages

Additionally, its necessary to make better decisions on technological and socioeconomic issues, agricultural land management, agroindustrial byproducts disposal, stakeholder opinions and formulation, monitoring and implementation of public policies under uncertain conditions and domestic needs of cane regions

Notwithstanding, the lack of efficient public policies for Mexican sugarcane agroindustry makes it difficult for stakeholders such as growers, and investors of sugar mill owners to make informed decisions about the economic viability of entire cane biomass utilization for ethanol biofuel. Besides the price paid for sugar cane in Mexico is high and there is no value addition with the production of biofuels, cogeneration and other bioproducts (Figure 7)

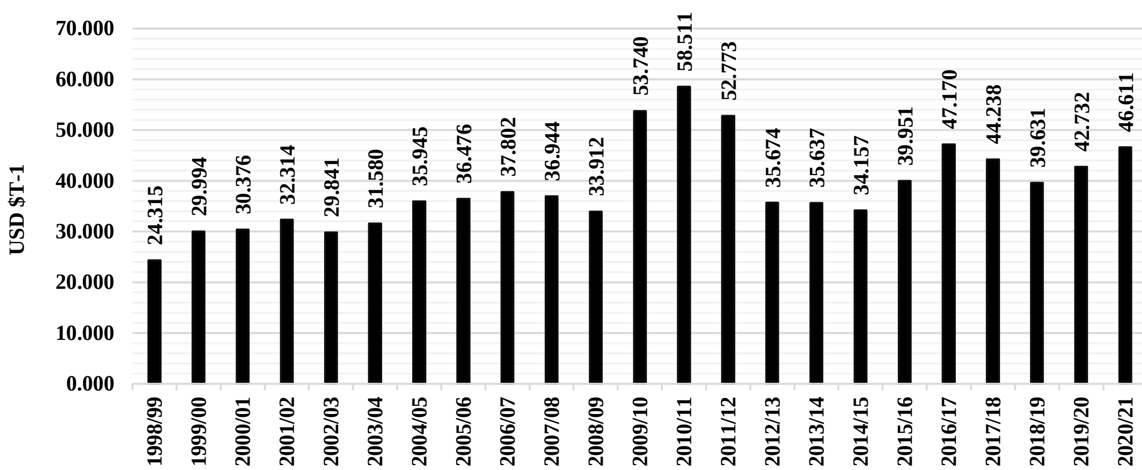

Figure 7. Cane price paid for sugar cane in Mexico by sugar mills (USD / t)
Source: Data from CONADESUCA, 2021

Therefore, the high price of cane as a raw material for sugar has created a productive inertia and is a factor that, together with stagnant productivity, limits the diversification of cane stalks and harvest residue towards other business options or is marginal such as piloncillo and livestock production.

In the particular case of the ethanol, the global trend has been driven mainly by environmental pollution and the reduction of oil reserves. Efforts have focused by Mexican researchers on the development of several technologies to achieve greater efficiency and performance in yield of ethanol with high profits. However, it is necessary to analyze the implications of ethanol biofuel from a perspective that allows to approach the factors complexity involved in the context of each region or sugar mill to obtain ethanol biofuels and bioproducts from byproducts (vinasse, yeast, CO_2) by observing the socio-economic generation and use of raw materials, available and future technologies, political, spatial, technological and environmental implications of the transition to a biofuel economy (Islas-Samperio et al. 2020; Aguilar-Rivera et al. 2019; Carrillo-Nieves, et al. 2019).

In Mexico, according to Islas-Samperio et al. (2020) and Aburto and Hernandez, (2020), there are technological, environmental and social conditions (soil, raw materials, qualified labor, etc.) through multidisciplinary research, carried out by researchers at universities and research centers. Consequently, there are comparative and competitive advantages for the production of ethanol from sugarcane to improve the performance of gasoline and mainly reduce Volatile organic compounds (VOCs) from gasoline evaporation (Mugica-Alvarez et al. 2020). However, to date there are no concrete agreements so that national ethanol producers (sugar mills) can sell a potential production to Petroleos Mexicanos (PEMEX) and the parastatal company carry out the logistical and technological operations for the mixture and distribution of gasoline and ethanol as established by the official Mexican standard NOM-016-CRE-2016, about the maximum content of ethanol in gasoline at the national level with reductions of ozone (O_3), especially the Metropolitan Zones of the Valley of Mexico, Guadalajara and Monterrey based in research results of the use of ethanol in gasoline (Koupal and Palacios, 2019) and other pollutants not derived from the combustion of ethanol

In relation to the above, it is required a national ethanol program developed by the stakeholders of the sugar industry that allows: Revalue the inertial cultivation of sugar cane so that the sale price does not depend exclusively on the volatility and geopolitics of sugar in the national and international market, which each year loses profitability and competitiveness due to the incorporation of other sweeteners such as corn syrup of high fructose (HFCS) and stagnant sugarcane productivity or affected by environmental factors, the burning of cane fields, conventional management practices, the impact of climate change and others and the marginal reconversion or productive diversification.

