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Exploring Corn Cob Gasification as a Low-Carbon Technology in the Corn Flour Industry in Mexico

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Abstract: In 2021, Mexico produced approximately 24.2 million tons of white corn, generating 3.6 million tons of corn cob residue. The final disposal of corn cob poses an environmental challenge in certain regions. This study examines the technical–economic feasibility and the greenhouse gas (GHG) mitigation potential of integrating a small-scale cogenerating gasifier fueled by corn cob into a nixtamalized corn flour manufacturing small and medium-sized enterprise (SME). This integration enables the generation of heat and electricity from the produced synthesis gas. Moreover, the process yields residual carbon, which can be used as biochar for soil restoration and removing atmospheric CO₂. This option holds significance for the corn flour agroindustry in Mexico, as, in 2021, it consumed approximately 601.9 GWh of electrical energy and 938,279 GJ of thermal energy from LP Gas in its manufacturing processes to produce 2.6 million tons of nixtamalized white corn flour. These processes contributed to a total emission of 410,232 tons of CO₂ into the atmosphere. The findings of this study demonstrate a cumulative reduction of 51.7% in CO₂ emissions, resulting in economic benefits of USD 85,401 in 2017 for a case study SME that annually produces 1039 tons of corn flour. This study reveals the integration of a gasifier–cogenerator system fueled by corn cob as an economically viable low-carbon technology in the corn flour manufacturing industry.

Keywords: small CHP gasification; corn cob; biochar; Mexican flour industry; low carbon technology



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1. Introduction

Unlike first-generation bioenergy, agricultural and forestry residues constitute a renewable source of energy that has a greater capacity to reduce GHG emissions and replace fossil fuels [1]. Among the agricultural residues available in Mexico, corn cob constitutes the second most abundant residue after sugarcane bagasse [2,3]. Globally, in 2021, Mexico ranked ninth in corn production [4] and exported this food to 18 countries [5], ranking as the tenth most significant exporter of corn grains worldwide. In 2021, approximately 24.2 million tons of white corn were produced [6], generating 3.6 million tons of residual corn cobs (15% in weight [7]). In the period from October 2020 to September 2021, the destiny destination of 54.5% of white corn production was for human consumption, 18.2% for livestock consumption, 20.7% for self-consumption, 1.8% for exports, 0.7% for seed, and the remaining 4.1% were losses [8]. Currently, the consumption structure remains almost the same, with very slight variations. Corn cob is one of the primary residues of the maize harvest, along with stover and leaves [3]. While most residues remain in the field, most of the corn cob is generated in the agroindustrial process of corn grain production [9]. The composition of corn cob consists mainly of cellulose, 45%, lignin, 15.8%, and hemicelluloses, 33.6% [10,11]. It serves as a support to mitigate soil erosion [12], and researchers have explored its potential for obtaining organic compounds [13] and other industrial products [14–16]. However, its high content of lignocellulosic materials limits its use as an input for chemical product transformation [17,18]. Due to the high degree of lignification of corn cob, its low digestibility, and its low nutritional content [19], it is used as cattle feed only during the dry or drought seasons.

However, some regions in Mexico exhibit a much higher corn production compared to consumption, resulting in the final disposal of corn cob as an environmental problem [2]. Thus, there is a need for a more modern energy valuation of corn cob. Studies on the energy utilization of corn cob have been conducted since the beginning of the last century. A wide variety of thermochemical processes have been studied and applied [20,21], such as direct combustion, pyrolysis, gasification, and also biochemical processes: fermentation [22] and biodigestion [23].

Numerous studies agree that the thermochemical conversion of biomass by gasification is a technological alternative that is already commercially available for the transformation of lignocellulosic biomass into syngas, bio-oil, and waste coal [10,24–26]. The synthesis gas, or syngas for short, which is obtained by gasifying biomass above 700 °C typically contains approximately $18\% \pm 4\%$ hydrogen (in mass units), $18\% \pm 3\%$ carbon monoxide, less than 4% methane, and $13\% \pm 3\%$ carbon dioxide [27]. The composition of syngas primarily depends mainly on the gasification temperature [9].

