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Profitability Using Second-Generation Bioethanol in Gasoline Produced in Mexico

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Abstract: Gasoline produced in Mexico by the productive company of the state Petróleos Mexicanos (PEMEX) mainly uses oil-derived ethers as oxygenators to reach the Mexican Regulatory 'Framework's octane number. An alternative to complying with these regulations could be to use bioethanol as an oxygenate. However, as a gasoline component, this could affect 'Mexico's food markets since sugar cane, and grains are the primary inputs for local production. The main objective of this study is to evaluate whether the use of bioethanol, produced from corn stubble, as an additive in gasoline produced by Petróleos Mexicanos (PEMEX) is profitable in Mexico, from the perspective of the evaluation of the supply chain and the finances. The purpose of this work is to contribute to the definition of the advantages and limitations for the existence of a second-generation bioethanol market produced from Lignocellulosic corn biomass and integrated into the gasoline market of national production in Mexico. The work starts with theoretical research to define the use of corn stubble as raw material, set up on its availability and feasibility determined based on a geographic information system (GIS), through the use of the agricultural production forecast approach, as well as the integration of costs and financial analysis. The results show that corn stubble bioethanol production is technically viable, but the production cost is not competitive yet. Although its price is not yet competitive compared to the imported price, using a fiscal incentive scheme and considering the decrease in energy dependence, it would be feasible to produce it in Mexico.

Keywords: bioethanol; lignocellulosic biomass; oxygenating agents; gasoline

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1. Introduction

As an alternative to the use of fossil fuels, in the 20th century, the United States of 'America's government implemented public policies that supported the conversion of chemical energy stored in plants by deriving starch conversion into ethanol. This conversion consumes a significant part of corn production in the United States of America. Starch is a simple glucose polymer that is easily converted to ethanol with existing technologies, although almost a third of starch energy is lost during the production process.

Bioethanol (ethanol from biomass, from now on, we will call it interchangeably ethanol or bioethanol) is single chain alcohol with two carbon molecules (C_2H_6O), produced mainly from the fermentative action of microorganisms of the genus Saccharomyces from biomass substrate (generally grains such as corn or carbohydrate-rich biomass). The most commonly used raw materials for the production of bioethanol include grains (corn, sorghum, and wheat), sugar cane, and cassava (first-generation fuels), as well as lignocellulosic biomass or stubble (second-generation biofuels).

Regardless of its origin, bioethanol or that produced by chemical synthesis from hydrocarbons can be used mainly as a solvent or raw material to synthesize other products, as a fuel substitute (component), and as an additive in gasoline used in the transport sector. In 'Mexico's latter case, it is assumed that it can be used as a substitute for Methyl Ter Butyl Ether (MTBE) since NOM-016-CRE-2016 [1] allows the use of ethanol as an oxygenator in gasoline in contents of up to 10% of the volume.

In terms of biofuels, ethanol works as a substitute and as a gasoline additive. Its molecular structure is composed mainly of carbon chains; its combustion leads (in a similar way to fossil fuels) to the emission of calculable amounts of carbon dioxide. In 2015, 11 countries consumed 97% of the ethanol produced for fuel, while production volumes averaged around 115.6 billion liters. The United States of America and Brazil dominate the bioethanol production market, producing, respectively, 49% and 25% of global production [2].

The use of ethanol/gasoline blends as fuel for spark ignition engines (SI engines) has been the object of many experimental investigations that highlight some advantages and disadvantages relying on the proportion of ethanol in the mixture, mainly due to the different physicochemical characteristics between ethanol and gasoline.

Iodice et al. [3] in their review of the literature on effect of ethanol on emissive behaviors of SI engines observed that the formation of exhaust emissions in SI engines is related to some of the physicochemical properties of ethanol/gasoline blends, such as calorific value, latent heat of vaporization and oxygen content. Their work lead them to document that when using ethanol/gasoline-blended fuels, carbon monoxide (CO) and hydrocarbon emissions decrease, while enhanced combustion is carried out because of the additional oxygen present in ethanol. They also expose that there is a maximum ethanol content in the mixture of approximately 15% v/v that causes an increase in the Reid vapor pressure (RVP) (in a non-linear dependence), which has the advantage of facilitating the fuel vaporization and the engine warm-up phase; and that when the ethanol content exceeds 20% v/v the PVR declines sharply.

The lack of unanimity in accepting biofuels from foods such as corn due to the risk it poses to food safety forces society to analyze the different options to obtain alternative energy [4]. Some of the options are crop residues, forest by-products, perennial grasses, and other biomass forms collectively known as lignocellulosic residues (second-generation biofuels) [5]. The agricultural residues are attractive due to their low costs and abundance [6]. However, Talebnia et al. [7] and Otero-Rambla et al. [8] clarify that, for the use of the residues of some crops such as wheat stubble, production costs based on current technology are very high [9].

In the case of Mexico, some researchers have reported studies from second-generation ethanol. As an example of these studies, it is possible to mention some cases, such as bioethanol produced from blue agave and sugarcane bagasse, reaching a conversion yield of 58 gallon/metric ton and production cost of 1.46 USD/gallon and a conversion yield of 48 gallon/metric ton and production cost of 1.34 USD/gallon, respectively [10]. It is essential to consider that Mexico is a country whose diet is based mainly on corn. Hence, although it is one of the main crops in the country, it is hazardous to consider its use for the production of unconventional energy, for which it is necessary to focus on biofuels produced from lignocellulosic materials, which have economic advantages, giving an alternative use for the agro-industrial wastes [11] and energy and environmental contributions to alleviate the global energy crisis and to improve environmental quality [12] compared to bioethanol produced from corn starch or sugar cane alcohol.