Self-sufficiency of ethanol for all industrial uses, pharmaceuticals, perfumery beverages and currently for the production of antibacterial gel and reduce imports

Installation of new distilleries in the face of uncertainty in current public policies and future prospects in renewable energies

Therefore, if the complexity generated by the lack of agreements between the stakeholders for a national ethanol program is resolved, the following scenarios should be considered:

1. Establish production from the main agribusiness in Mexico, that is, the sugarcane industry due to experience in cultivation and processing, existing technology that can be significantly improved with technological developments by Mexican researchers to increase productivity and profitability without involving considerable increases of new agricultural land, water and inputs or compromise the production of food, sucrose or molasses in all its types under national and regional conditions

2. Initiate an ethanol production program in the main sugarcane producing area, the state of Veracruz, which presents ideal agroecological conditions today underused as the most important university in the southeast with a postgraduate degree in sugarcane and numerous research centers and technological institutes, technological universities, besides high poverty and rural marginalization that could be improved by creating infrastructure for the production of sugarcane and ethanol. This scheme represents for Mexico an opportunity for employment, investment and promotion of other types of alternatives for the main producing state of the sugarcane agribusiness.
3. If PEMEX does not have technological or financial capabilities for the production and distribution logistics infrastructure to handle ethanol-gasoline mixtures, encourage private investment that could come directly from sugar groups. However, it is not ruled out that PEMEX and CFE give certainty regarding the use of bioenergy in the medium term.
4. The sugar groups could satisfy the national demand for ethanol and electric energy cogeneration, export and explore the production of Second-Generation ethanol and chemical ethanol as a complement to the production of first-generation ethanol (Bautista-Herrera et al. 2021)

The self-sufficiency of ethanol in its anhydrous or hydrated type to satisfy the current needs of the food and beverage, pharmaceutical, perfumery industries, and as a biofuel or oxygenate for gasoline requires the transition of the current sugar agribusiness in three options.

1. Reconversion of mills very low productivity sugar mills (high consumption of external energy such as fuel oil or electrical energy), low level of utilization of installed capacity and high level of losses in the handling of cane to distilleries based on cane juice, molasses or both.
2. The revitalization of distilleries attached to most efficient sugar mills considering the use of cane juice, molasses A, B or C and energy self-sufficiency with harvest residues and bagasse.
3. The installation of autonomous distilleries based on cane juice or molasses.

In all three cases, it is essential to consider the gradual reduction of the harvest with the burning of cane fields, agroecological cultivation, optimization of inputs and technical irrigation and good management practices to increase productivity with the same area and therefore the increasing availability of the residue of harvest as an energy source in the own distillery, sugar mill and a cogeneration system and other derivatives (Klein et al. 2019; Cardoso et al. 2019).

Besides is fundamentally necessary to establish a constant link with universities and research centers to optimize the processes of sustainable production of sugarcane, sugar, anhydrous and hydrated ethanol, handling of by-products, and logistics, administrative, financial and environmental management processes and looking for ISO certifications and BONSUCRO.

In a national sugarcane biofuel ethanol program, entrepreneurs and owners of sugar mills must strongly consider various aspects such as strategic relationships with stakeholders, conflicting goals and participation of the automotive industry, economic valuation, finance and business strategy, carbon, capitals, and futures markets, climate change risk management and corporate social responsibility (CSR) (Figure 8) because ethanol projects are highly strategic, therefore their valuation should not be based solely on technological or market analysis, but on real options and other industry-specific methodologies.