Syngas is usually used by direct combustion in boilers, burners, furnaces, and dryers [28]. When burned in an internal combustion engine, the mechanical energy produced can also produce electricity when coupled to a generator [29,30]; in addition, heat can be recovered from engine exhaust gases [31] or by direct combustion in burners [28].

Biomass gasifiers also have liquid by-products such as tar or bio-oil [32,33]. Second-generation liquid biofuels such as ethanol, methanol, and diesel can be produced from syngas refining [33].

In theory, an ideal gasifier regularly operating at temperatures above 700 °C [34,35] should not produce residual carbon; however, in practice, 5% to 10% by weight of the input biomass is converted to residual carbon or biochar [36,37]. This biochar has a high carbon content and has multiple applications, including its use in producing supercapacitor catalysts [38], filtering tar from combustion or gasification gases, acting as a catalyst in biodiesel production, and reducing nitrogen oxides [39]. The IPCC 1.5 °C special report recognizes biochar as a carbon removal technique due to its capability of sequestering carbon from the atmosphere, and when biochar is reintegrated into the soil, as a soil structure improver or fertilizer as it has the potential to remain in the soil for hundreds of years [40–43].

The total mitigation potential of residual biomass gasification is then the sum of the CO₂ emissions removed from the atmosphere, as they are stored underground in biochar, and the avoided emissions are due to the substitution of fossil fuels used for the cogeneration of heat and power.

This article displays the corn flour manufacturing industry's technical–economic feasibility and GHG mitigation potential by integrating a commercial small CHP gasifier fed by corn cob; it will co-generate heat and power from the synthesis gas obtained. This article quantifies the potential for mitigating GHG emissions in the corn flour industry. It considers substituting LP gas in conventional boilers by introducing corn cob as a fuel in a gasifier to produce synthesis gas and co-generate heat and electricity with it and biochar as a by-product. The mitigation potential also includes substituting electricity from the grid and carbon removal from the atmosphere due to using biochar for soil restoration, resulting in carbon storage.

We are considering, on the one hand, the abundant amount of residual corn cob in some regions of Mexico and, on the other hand, the energy needs of the corn flour industry in Mexico. In this article, we propose, for the first time in the literature, the gasification of corn cob for heat and power generation in this industry. We also are accounting for the GHG mitigation benefit from the reutilization of residual carbon as biochar for soil restoration and CO₂ sequestration. Furthermore, we present the technical–economic feasibility results and the potential of GHG mitigation in an SME of nixtamalized corn flour case study.

2. Materials and Methods

2.1. Corn Characterization

We conducted a literature review on studies that performed proximate and elemental analyses of corn cob. The results of the proximate analyses are presented in Table 1. The corn cob is a residue from the corn grain agroindustry and it can be directly utilized as fuel due to its calorific value and high carbon content [44]. Table 1 provides typical values for the fixed carbon content in corn cob from various countries. The results obtained from proximate analysis range from 11.7% to 21.3% by weight [9,10,28,45–48]. Fixed carbon represents the mass of organic matter that remains after moisture and volatile material release due to increasing biomass temperature in this analysis. It plays a crucial role in energy applications, as almost all fixed carbon forms carbon dioxide during combustion reactions [49].

Table 1. Values obtained from the proximate analysis of corn cob.

Moisture (%)	Volatiles (%)	Ash (%)	Fixed Carbon (%)	Country	Reference
10.00	80.79	1.81	17.40	Colombia	[9]
5.30	74.85	8.18	11.70	USA	[10]
-	78.70	0.90	16.20	Thailand	[45]
4.60	79.90	1.80	13.70	South Africa	[46]
10.10	80.06	2.12	17.82	Italy	[28]
5.10	65.10	8.50	21.30	South Africa	[48]
10.52	65.23	7.71	16.54	Colombia	[50]

Elemental values of C, H, O, N, and S and the higher calorific value obtained through calorimetry are displayed in Table 2. The higher calorific value ranges from 14.37 to 19.34 MJ/kg. Based on the provided information, the elemental composition, calorific value, emission factors, and amount of ash per biomass unit were determined to characterize the corn cob.