The use of other energies for irrigation and ensuring the supply of raw material to make corn ethanol calls into question this alternative. The unknown factors of corn-producing 'systems' energy performance arise when they incorporate irrigation, based on energy consumption [13]. Morales et al. [14] indicate that bioethanol production from mixtures of secondary juices of sugar production requires studies that develop models for the stages of preparation, milling, and clarification to simulate low error rates in the process. The same process for producing sugar and bioethanol generates waste. The production of ethanol from the sugar industry generates some waste that can generate energy, which the distillation of ethanol requires, helping to maintain an efficient cycle [15].

According to information from [16], the area dedicated to agricultural activities in Mexico in 2017 was 32.4 million hectares, of which 21.02% was irrigated area, while 78.98% was temporary. Based on the works of Lozano-García et al. [17], the available base area of corn cultivation for the generation of lignocellulosic biomass (stubble), able to be used as an input for the generation of ethanol is approximately 226,113 km^2, within the categories of high and very high suitability. This area will be taken as a reference in the second-generation bioethanol production estimation model.

Concerning the research carried out in Mexico in biofuels, several authors research different approaches. Islas et al. [18], in their work estimate based on the construction of projected scenarios for Mexico by 2030, suggest that the transport sector will be the largest consumer of biofuels, with 8.60% of the energy consumed of the total of the sectors; this means 20.17% of liquid fuels. Based on these figures, his work projects a potential reduction of 12.7% in 'Mexico's CO_2 emissions. Their results suggest that biofuels as substitutes for fossil fuels can be essential in the energy sector for the achievement of environmental sustainability.

In their research, Rendon-Sagardi et al. [19] refer to various studies on the impacts generated by biofuels in Mexico. Awudu and Zhang [20] indicate that these studies have proven that the use of biofuels results in a decrease in greenhouse gas (GHG) emissions expressed in CO_2 equivalents (CO_2e). According to García et al. [21], Mexican fossil fuels can generate 3104.64 kg of CO_2 per ton (kgCO_2e/t), while biofuel mixtures (gasoline added with 10% by volume of ethanol) has the potential to generate 2722.82 kgCO_2e/t on average. These values were obtained considering a density of 722.5 t/m^3 for fossil fuels.

This represents 351,889.68 tons of CO_2 per thousand barrels of fossil fuels (tCO_2e/mb) and 312,791.21 tCO_2e/mb for biofuels. In their works Rendón-Sagardi et al. [19] find, based on a sensitivity study, that under current regulatory conditions and policies, Mexico is not self-sufficient in the production of fuels, due, among other things, to the shortage of production oil (based on 1P oil reserves). This is in such a way that said shortage must be covered with the importation of fuels to satisfy the demand, which does not generate any environmental or economic benefit considering that imports contain additives other than ethanol.

Aldana et al. [22] propose an analysis tool (Mixed Integration Linear Model (MILP) created based on specific information from Mexico (production, transportation, distances, and demand) to demonstrate the feasibility of producing biofuels. His work shows that 'biofuels' production from gas synthesis and fermentation techniques can generate a positive energy balance, considering various supply chain elements. They also conclude that biomass waste can diversify 'PEMEX's and the 'nation's energy portfolio and help reduce CO_2 emissions in Mexico by up to 2.6%, producing enough ethanol to replace the MTBE additive in gasoline produced in Mexico entirely. Lozano-García et al. [17] carried out a base model as a Geographic Information System (GIS) to determine the areas in Mexico with the most significant potential for the production of renewable energy from by-products and agricultural residues of crops of corn, sorghum, wheat, sugar cane, barley, agave, rice and pecan nuts produced in the valleys of the Gulf of Mexico, the Pacific and the Bajío region. Their results show a generation potential of 70,951 MWh of electricity or 18,373 Gg of Fischer–Tropsch liquids (hydrocarbons from synthesis gas) using only 60% of the residual biomass.

Finally, Elizondo and Boyd [23] conducted studies using a general equilibrium calculation model (CGE) that estimates ethanol 'production's impact (indistinctly bioethanol or ethanol) on 'Mexico's economy. Using cost information from Brazil, they introduce ethanol into the social accounting matrix and insert a latent sector in their model to analyze the promotion of bioethanol. Among their conclusions, they find that, in terms of the aggregate economy, the benefits of a policy designed to promote the use of ethanol are not obvious. The promotion of ethanol has been labeled as the means to diversify energy production, increase the most deficient 'agents' income, and reduce greenhouse gases in Mexico; however, the poor design of energy policy and its limited focus do not necessarily contribute to these goals. Finally, this study shows that public promotion of ethanol cannot easily be justified in terms of social benefit, GDP, or energy security.

The literature review carried out allowed us to observe that none of the research addressed the profitability of bioethanol as an additive in gasoline. Specifically, that produced from lignocellulosic biomass, which constitutes the novelty of this work. In this context, this 'study's main objective is to assess whether the use of bioethanol as an additive in gasoline is profitable, taking Mexico as a case study. Specifically, it is intended to analyze 'bioethanol's viability produced from corn stubble as a substitute for MTBE for use as an additive in the gasoline produced by Petróleos Mexicanos (PEMEX), from the perspective of the evaluation of the supply chain and finance.