Figure 8. corporate social responsibility (CSR) for ethanol industry
Source: Data from Sawaengsak et al. 2019; De Rosa, 2018; Souza et al. 2018

The ethanol program in the state of Veracruz should consider several stages to resolve multidimensional limiting factors step by step according to López-Ortega et al. (2021) and Klein et al. (2019) employ some of the expertise acquired by Brazil during its transition from typical sugar mills into advanced biorefineries or integrated sugar-agro-complex to retrofit the Mexican sugar industry (Figure 9)

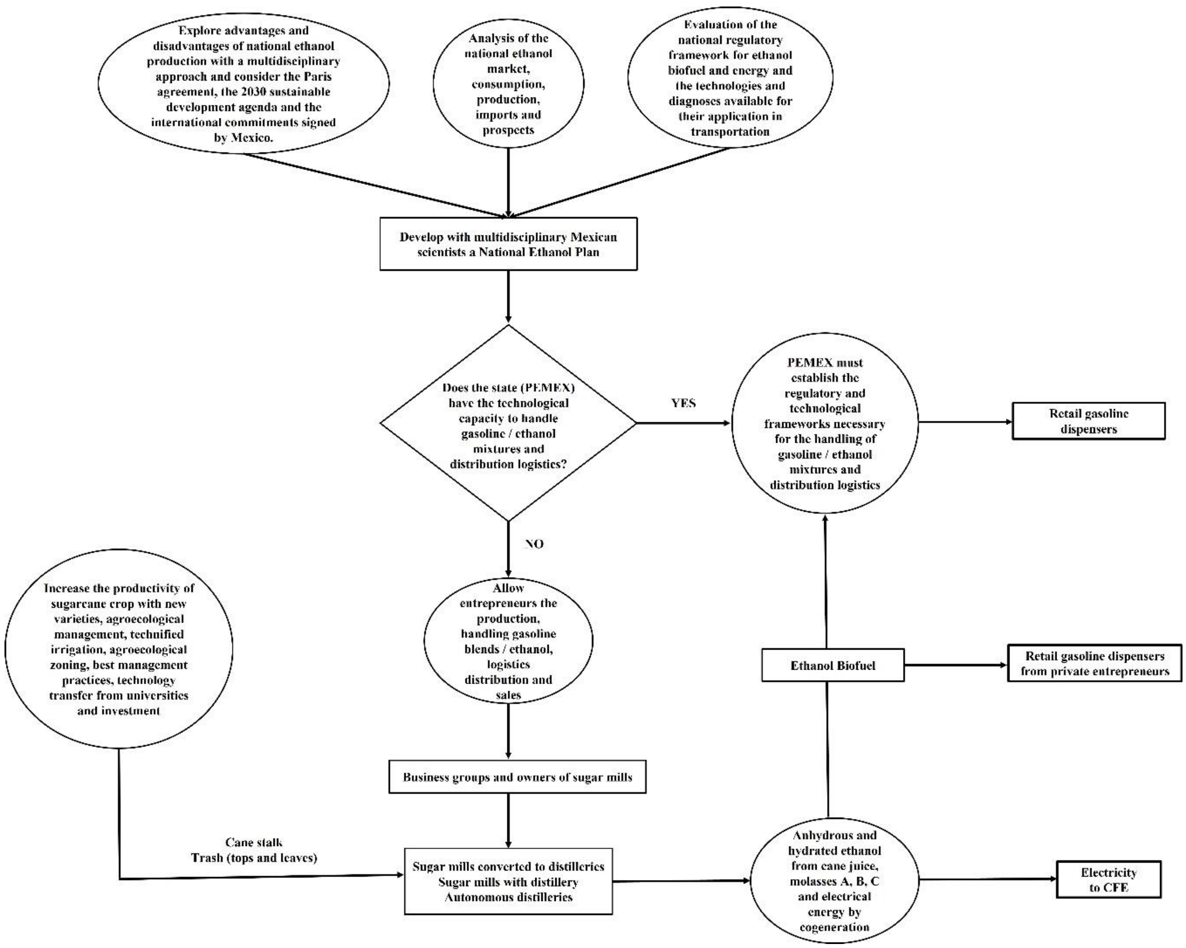

Figure 9. National program of ethanol biofuel from sugarcane

6. Veracruz Mexico and the challenges for the production of sugar, ethanol and energy

The state of Veracruz covers an area of 71,826 km^2 in northeast Mexico. The climate is warm subhumid and warm humid, with an average annual temperature of 23 ° C and average annual rainfall of 1,500 mm. It is Mexico's third most populous state with 8,112,505 inhabitants. In addition, 38,9 % of the population in the state lives in towns with less than 2,500 inhabitants, making it the state with the largest rural population in the country. The state is made up of 212 municipalities,

Veracruz is the third state of 32 with the largest population in poverty with where the 33 % are indigenous. Today, Veracruz residents are subject to increasing insecurity due to the rise in organized crime activity, including drug trafficking. Nationally, Veracruz is the state with the fourth lowest Human Development Index (HDI), just after Chiapas, Oaxaca and Guerrero. At the same time, state residents suffered the greatest decrease in real labor income in the period 2010 to 2020 and a considerable number of people live in extreme poverty (Table 1).