Table 2. Corn cob elemental analysis.

C (%)	H (%)	N (%)	S (%)	O (%)	Lower/Higher Calorific Value (MJ/kg)	Reference
47.82	5.50	0.38	0.40	44.09	17.97/19.34	[9]
51.80	5.50	0.84	0.34	41.60	-	[10]
45.50	6.20	1.30	-	47.00	-	[45]
50.20	5.90	0.42	0.03	43.50	19.14 *	[46]
47.60	6.10	0.52	-	45.78	17.33/18.56	[28]
46.2	5.42	0.92	0.24	47.22	18.36 *	[51]
44.40	5.6	0.43	1.30	48.27	18.02 **	[48]
39.95	4.97	0.60	-	47.42	14.7 ***	[50]

* Higher Heating Value; ** Non specified; *** Lower Heating Value.

Carbon and oxygen are the main components of solid biofuels and are involved in an exothermic reaction during combustion, generating CO₂ and H₂O [52]. Table 2 exhibits that for all corn cob samples, carbon content ranged from 39.3% to 51.8%, oxygen content ranged from 41.6% to 48.3%, and hydrogen content ranged from 5.0% to 6.2%.

The literature normally recommends a biomass moisture content below 20% for optimal gasification. In this article, we assume a 10% average moisture content, an 80.42% volatile material content, and a 17.65 MJ/kg lower calorific value, which represents the average values obtained from [9,28]. Based on these assumptions, it can be asserted that the volatile content is relatively high compared to other biomass studies, which creates favorable conditions for the generation of synthesis gas. Furthermore, the calorific value and the percentage contents of fixed carbon and ash are considered average.

2.2. Gasification of Corn Cob for Cogeneration and Residual Biochar

There are many routes for treating biomass for bioenergy; among the most employed are the biological and thermochemical processes. Gasification, as one of the thermochemical options, has gained significant recognition [53]. Gasification involves the conversion of biomass via partial oxidation reactions into synthesis gas, also known as syngas or producer gas. Syngas primarily consists of hydrogen (H_2), methane (CH_4), carbon monoxide (CO), carbon dioxide (CO_2), and water vapor (H_2O), making it suitable for environmentally friendly cogeneration applications [53]. In addition to syngas, the gasification process allows for the production of valuable by-products, including bio-oil and biochar. Utilizing corn cobs through gasification presents a sustainable approach to valorizing this residue, a by-product of the grain corn agroindustry [14].

Some authors are still considering gasification technology as emerging [54]; nevertheless, a range of small-scale gasifier manufacturers are already available in the market, typically designed for capacities between 5 and 100 kW_t . Most gasifiers require forest biomass with a maximum moisture content of 20% [55]. To accommodate a broader range of biomass inputs, including firewood, agricultural residues, and agro-industrial residues, we sought a versatile gasifier capable of accepting biomass with a moisture content of up to 30% (by weight). The Power Pallet [56] meets these criteria. According to the manufacturer's specifications, this gasifier incorporates a multi-stage gasification system, which involves preheating the biomass input to reduce its moisture content to suitable levels for gasification. This flexibility enables the utilization of different forest or agricultural biomass sources with high efficiency, as shown in Figure 1 and Table 3. The PP30 gasifier integrates a 25 kW_e electric generator and cogenerates up to 50 kW_t of thermal energy through process heat recovery. It operates with a specific biofuel consumption of 1 kg Biomass/ kW_h and produces up to 0.08 kg of biochar per kilogram of biomass input [57].