This document consists of the following parts: in the introduction, the subject under study is contextualized, the relevant literature is reviewed, and the 'research's objective is stated. In the second section, the situation of the development of the use of biofuels in developing countries is described. In the third section the theoretical research based on some other authors in which this investigation is supported is shown, showing the application of some aspects of the methodology that they used, focused on the definition of corn stubble as raw material for the production of second-generation bioethanol on a national basis, founded on its availability, as well as on the selection of the appropriate transformation process. Then, the annualized investment cost and operation cost are estimated through the performance of a financial evaluation. In the fourth section, analysis and discussion of the results obtained are carried out. Finally, the conclusions are presented.

It is essential to consider that this work is based on theoretical research that is susceptible to being affected by changes in technology and 'Mexico's legal and regulatory framework.

2. Situation of the Development of the Use of Biofuels in Developing Countries

The increasing interest of developing countries in achieving the 2030 Sustainable Development agenda has driven various renewable energy projects, including biofuels. Some reasons for joining biofuel production include diversification of energy resources, reduction in dependence on fossil fuels, and reduction in greenhouse gas (GHG) emissions [24,25]. The developing countries are looking for different inputs for the production of biofuels. The net effect of biofuels on the environment is closely linked to the source used for their production [26,27].

Janssen and Rutz [28] suggest that in developing countries, it is not possible for unjustified burdens to be imposed on biofuel producers, nor for development opportunities to be blocked in order to meet sustainability requirements. First, harmonization is urgently required to avoid market distortions and barriers or exclude developing countries from the emerging biofuel trade resulting from many existing certification scheme initiatives. Second, a practical and globally accepted sustainability program is required to avoid the negative impact of biofuel production. Third, further research is required in various aspects related to the impact of production. Finally, close cooperation between stakeholders and decision-makers from Latin America, Europe, North America, Asia, and Africa is required to ensure that future sustainability schemes benefit both importers and producers of biofuels. Concerning this situation, the following drawbacks are the most significant:

- First, it is essential to note that different countries seek various inputs for biofuel production. The viability of said production is highly determined by the type of input used in bioethanol production.
- Institutional arrangements have made the difference for viability; biofuel business models can be based on the type of crop, agricultural production capital, and, on the other hand, on outsourcing schemes.
- Other important factors include the cost of capital, company size, process technology selection, and industrial and organizational schemes. Quintero et al. [29] suggest that the inclusion of small producers in the supply chain can, under certain conditions,

be competitive for the production of liquid biofuels. However, despite the statistical significance of the average size–cost ratio, some experts argue that the average capital cost of a given size plant in a particular location is highly variable due to the costs associated with possibly unique circumstances, due to the availability of water, access to public services, and compliance with environmental regulations [30].

- Additionally, the cost of labor or wages, productivity, energy and transportation, type and price of inputs, among others, influence viability.

Biofuels have proven to be one of the most successful ways of decarbonizing the transport sector. The report B.P. Statistical review of world energy shows that production and consumption increased from over 64 billion liters in 2007 to over 145 billion liters in 2017 [31]. The Americas and Europe continue to produce and use most of the world's biofuels in 2017: 45.5% North America, 26.9% South and Central America, 16.8% Europe [32]. However, the most significant growth corresponds to the Asia Pacific region (annual growth rate of 20.1% from 2006 to 2016 and a 6% increase from 2016 to 2017) [31].

The legal framework in energy matters for Mexico opens the door to renewable energies and the diversification of the energy matrix. In accordance with the provisions of the General Law on Climate Change, there is a commitment to reduce CO2 emissions in 50% by 2050. The Law for the Use of Renewable Energies and the Financing of the Energy Transition mandates within its transitional regime, the reduction of energy consumption based on fossil sources for Mexico to a maximum of 65% for the year 2024, 60% for the year 2035 and 50% for the year 2050. The Mexican energy policy dictated through the Sectorial Program of Energy 2020–2024, considers in its priority strategy 4.1 to establish a policy on the diversification of energy sources, making optimal use of all the nation's resources, advancing in the use of clean and renewable energies, to guarantee a sovereign and orderly energy transition.

3. Materials and Methods

For this research, the work of Lozano-García et al. [17] (p. 5) was used as a basis. The authors used a geographic information system (GIS) to select suitable crops, construct geographic databases, the generation of variables used as qualifiers or restrictors on the selection of the substrate for production of bioethanol, and specific sources of lignocellulosic biomass. Lozano-García et al. [17] followed up a line of research that allowed them to carry out a classification of areas with high potential for the sustainable production of residual biomass that permits to estimate the energy generation capacity, based on a nation-wide GIS model. Their work allowed the identification of the most suitable crop selection (based on information from the Food and Fisheries Information Service of the Federal Government of Mexico) that can yield more residual biomass for energy generation through selection of the waste sources, 'qualifiers' layer (municipal boundaries, slope, road and highway networks, electrical networks, and population) and restrictive layers (includes a slope, vegetation, covered area, rivers and water bodies (lakes and reservoirs), protected natural areas, airports, historic sites, electric power networks, roads, highways, and railways) [17].

This research work considers the results reached by Lozano-García et al. [17] and additionally proposes and analyzes a profitability scope to evaluate the feasibility to use corn stubble in order to produce bioethanol for its use as an oxygenating additive in types of gasoline produced by Pemex, based on a group of lignocellulosic biomass sources, trying to justify corn stubble as the crop that allows a nation-wide basis in Mexico.