Table 1. Poverty indicators in Veracruz (%)

Poverty /Year	**2008**	**2010**	**2012**	**2014**	**2016**	**2018**	**2020**
Population in poverty	51,2	57,6	52,6	58,0	62,2	60,2	58,6
Population in moderate poverty	34,3	38,8	38,4	40,9	45,8	44,0	44,7
Population in extreme poverty	16,8	18,8	14,3	17,2	16,4	16,1	13,9
Vulnerable population due to social deprivation	32,7	23,6	30,6	24,8	19,9	20,7	21,7
Vulnerable population by income	3,1	4,5	4,0	5,0	5,0	7,0	5,9
Non-poor and non-vulnerable population	12,9	14,3	12,8	12,2	12,9	12,2	13,7
Social deprivation							
Population with at least one social deprivation	83,9	81,2	83,2	82,8	82,1	80,9	80,4
Population with at least three social deprivations	46,7	41,9	36,9	37,3	33,4	35,0	36,8
Indicators of social deprivation							
Educational backwardness	28,4	25,8	25,8	27,8	25,7	26,4	27,8
Lack of access to health services	42,9	34,9	25,7	21,7	19,4	16,7	31,0
Lack of access to social security	72,1	69,2	68,5	68,5	68,0	65,7	65,2
Lack of quality living space	30,5	24,0	19,7	16,8	17,5	16,9	15,0
Lack of access to basic housing services	42,7	39,3	39,2	40,0	39,2	42,1	37,8
Lack of access to food	25,6	26,1	28,2	30,0	22,2	28,5	24,4
Wellness							
Population with income below the extreme poverty line by income	20,8	27,8	24,0	29,2	30,6	26,2	24,4
Population with income below the income poverty line	54,3	62,1	56,6	63,0	67,1	67,1	64,5

Source: CONEVAL 2021

In contrast, it has the geographical, climate and soil conditions conducive to carrying out competitive agricultural activities as agriculture, livestock farming, forestry, hunting or fishing; however, low returns are obtained. There are several product systems operating in the state that cover the most economically important crops in Mexico. However, most of these crops require a larger acreage to reach these indicators, one of the most important being sugarcane (Figure 10).