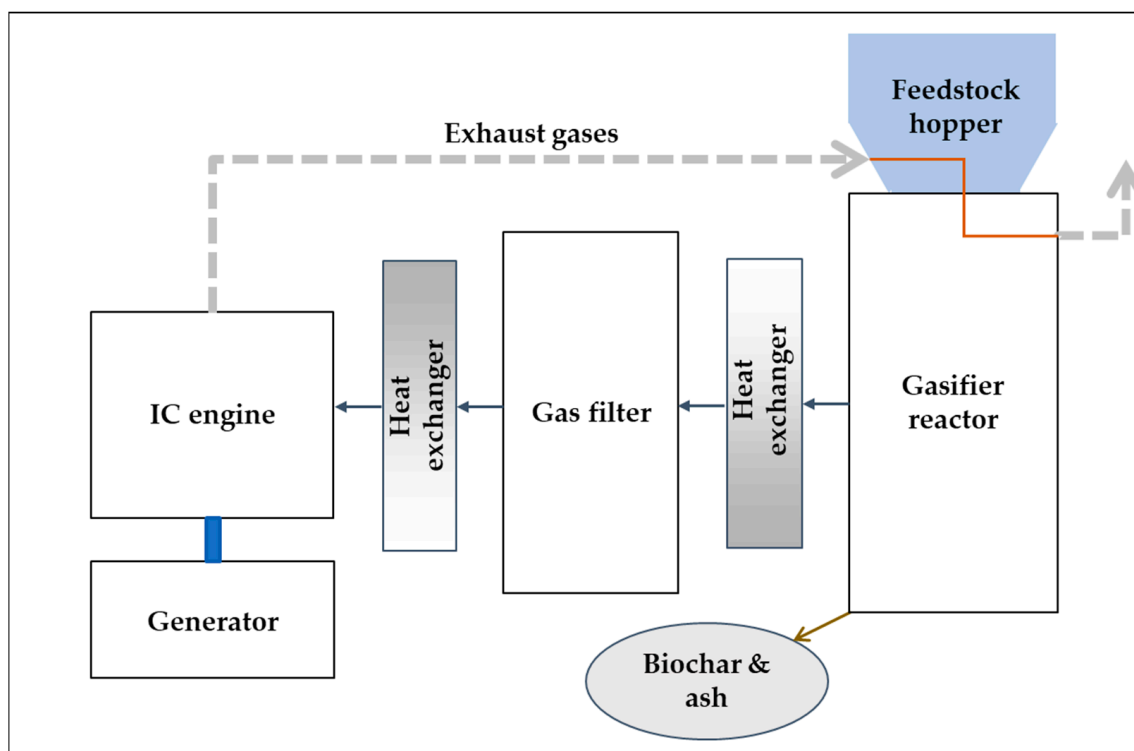


Figure 1. Simplified arrangement of components of the PP30 gasifier. Source: [58].

Table 3. All Power Labs PP30 operation specifications.

Parameters	Value	References
Max. continuous operation	24 h	[56]
Electrical efficiency (wood to power)	23%	[56]
Gasification efficiency (wood to gas)	82%	[56]
Cost without shipping and installation	55,000 €	[57]

In this study, we utilized the available information of a small-scale cogenerating gasifier manufactured by All Power Labs, model PP30, which features a downflow reactor with fixed bed architecture and has a single throat and a patented Imbert-type design (refer to Figure 1) [58]. Once the user turns on the reactor, it reaches operating temperature in approximately 30 min, ranging from 860 to 950 °C. The heating rate varies depending on the balance between combustion and reduction reactions. At the bottom of the reactor is a stirring and moving grate, facilitating the discharge of biochar through an auger. Considering the grate basket's consumption and geometrical data, the char's residence time is estimated to be around 4 h. The plant design incorporates dry filtration for gas cleaning, wherein the gas is cooled and filtered using felt bags above the water dew point. This method enables gas filtration without condensing tarry compounds, as they are retained within the baghouse [58].

2.3. Scenario Building Methodology

The methodology employed in this study involves comparing technological scenarios to assess the feasibility of integrating corn cob gasification into the corn flour manufacturing process. The reference year chosen is 2022, as it provides the necessary technical and economic information for scenario construction. The analysis period is 20 years, which aligns with the typical equipment lifetime.