3.1. Selection of Corn Stubble as Raw Material, Criteria, and Sources of Information

The GIS Model database constructed by Lozano-Garcia et al. [17] made the selection of crops for Mexico, based on the following criteria: (1) selection of residual biomass that could be stored and processed, (2) crops that produce sufficient amounts of residual biomass (whose volume varies from hundreds to thousands of tens of millions of Mg (1 Mg = 1 Ton).

Although different crops meet these characteristics, for the purpose of this study, only corn biomass will be selected, given its high transformation potential and its extensive production at the national level in Mexico (7,179,027.22 hectares of the harvested area and 31,212,167.52 metric tons produced for the year 2019 [16]). Considering the use of 60% of the biomass potential (corn stubble) for ethanol production, and the remaining 40% being left in the fields or used locally for other purposes. The general situation of residues per crop mass is within the range of 0.55–1.8 kg/kg (the ratio of the kg/kg refers to the kilogram of stubble generated for each kilogram of corn grain harvested), with 0.825 being the kg/kg factor for corn residues. The joint national grain corn production in the period 2009–2019 was 264,191,529.07 Tons. Table 1 shows the statistical information of the national corn production, yields, and residue estimation.

The total residual amount of 217 Tg (millions of tons) for corn is essential for a fair economy of scale. Simultaneously, a substantial availability of biomass will generate a more significant profit margin for possible processing facilities.

In the GIS Model carried out by Lozano-García et al. [17], which has been taken as the basis of this work, the municipal agricultural information was associated with its corresponding municipal polygon; thus, they showed the residue estimated harvest according to each municipality. In any case, given that not the entire area of the municipality carries out agricultural activities, this approach generates a bias. Comber et al. [33] identify this as a fundamental problem when facing the use of multi-criteria evaluation models, given that through these approaches, "suitable areas are identified, which are not identified in discrete locations"; therefore, a land-cover/land-use map from the Instituto Nacional de Estadística, Geografía e Informática (INEGI is its acronym in Spanish; National Institute of Statistics, Geography and Informatics) [16] was used to solve this problem. The agricultural states within which each municipality were selected and the resulting harvest 'residues' values subsequently added [17].

Table 1. Statistics and estimation of the National Weighted Average Yield of corn grain in the accumulated period 2009–2019.

Corn Grain	Sown Area (Ha)	Harvested Area (Ha)	Production (Ton)	Yield (Ton/Ha) (α)	Weighting (Production of Each Variety/Total Production) (β)	Average Yield Weighted (Ton/Ha) (α x β)	Estimated Residue (Ton)
Yellow grain corn	5,256,980.98	5,132,841.53	28,706,408.20	5.59	0.108657565	0.607395787	23,682,786.77
Blue grain corn	40,672.35	40,672.35	65,461.56	1.61	0.000247781	0.000398927	54,005.79
White grain corn	77,201,735.65	70,668,087.63	234,258,104.86	3.31	0.886698017	2.934970435	193,262,936.51
Color grain corn	453,421.44	422,651.65	778,001.46	1.84	0.002944839	0.005418503	641,851.20
Corn grain pozolero	85,759.55	83,777.55	369,310.41	4.41	0.001397889	0.00616469	304,681.09
Corn grain without classification	11,741.50	10,280.50	14,242.58	1.39	5.39101×10^{-05}	7.4935×10^{-05}	11,750.13
TOTAL	83,050,311.47	76,358,311.21	264,191,529.07	0	1	3.554423278	217,958,011.48

Source: Own elaboration with information from SIAP—SIACON-Agri-food and Fisheries Information System [34].

Lozano-García et al. [17] combine the harvest information with the agricultural areas and classify the ranges of harvest residues into five categories for use in the GIS model (very low, low, medium, high, and very high), which were obtained by calculating the value of the five quantiles (20%) of the average residual. Starting with these five categories, this work took the areas of high and very high suitability for corn (226,113 km^2) as a basis to estimate the residue (corn stubble biomass) generation on these areas. This work assumes a combination of optimal technologies in the on-site process so that profit is maximized.

3.2. *Estimation of the Variables and Parameters for the Profitability Evaluation*

The model to estimate profitability is based on raw material availability, shown in the previous section. It calculates production potential for Bioethanol as well as production and investment costs and environmental parameters for the technology of Simultaneous Saccharification and Fermentation (SSF). Finally, the profitability analysis is carried out, estimating income based on domestic demand and formula price through a Net Present Value—Internal Rate of Return (NPV-IRR) analysis.

In order to estimate the lignocellulosic corn biomass (estimated residue), production data were obtained from the SIAP – SIACON (Agri-food and Fisheries Information System) [34] for the period 2009–2019 (see Table 1) and then weighted using the average yield. The residue production ratio for the area of 226,113 km^2 of high and very high suitability for corn was used to estimate the amount of residues (corn stubble) generated (see Table 2).

To calculate the amount of substrate required for ethanol production, the specific source of lignocellulosic biomass that was previously defined is considered, given the generation of lignocellulosic residues implicit in their harvest. The works of Lozano-García et al. [17] and Aldana et al. [22] allow us to calculate the specific basis of the amount of substrate available (residues of lignocellulosic biomass from the corn harvest, which is also known as corn stubble) at the national level as well as its performance for the production of ethanol from the mathematical model proposed by Aldana et al. [22].

In his work, Aldana et al. [22] developed a tool (Linear Mixed Integration Model) based on accurate information for crop production, transport information, distance, and specific demand in Mexico, that allows the selection of conversion technologies, capacities, biomass location, transport logistics from agricultural fields to storage sites, processing plants, and final consumer markets. Its purpose was to demonstrate the feasibility of producing biofuels on a large scale in Mexico from lignocellulosic waste, using routes not currently considered in the Mexican 'government's strategies, determining the most convenient technological routes for obtaining more energy at the lowest cost and with lower environmental impact. At the same time, potential sites for process plants and potential consumers are identified.