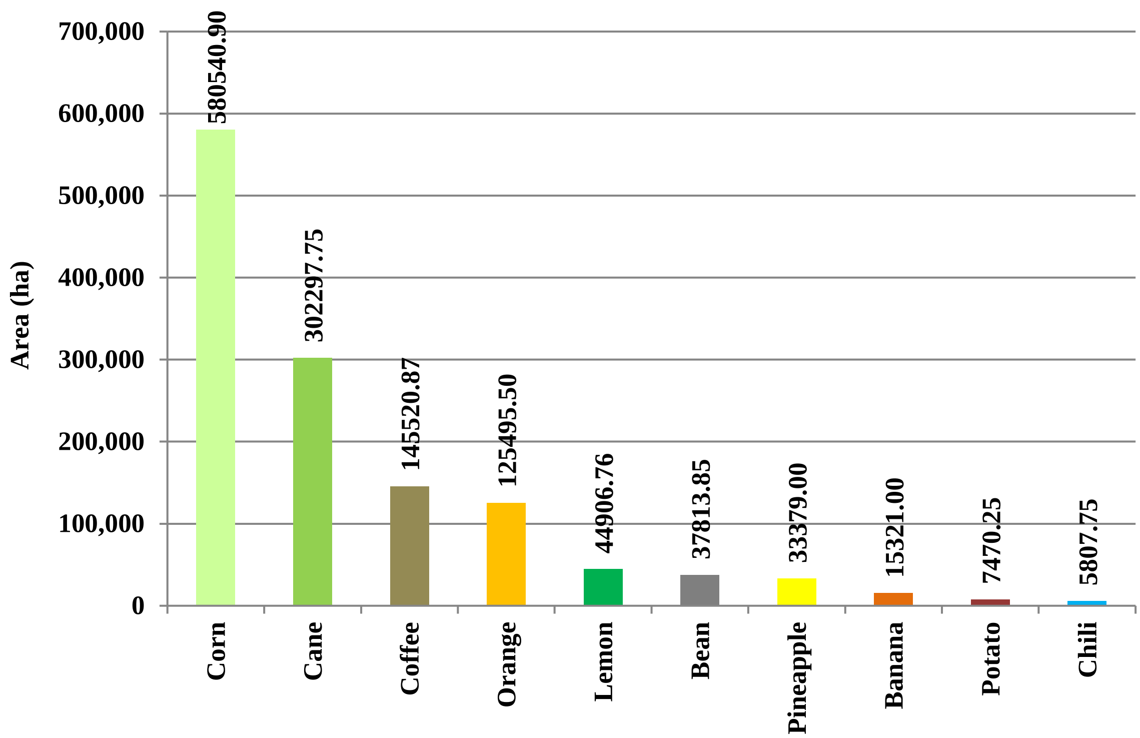

Figure 10. Crop area of Veracruz, Mexico
Source: Data from SIAP, 2021

In this context, the agricultural sector has two major challenges. On the one hand, the productive performance of crops such as sugarcane, fruit species and other crops with potential must be improved through the accumulation of capital by small producers, because the 10 most important crops represent 88% of the planted area of the state of Veracruz and their conversion to more productive crops and the use of byproducts with a firm basis in sustainability and the circular bioeconomy is a priority. Moreover, the great variety of crops that are cultivated should use sustainable technologies to increase productivity and the value chain by exploiting the state's comparative advantages.

In this sense, in the state of Veracruz there are 173 municipalities where sugar cane is grown for delivery to sugar mills, trapiches, livestock farmers as survival food and other uses of which 92 are the most significant for the sugar agroindustry having the indicators presented in table 2 and Figure 11

Table 2. Sugar industry indicators in Veracruz Mexico

Indicator/Harvest season	**1999/2000**	**2019/2020**	**Difference (%)**
Cane production			
Number of sugar mills installed	22	18	-18,182
Average duration of crushing (Days)	173	148	-14,451
Average cane yield (t/ha)	74,17	56,587	-23,706
Sugar yield (t/ha)	8,111	5,766	-28,911

Area under sugarcane cultivation (ha)	241256	325405	34,880
Sucrose % cane	13,490	13,349	-1,045
Fibre % cane	13,14	13,421	2,139
Cane harvested with burning (%)	93,3	90,063	-3,469
Cane mechanically harvested (%)	7.110	12.554	76,568
Cane mechanically loaded (%)	76,281	73,018	-4,278
Sugarcane price ($/t)	30,8	43,75	42,045
Sugar mill			
Sugarcane production (t)	17262712	17630181	2,129
Brix % clarified juice	16,270	15,38	-5,470
Sucrose loss (%)	2,25	2,358	4,800
Sucrose recovery rate (%)	82,883	81,088	-2,166
Sugar mill Yield (%)	11,01	10,191	-7,439
Total time loss (%)	25,90	17,33	-33,089
By products			
Sugar (t)	1956940	1876437	-4,114
Raw sugar (t)	807053	1383021	71,367
Refined Sugar (t)	1121062	490114	-56,281
Muscovado Sugar (t)	28825	3304	-88,538
Ethanol (L)	41778451	1841991	-95,591
Ethanol per tonne of molasses	290,75	235,639	-18,955
Molasses (85º Brix Total)	618105	713691	15,464
Molasses per tonne of cane	36,048	38,759	7,521
Molasses for ethanol (t)	70907	7817	-88,976
Filter Mud (Filter Cake) (t)	741761	866495	16,816
Filter Mud (% cane)	4,487	4,915	9,539
Bagasse (t)	5175583	5457673	5,450
Bagasse % cane	29,17	29,639	1,608
Bagasse for derivatives (t)	437117	10392	-97,623
Cogeneration (KWH)	268846821	488124576	81,562
Steam generation (energy) (t)	10664242	10166781	-4,665
Energy and termal balance			
External electricity (KWH)	15031898	15063889	0,213
Petroleum consumed in sugar mill (L)	296437388	7664012	-97,415
Petroleum (consumption per tonne of cane)	13,575	0,378	-97,215
Electricity consumption per tonne of cane	16,527	17,528	6,057
Steam (consumption per tonne of cane)	0,610	0,552	-9,508

Source: CNPR, 2021, CONADESUCA, 2021

No.	Producing municipality	No.	Producing municipality
1	ACAYUCAN	47	MARTINEZ DE LA TORRE
2	ACTOPAN	48	MISANTLA
3	ACULA	49	NAOLINCO
4	ALTO LUCERO DE GUTIERREZ	50	NARANJAL
5	ALVARADO	51	NARANJOS AMATLAN
6	AMATITLAN	52	NAUTLA
7	AMATLAN DE LOS REYES	53	OMEALCA
8	ANGEL R. CABADA	54	OTATITLAN
9	ATOYAC	55	OZULUAMA
10	ATZACAN	56	PANUCO
11	BANDERILLA	57	PASO DE OVEJAS
12	BENITO JUAREZ	58	PASO DEL MACHO
13	CAMARON DE TEJADA	59	PLATON SANCHEZ
14	CARRILLO PUERTO	60	PUENTE NACIONAL
15	CATEMACO	61	RAFAEL DELGADO
16	CHACALTIANGUIS	62	RIO BLANCO
17	CHALMA	63	SALTABARRANCA
18	CHICONAMEL	64	SAN ANDRES TUXTLA
19	CHICOTEPEC	65	SANTIAGO TUXTLA
20	COATEPEC	66	SOCHIAPA
21	CHINAMPA DE GOROSTIZA	67	SOLEDAD DE DOBLADO
22	CHOCAMAN	68	TAMPICO ALTO
23	COETZALA	69	TANTOYUCA
24	COMAPA	70	TECOLUTLA
25	CORDOBA	71	TEMPOAL
26	COSAMALOPAN	72	TEOCELO
27	COSAUTLAN DE CARVAJAL	73	TEPATLAXCO
28	COTAXTLA	74	TEPETLAN
29	CUICHAPA	75	TEZONAPA
30	CUITLAHUAC	76	TIERRA BLANCA
31	EL HIGO	77	TLACOJALPAN
32	EMILIANO ZAPATA	78	TLACOTALPAN
33	FORTIN	79	TLACOTEPEC DE MEJIA
34	HUATUSCO	80	TLATETELA
35	HUEYAPAN DE OCAMPO	81	TLILAPAN
36	IXCATEPEC	82	TOMATLAN
37	IXHUATLANCILLO	83	TOTUTLA
38	IXMATLAHUACAN	84	TRES VALLES
39	IXTACZOQUITLAN	85	TUXTILLA
40	JALCOMULCO	86	URSULO GALVAN
41	JILOTEPEC	87	VEGA DE ALATORRE
42	JOSE AZUETA	88	VERACRUZ
43	LA ANTIGUA	89	XALAPA
44	LERDO DE TEJADA	90	XICO
45	MANLIO FABIO ALTAMIRANO	91	YANGA
46	MARIANO ESCOBEDO	92	ZENTLA

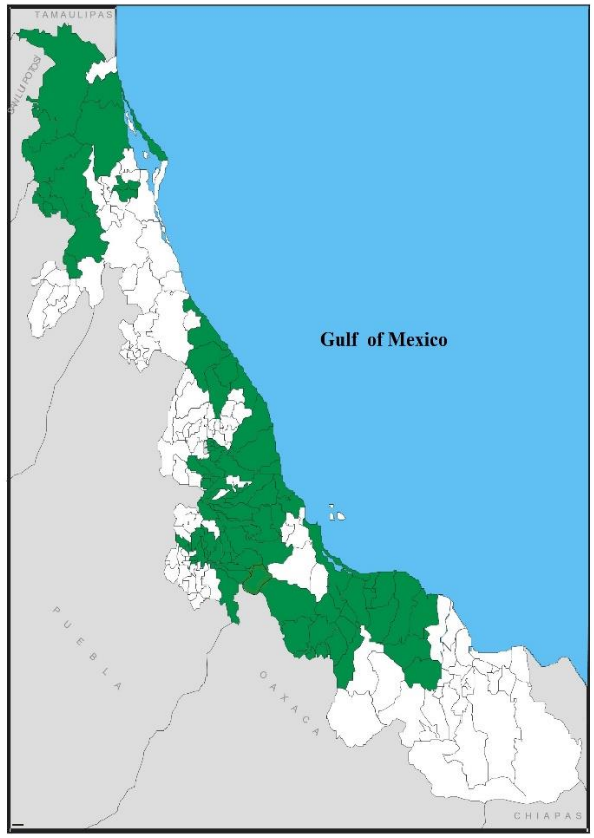

Figure 11. Sugar cane producing municipalities for sugar mills

In the 2020/2021 harvest season there was a planted area of 302,297.75 ha, 294,777.75 ha harvested with an average productivity of 65,083 tha^{-1} distributed in 18 supply areas to sugar mills (Table 3)

Table 3. Sugar industry indicators in Veracruz Mexico harvest season 2020/2021 (Zafranet, 2021)