The selected method for ethanol production is based on fermentation [22]. Fermentation refers to the use of microbial consortia to obtain ethanol from carbohydrates. The ethanol production process using lignocellulosic biomass as a substrate, requires the high performance of the substrate, considering the pretreatment to increase the availability of carbohydrates, detoxification to avoid the deviation of the metabolic routes of the microbial consortia and enzymes, hydrolysis to break the polysaccharide chains to oligosaccharides and simple carbohydrates and lastly the process separation/distillation to isolate value-added products and by-products [35] Simultaneous Saccharification and Fermentation (SSF) was selected since it has some advantages and requires a reduced number of reactors and the promotion of glucose consumption as soon as it is generated [36].

The amount of ethanol produced, expressed as theoretical efficiency of conversion in fermentation, is estimated based on the yield, considering as a base the content of cellulose and hemicellulose (substrate). Based on the design proposed by the National Renewable Energy Laboratory (NREL) [37] two upper limits were established, which delimit the conversion of 76.5% of hemicellulose and 85.5% of cellulose to ethanol by fermentative methods [22]. These values were used for the construction of the equation obtained from the stoichiometric analysis:

$$CEf_{ethanol} = 0.51 * (1 - H)(0.855X_{Cellulose} + 0.765X_{Hemicellulose}) \quad (1)$$

where 0.51 is the theoretical yield of 2 mol of ethanol/mol of hexose or 0.51 g ethanol/g hexose (1.67 mol/mol pentose or 0.51 g/g pentose) [37]; $X_{Cellulose}$ represents the fraction of cellulose in the dry base residue. $X_{Hemicellulose}$ represents the fraction of hemicellulose in the residue on a dry basis, and H represents the fraction of water in the substrate as received.

Table 2 shows the estimated annual average potential waste generation, based on the area of high and very high availability established by Lozano-García et al. [17], and average information on agricultural residues for Mexico in the period 2009–2019 as well as its chemical composition [38].

Table 2. Estimated annual average potential generation of residues from corn and its chemical composition.

Crop	Production Corn Base High and Very High Adequacy (Tg/Year)(a, b)	Residue/Production Ratio (c)	Residues Generated Base 60% (Tg/Year)	Hemicellulose (d)	Cellulose (d)	Lignin (d)	Carbon Content (e)
				Percentage of Mass on a Dry Basis in Corn Stubble			
Corn	80.37	0.825	39.78	26	38	23	56

Source: Own elaboration with information from: a [34], SIAP:2020; b [17], Renew. Sustain. Energy Rev.: 2020; c [22], Biomass Bioenergy: 2014; d [38], Handbook of Cellulosic Ethanol: 2013; e [39], Renew. Sustain. Energy Rev.: 2009.

The dry base yield obtained from Equation (1) from Aldana et al.'s study [22] is consistently higher than those reported by other authors, for example the authors of [40], who use an average yield value of 22.7% for corn stubble and 26.2% for wheat stubble. Therefore, a reduced value is considered for this parameter equivalent to 70% of the value estimated by the equation. This value of conversion efficiency is considered in the results section.

The estimation base of the potential demand for bioethanol for use in gasoline is obtained from the production of gasoline in Pemex reported by the *Sistema de Información Energética* (SIE is its acronym in Spanish; Energy Information System) [41], considering substitution of the MTBE used as an additive in a 10% maximum bioethanol base, following the provisions of the Official Mexican Standard (NOM-016-CRE-2016). It is important to note what was declared in previous sections, where the dual use of ethanol in gasoline is specified, both as a component (substitute) or as an additive (oxygenating) [22]. In this sense, it should be noted that, according to the works of Rendon-Sagardi et al. [19], to incorporate the benefit of reducing greenhouse gas emissions into the discussion, the use of ethanol as an additive (oxygenator) to replace MTBE will be discussed.

For the base of incorporation of ethanol in fuels, two scenarios are considered. Scenario 1 consists of a base of incorporation of ethanol in gasoline at 5.8% (E5.8), and scenario 2 consists of a base of incorporation of ethanol in gasoline at 10% (E10) in percentage volume/volume (v/v).

From the definition of the potential demand, the potential supply estimation is made using Equation (1) in the information provided in Table 2. For the estimation of the economic parameters, the work of Aldana et al. [22] is taken as a basis. In his work, Aldana bases the estimates of the annualized investment cost (AIC) and the Cost of Operation (COp) on the information provided by Aden et al. [37]. An exponential scale factor of 0.7 is used to determine the investment cost, as recommended in the work of Polagye et al. [42]. From this analysis, it is possible to determine the economic viability of second-generation bioethanol production in Mexico, thereby showing its use as an additive in gasoline.

The investment analysis approach takes a long-term perspective [43]. A detailed valuation and analysis of future cash flows, costs, and benefits of biofuel companies are considered, including the risks associated with price volatility, technology, among others. It is assumed that the competitiveness and viability of the bioethanol industry are mainly determined by the fossil fuel market and international ethanol reference prices (U.S. Gulf Coast).

The estimation of environmental parameters is made as an emission factor for MTBE combustion. Taking into account the data provided by Corezen and Kampman [44] the complete combustion of the material was considered, and the emission mitigation factor was obtained, assuming MTBE substitution with ethanol according to Aldana et al. [22].