Sugar mill	Cane yield (t/ha)	Factory yield (%)	Agroindustrial yield (t/ha)	Factory efficiency (%)	Pol % cane	% Fiber	Purity of mixed juice (%)
El Modelo	92,298	10,339	9,54	80,494	12,778	14,544	83,078
La Gloria	83,09	11,126	9,24	83,58	13,27	14,422	80,954
Mahuixtlán	69,519	10,548	7,33	84,991	12,34	12,751	83,332
Central San Miguelito	68,422	9,935	6,8	81,736	12,037	13,388	77,616
Pánuco	66,068	11,25	7,43	80,229	13,926	14,732	83,799
Central Motzorongo	64,907	10,642	6,91	82,475	12,813	12,44	81,63
San Nicolás	64,105	9,909	6,35	79,969	12,357	13,56	80,905

Central El Potrero	63,738	10,714	6,83	77,724	13,771	13,121	83,671
El Higo	63,478	11,275	7,16	83,501	13,426	13,391	80,963
Plan de Ayala	62,307	11,765	7,33	81,114	14,493	13,127	83,899
San José de Abajo	62,019	10,432	6,47	78,894	13,399	13,437	80,769
San Pedro	61,245	9,4	5,76	81,865	11,447	13,598	77,81
Central La Providencia	60,484	10,717	6,48	83,253	12,763	13,633	80,433
El Carmen	59,998	8,479	5,09	75,209	11,243	14,245	78,894
Constancia	57,992	10,069	5,84	82,98	12,079	13,4	76,939
Tres Valles	51,471	11,014	5,67	83,611	13,16	14,829	83,672
CIASA (Cuatotolapam)	51,405	11,237	5,78	83,234	13,408	14,096	82,552
Central Progreso	51,391	12,302	6,32	83,847	14,595	13,317	83,959
San Cristóbal	50,6	10,273	5,2	81,004	12,582	14,96	79,516
Average	65,083	11,151	7,26	82,428	13,227	13,261	80,493

The cultivation and processing of sugarcane, according to its indicators in 20 years and the las harvest season (2020/2021) represents an inertial and stagnant agribusiness, without growth options that are reflected in a decrease in the production of superior quality sucrose such as refined and muscovado, an increase in the production of low quality sugar as standard and raw, the disastrous reduction of 95.6% in the production of ethanol in addition to a reduction in the field and agro-industrial yield with increase in the harvested area, generation of by-products and the price of sugarcane on the rise due to an increase in production costs and low profitability. Among the indicators, the almost total reduction in oil consumption is important, but agribusiness is still dependent on external electricity. Some of the causes are:

- Smallholder ejidal agriculture
- Deforestation by the slash-and-burn method to expand the agricultural frontier
- Lack of application of precision agriculture strategies, agro-ecological zoning, subdivision and compaction of ranches, best management practices that increase productivity, profitability and reduce production costs
- Inertial management practices based on experience in monoculture and burning harvesting for old crop varieties
- High use of agrochemicals without technical recommendations
- Low technology transfer in sugarcane production and processing in sugar mills
- Rainfed cultivation highly vulnerable to environmental changes (rains, floods, droughts and their consequences)
- Monoculture for the mono production of sugar supported by public policies, federal government institutions, unions and owners of sugar mills

Therefore, significant changes are required in monoculture, the productive structure, energy self-sufficiency, production costs and profitability and in general the revaluation of sugarcane and by-products within the approaches of circular bioeconomy and sustainable development in the face of changes in the global sugar consumption patterns that will necessarily imply a reduction in the demand for this sweetener and the potential projects to diversify the use of sugarcane (sucrochemical, ethanolchemical, lignochemical, etc.).

7. Agroecological zoning of sugarcane cultivation

The regionalization or agroecological zoning of the sugarcane crop is a tool that would allow the evaluation and determination of the productive surface susceptible to the implementation of bioenergetic projects for the production of anhydrous ethanol and the cogeneration of electrical energy, defining the zones and the potential in tons of sugarcane per hectare and the agro-industrial yield, in liters of ethanol and KWH per ton of sugarcane that allows a profitable and synergistic sharing. That is, to produce raw material, with the current surface area, reducing inputs mainly fuels, agrochemicals, land and water and consequently reducing production costs, environmental impacts and optimizing inputs, variety replacement, reducing the harvest with burning and generating new productions of harvest waste, management of impacts of climate change, direction of management practices, mechanization and harvest, minimizing restrictions or limiting factors to the possible expansion of crop in the future.

For the agroecological zoning modeling, the MaxEnt software (Gao et al. 2021; Kogo et al. 2019) was used, which is based on the maximum entropy theory, whose mathematical foundation determines the environmental variables that intersect at the georeference point of the presence of the crop to be analyzed generating zoning as a spatial decision-making instrument generating cartography in a Geographical Information System (ESRI ArcMap 10.1), (Figure 12)

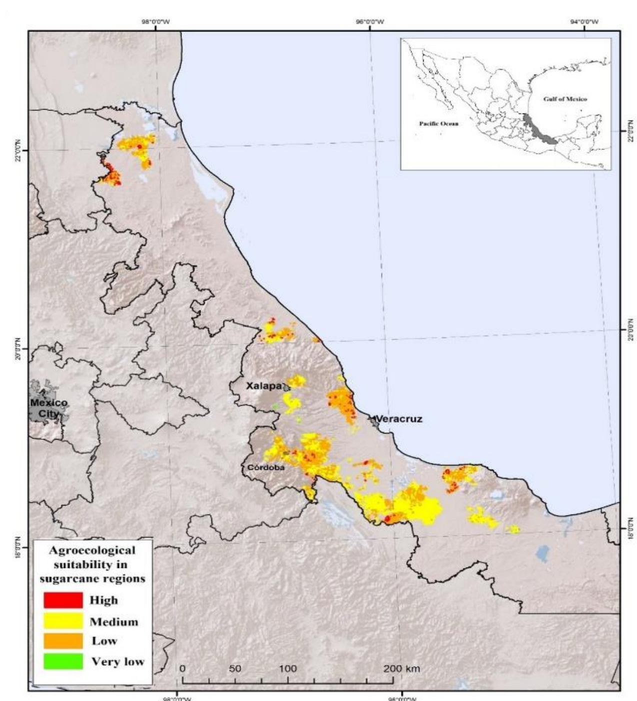

Figure 12. Agroecological zoning of cane areas in Veracruz, México

Of the total of the Veracruz area currently destined to the cultivation of sugarcane, 4.186% presented an average aptitude or high agroecological potential, 57, 114% medium 38.643% low and 0.057% very low. As a result, sugarcane production in different regions of sugar mills needs different use of new crop varieties, environmental management techniques and stakeholders participation to increase productivity reducing cost.

Sugarcane regions of high potential are located in the Higo Sugar Mill, medium potential areas are grouped around El Modelo, La Gloria, Central El Potrero, San José de Abajo, Central San Miguelito, San Pedro, Panuco, Central Progreso, La Constancia, San Nicolás, Central Motzorongo, Central La Providencia and El Carmen sugar mills. Most of the area with low potential is in the region of Mahuixtlan, CIASA Cuatotolapan, San Cristobal and Tres Valles areas

8. Strategies to produce ethanol in sugar mills

Evaluate the distance and strategic location to mixing and distribution centers and in the future to PEMEX refineries.

Incorporate cogeneration schemes in the mills for the steam and energy needs of the sugar and ethanol production processes and the surplus can be offered to CFE and / or associated companies or nearby cities.

Employ adequate technology and infrastructure for the treatment of stillage to agricultural irrigation and considering the recovery of yeast as livestock feed.

For sugar groups, it may be envisaged that one or two sugar mills in the group displace the equivalent of excess cane or molasses in ethanol production, in addition to their sugar production.

Increase competitiveness by reducing production costs and establish technological strategies for the flexibility of ethanol processes based on the fermentation of molasses A, B, C, cane juice or any combination of them according to the demand of the national or international market for ethanol, molasses and sugar

Therefore, the sugar mills must evaluate the infrastructure required for the production of sugar, ethanol and electrical energy such as: process equipment, civil infrastructure, electrical installations, instrumentation / automation, detailed engineering, environmental control and water treatment, generation of steam, batey and extraction (increased milling capacity), distillery, modifications in the sugar factory, turbines and power generation, industrial inputs, by-product management, professional services for administration and operation, among others.

9. Conclusions and prospects

The problems related to generation of greenhouse gases, have become more pronounced in recent years due to the rapid pace of development towards modernization throughout the world. Therefore, the sustainable production of biofuels is a priority in Mexico in terms of improving energy security, environmental protection, and the well-being of the population. The state of Veracruz, Mexico, an impoverished region with social conflicts and an economy heavily oriented towards agricultural and livestock activities with comparative and competitive advantages for the production of sugar cane presents a real potential for the production of biofuel ethanol. This work showed that even with conventional technologies, cane stalks, molasses and trash can be successfully transformed into ethanol and new value chains can be started to reduce rural poverty and dependence on gasoline additives. At the same time, it is necessary a program with stakeholders for the use of cane and agro-industrial by-products in bioproducts

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