At the end of the next section, a financial evaluation of a biorefinery project with 2 Gg/day production is presented to assess its financial viability, taking as a tool of analysis the Net Present Value and the Internal Rate of Return. Likewise, derived from the agricultural production forecasting and cost analysis approaches, a base unit cost per liter of ethanol is obtained, which allows establishment of a point of comparison with the prices of anhydrous ethanol in the United States of America, as well as with the main oxygenating additives used in gasoline (MTBE and ETBE). In this way it will be possible to discuss the convenience in a complementary manner, from an economic perspective, of using second-generation bioethanol as an oxygenating additive and as a component of gasoline in Mexico.

4. Results and Discussion

From the estimation of the corn crop residues (stubble) available as inputs for ethanol production and Equation (1), it is possible to calculate the national base 'production's estimated potential, shown in Table 3. The density for ethanol at 99% purity is considered to be 0.79111 g/cm^3, and the average humidity of corn stubble is 40% [22].

Table 3. Potential for ethanol production from corn stubble.

Corn stubble Average Humidity (%)	Available Cellulose (Tg/Year)	Available Hemicellulose (Tg/Year)	Ethanol Potential Production (m^3/Year)
40	1511.76	1034.36	5,642,193.31

This work considers a scenario with a minimum annual demand of 1 Tg of ethanol, whose volumetric equivalence would correspond to approximately 1,264,046 m^3/year, an amount that represents around a quarter of the potential for annual ethanol production from the stubble of corn, which is shown in Table 2. The proposed demand is estimated based on the substitution of MTBE in gasoline (oxygenating agent), based on the data of the average gasoline production in Mexico in the period 2010–2019, reported by the Secretaría de Energía (SENER is its acronym in Spanish; Ministry of Energy) through the SIE [41] and consists of around 1 Tg of ethanol for the 5.8% incorporation scenario (E5.8) and 1.7 Tg of ethanol for the 10% incorporation scenario (E10). Both 'scenarios' input requirements are well below the estimated potential for annual ethanol production from corn stubble (5,642,193.31 m^3/year, equivalent to 4.46 Tg/year).

It should be noted that scenario E5.8 altogether provides the mass fraction equivalent to 2.7% oxygen (maximum), as established by the Official Mexican Standard NOM-086-SEMARNAT-SENER-SCFI-2005. Likewise, scenario E10, considering ethanol exclusively as an oxygenator, would be out of specification, derived from the ruling issued by the Supreme Court of Justice of the Nation in January 2020, in which the use of ethanol at 10% was declared unconstitutional in gasoline [45]. However, given the potential of ethanol as a component, and based on the precedent of NOM-086-SEMARNAT-SENER-SCFI-2005, which allowed 10% ethanol–gasoline mixtures for some years, as well as possible future resolutions of the authority (Energy Regulatory Commission), which makes the E10 scenario remain a potential.

Table 4 shows the average annualized cost by plant size (investment and operation) and the mitigation factor. An evaluation and amortization of the biorefinery assets over 20 years are considered.

Table 4. Cost and environmental parameters for the technology of Saccharification and Simultaneous Fermentation of lignocellulosic biomass of corn crops. Reproduced from [22], *Biomass Bioenergy* 2014.

Process	Annualized Plant Cost 2 Gg/Day	Annualized Plant Cost 4 Gg/Day	Annualized Plant Cost 6 Gg/Day	Operation Cost (USD/Mg)	Emissions Factor	Mitigation Factor
		M USD/y			Mg/Mg	
SSF	24.9	41.5	56	21.62	0	1.91

The use of biomass absorbs the CO_2 emissions generated during its process and final use from the photosynthesis that provides its origin [22]; this makes it a neutral source of emissions when completing its cycle as a biofuel.

To meet the estimated demand in 1 Tg of ethanol and based on what is shown in Table 4, any of the plant size options are adequate. Their selection will depend on the region where it is to located and the nearby availability of crude, raw material (corn stubble), and proximity to the PEMEX Storage and Distribution Terminals (SDT). According to Aldana et al. [22], 19 municipalities in Mexico, distributed throughout the national territory, have the potential to locate a biorefinery due to the conditions mentioned above. Table 5 shows these results.

Table 5. Municipalities with the potential for bioethanol production and maximum distance from the input sources (lignocellulosic biomass). Reproduced from [22], *Biomass Bioenergy* 2014.

Number	Municipality	State	Maximum Distance (km)
1	Mexicali	Baja California	0
2	Hermosillo	Sonora	348
3	Cajeme	Sonora	86
4	Chihuahua	Chihuahua	101
5	Culiacán	Sinaloa	120
6	Durango	Durango	474
7	Gómez Palacio	Durango	455
8	Cadereyta de Jiménez	Nuevo León	62
9	Valle Hermoso	Tamaulipas	127
10	Altamira	Tamaulipas	155
11	Juanacatlán	Jalisco	74
12	San Luis de la Paz	Guanajuato	139
13	Tula de Allende	Hidalgo	399
14	Pedro Escobedo	Querétaro de Arteaga	142
15	Cuautlancingo	Puebla	216
16	Acapulco de Juárez	Guerrero	112
17	Medellín	Veracruz—Llave	111
18	Palizada	Campeche	483
19	Othón P. Blanco	Quintana Roo	333

For diversification purposes and a more significant national presence, the financial evaluation is carried out based on the biorefinery model of smaller capacity (2 Gg/day) and considering a payback period of 20 years.

Table 6 shows that in the Saccharification and Simultaneous Fermentation process, the most critical costs are fixed (related to investment), equivalent to 41%, followed by the costs of inputs (biomass and enzymes) equivalent to 35% of the total. Variable costs represent 15%, those corresponding to the transport of waste 8% and, finally, the transport of products is estimated at an equivalent cost of 1% [22].

Table 6. Distribution of costs for ethanol production from corn stubble.

Total Cost	0.5946	(USD/L)
Fixed costs	41%	0.2438
Variable costs	15%	0.0892
Raw material	35%	0.2081
Transportation of products	1%	0.0059
Transportation of residues	8%	0.0476

Source: Own elaboration based on data from Aldana et al. [22], Biomass Bioenergy: 2014.

The total cost of the technology is obtained by following the work of Aldana et al. [22] on an energetic basis of the ethanol molecule. The average calorific value reported by SENER [46] is changed to a comparative basis of US dollars per liter (USD/L). The value obtained as a total cost is 59 cents, equivalent to 11.89 pesos per liter of ethanol, considering an exchange rate of 20 pesos per dollar.

Ethanol prices on the United States of 'America's Gulf Coast (U.S. Gulf Coast, the reference price for PEMEX) have been highly variable (presenting a maximum of 0.86 USD/L in 2014 and a minimum of 0.24 USD/L in 2020, in the analysis of the last decade). They frequently follow gasoline (being lower than those of MTBE), except when the price of crude oil is low, and then the ethanol price floor is determined by the costs of the agricultural sector [47]. When gasoline prices go up, ethanol prices go up too, although there is a floor price below which it is unlikely to reach [47]. The reference prices of ethanol spots on the U.S. Gulf Coast are relevant because they define the price at which PEMEX is willing to pay based on the opportunity cost criterion, that is, the import price.

In 2012, the MTBE/ethanol price differential exceeded MXP 4.47 pesos/L, while the lowest differential was MXP 0.36 pesos/L in 2016 (in average 1 mexican peso or MXP is approximated to 0.050 USD), being the constant during the last decade that MTBE prices were consistently higher than those of ethanol in the U.S. Gulf Coast market, according to Mayers et al. [47]. In addition to the price benefits, ethanol contains higher octane when mixed (115 for ethanol compared to 110 for MTBE [48]). These conditions allow refiners to produce a lower octane base for blending to achieve the required octane number of 87 for regular gasoline and 91 for premium gasoline (according to the Mexican Regulatory Framework) [47].

Under the national 'supply's current conditions, PEMEX cannot acquire ethanol under a scheme that implies incurring additional costs or direct subsidies since this situation would violate its legal obligation to create economic value for the company. Currently, PEMEX only can purchase ethanol under a scheme that considers the capacity for the production of inputs in the country, the demand for gasoline that can be replaced without complicating the regular operation of the company, and to the premise of zero subsidies (maximum price comparable to an international reference plus the cost of logistics and importation) [49].

According to SENER [49], the price of ethanol must be calculated following the provisions of Equation (2) as shown below:

$$PE = \frac{(PE_{spot} * (1 + CI) * FC_1) + LI}{FC_2} * TC + CT \quad (2)$$

where PE is the price of ethanol in each Storage and Distribution Terminal (SDT) in pesos per liter; PE_{spot} is the average of the spot price (high and low prices) of ethanol, published in 'Platt's Market Scan from period 21 of month *T-2* to 20 of month *T-1*, where T is the month of application of the price, UScts/gal; CI are the import costs of ethanol, which will be the applicable percentage according to the import duties established by the *Secretaría de Economía* (Ministry of Economy) and applied by the Tax Administration Service (percentage); FC_1 is the conversion factor UScts/gal to USD/bl (equivalent to 0.42); LI is import logistics, logistics cost including maritime transport and storage in maritime terminal (land for Cadereyta), reported by companies specialized in importing products in USD/bl; FC_2 is the conversion factor from barrels to liters, equivalent to 158.9873; *T.C.* is the average of the publications made by *Banco de México* in the *Diario Oficial de la Federación* (Official Gazette of the Federation), between the 21st of the month *T-2* and the 20th of the month *T-1*, with T being the month of application of the price, of the exchange rate to settle obligations denominated in foreign currency payable in the Mexican Republic; *C.T.* is the cost of ground transportation from the point of import to each SDT, corresponding to that reported by companies specialized in MXP/L.

Based on what is shown by Equation (2), regardless of the origin of the ethanol, the purchase price of PEMEX must be equivalent to the import price. This premise puts second-generation production technologies at a disadvantage since what is required as an initial investment, during the pretreatment of the raw material and during the process, makes it more expensive in comparative terms with first-generation technologies (as the primary basis of production in the United States of America) and in this sense they are related to lower competitiveness concerning their price.

Applying Equation (2), and based on average data corresponding to the year 2020 (average PE_{spot} of 1.35 USD/gallon; estimated CI of 0.01%; estimated LI of 5.56 USD/bl; annual average exchange rate (TC) of 21.59 MXP/USD; estimated CT of 0.32 MXP/L), a purchase price for PEMEX for ethanol of around 8.86 Pesos/Liter (equivalent to 0.41 USD/L) would be obtained, considering an ethanol price in the Gulf Coast market of the United States of America of 0.37 USD/L (reference). Logistics and import costs are considerably reduced since, under the Free Trade Agreement of the United States, Mexico, and Canada (USMCA or T-MEC by its acronym in Spanish), an exemption from the General Tax Imports (tariffs) is established for this product. Table 7 shows the average prices and projected prices for anhydrous ethanol (second-generation fuel) in the USA; we can see that 'Mexico's production prices are still not affordable compared to those prices.

Table 7. Average prices and price projection for anhydrous ethanol in the United States of America.

Year	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Anhydrous Ethanol Average Price (USD/gallon)	1.38	1.35	1.40	1.47	1.46	1.45	1.50	1.52	1.56	1.62	1.66	1.75
Anhydrous Ethanol Average Price (USD/L)	0.37	0.36	0.37	0.39	0.39	0.38	0.40	0.40	0.41	0.43	0.44	0.46

Source: Own elaboration based on information from the Energy Information Administration, Annual Energy Outlook 2020. U.S. Prices Gulf Coast [50].

In this context of ethanol prices in the United States, within the framework of the T-MEC and under 'PEMEX's opportunity cost criteria, currently, there are no conditions in Mexico that favor the production of second-generation bioethanol because this technology would be subject to competition against the reference price in the United States (Gulf Coast of the United States), so in practical terms and the light of this work it is unfeasible, especially considering that 'Pemex's maximum purchase price is USD 0.41/L and the production cost of second-generation bioethanol calculated is USD 0.59/L.

Although in a strict sense, the price of producing second-generation ethanol is above the limit established by PEMEX and also the cost of the imported product, it is considered that it is possible to establish incentives for its production in Mexico. Such as the reduction in dependence on imported gasoline, the increase in the fuel inventory, the generation of related direct and indirect jobs, an additional economic spill in the corn-producing sector, as well as annual revenues for the State estimated at around 3 trillion pesos (millions of millions) for the Value Added Tax and estimated income of 862 million pesos from the Income Tax, which could be reoriented as a tax incentive to reduce the effect of the surcharge.

The financial evaluation of an ethanol biorefinery project is carried out, which works from the transformation of lignocellulosic biomass, with an installed capacity of 2 Gg/day (stubble) of corn, using the simultaneous saccharification and fermentation technology (SSF). A profit margin of 15% is considered based on total costs and taxes, with a base price of 0.6996 USD/L and an operation of 300 days a year at 80% of the installed capacity for a 20 years period. According to the *Secretaría de Hacienda y Crédito Público* (SHCP is its acronym in Spanish; Ministry of Finance and Public Credit), the social discount rate used is 10%. The initial investment of plant and land (fixed assets) is estimated at USD 498 million, and the residual value after 20 years is assumed as 10% of the value of the initial investment.

Under the assumptions considered in the previous paragraph, the calculated Net Present Value (NPV) is USD 51.5 million, and the Internal Rate of Return (IRR) is 11.45%.

Despite the assumptions considered in the above paragraphs, some alternatives, based on the development of new cellulolytic enzyme blends, can make a difference in the lignocellulosic 'biorefineries' economic feasibility. One of the main costs in the SSF process is related to the pretreatment of the raw materials because the enzymes (enzymatic hydrolysis) used to go up to 30% of the production cost [51]. According to Patel et al., 2021, the integrated lignocellulosic biorefinery has a high potential to provide second generation ethanol at a competitive price to the end user by conjugating bulk production of value added products like oligosaccharides, lactic acid, and polyhydroxyalkanoates. Patel et al., 2021, also show enormous potential opportunities to develop commercially feasible routes to extract and convert biomass lignin and hemicelluloses for high-value products and second-generation ethanol production from cellulose to utilize the full value [51].

5. Conclusions

Lignocellulosic biomass as an input in the production of anhydrous ethanol (second-generation fuels) is feasible from a technological perspective since, in addition to not competing directly with food production (and the effects that this entails), processes such as SSF allow efficiency transformation rates greater than 10% by weight.

An essential advantage of using corn stubble as an input in ethanol production in Mexico is the potential for job creation coupled with the emergence of a stubble market, which currently has no significant commercial value. This small change in the value chain would incorporate the potential for generating and spilling resources of 1144 million dollars per year in addition to what is currently generated by the market for agricultural corn production at the national level.

The ethanol demand to cover the E5.8 scenario (as currently allowed by the Mexican Regulatory Framework) is estimated to be equivalent to 1 Tg (concerning the average gasoline produced by PEMEX), a value that is well below production potential. Even in Scenario E10, demand does not reach 2 Tg (less than half of the production potential), so the use of this technology does not represent a limitation in this regard.

The significant drawback of the possible use of second-generation ethanol under the conditions considered in this work is the price since the opportunity cost criterion set by PEMEX for the purchase of ethanol makes this input compete in price against first-rate ethanol from the U.S. market generation on the Gulf Coast, which currently leaves it out of the competition. Possible alternatives can be found in what other countries have done, such as the United States itself, which started with the National Energy Act of 1978 and took the first step towards developing the ethanol market based on mechanisms and tax incentives schemes.

Finally, if a base price for ethanol in Mexico of USD 0.6996/L (29 cents above the price set with the opportunity cost formula) is considered, a biorefinery project with an installed capacity equivalent to 2 Gg/day would be financially viable, generating an IRR of 11.45%, which exceeds the Social Discount Rate established by the SHCP for this type of project (10%).

There is a great leap to be made in using this type of technology in Mexico; however, the technical feasibility bases seem trustworthy. It only remains to develop economic feasibility. The improvements on the enzymatic blends in conjunction with obtaining and marketing high-value by-products make the future of this process promising.

The limitations of this work rely on the fact that some assumptions come from theoretical research based on other authors that could be updated by the advancement of technology and is also limited by the legal framework in Mexico, which is not a constant.

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