The first scenario, known as the Base Scenario (BS), uses steam boilers fueled by LP gas to provide process heat to corn flour production in small and medium enterprises in Mexico. The required electricity is purchased from the CFE distribution network. This scenario presents the calculations of thermal and electrical energy consumption and GHG emissions.

In the Alternative Scenario (AS), a significant portion of the heat required for corn flour manufacturing is provided by cooling both the syngas from corn cob gasification and the exhaust gases resulting from the combustion of the syngas in an internal combustion engine that drives an electric generator. We assume that all the electricity generated in this scenario is consumed in the corn flour production process, with any remaining demand being met by electricity from the grid. Unlike the Base Scenario, a smaller LPG-fired steam boiler is utilized to cover the thermal demand not met by the cogenerating gasifier. The scenario calculates thermal and electrical energy consumption and the associated GHG emissions.

Furthermore, we conduct a cost–benefit analysis to determine the economic feasibility of both scenarios, making the following assumptions. We assume a zero cost for the corn cob because, as already mentioned, some Mexican regions have high corn productivity, such as the one assumed in this case study, where the corn cob is a residual product that involves transportation costs to its final disposal site; in contrast, in this study, we assume that the corn cob is in situ at the flour plant and therefore its cost is zero. Also, to determine the cost of LPG and electricity over the 20-year analysis period starting in 2022, we use official forecasts, see Figure 2.

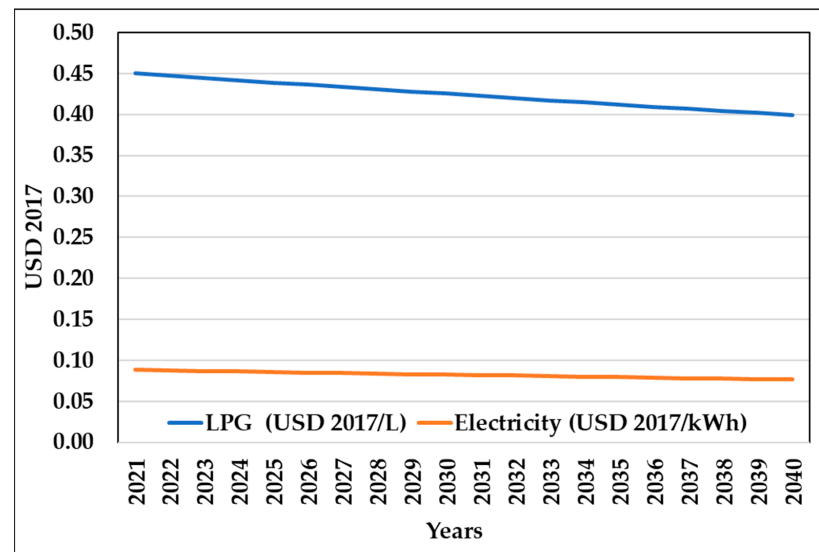


Figure 2. Electricity and LPG future price scenarios. Source: Own elaboration based on data from [59–61].

2.4. Cost Analysis Methodology

The following cost model was developed following [62], and was applied to estimate the costs of the options analyzed in the comparison between feedstock LPG and electricity in the Base Scenario and corn cob feedstock for heat and power generation in the Alternative Scenario, where:

$$CT_{AS-BS} = C1_{AS-BS} + C2_{AS-BS} + C3_{AS-BS} \quad (1)$$

$C1_{AS-BS}$ = Investment incremental costs in present value in the AS

$C2_{AS-BS}$ = Operation and maintenance costs in present value in the AS

$C3_{AS-BS}$ = Avoided energy costs in present value in the AS

with:

$$C1_{AS-BS} = \sum_{y=0}^p \frac{IC_{ASy} - IC_{BSy}}{(1+r)^y} \quad (2)$$

where:

IC_{ASy} = Investment costs in relation to the implementation of the AS for any year y of period p .

IC_{BSy} = Investment costs incurred from the BS for any year y of period p .

y = Year

p = Analysis period

r = Discount Rate

with:

$$C2_{AS-BS} = \sum_{y=1}^p \frac{OMC_{ASy} - OMC_{BSy}}{(1+r)^y} \quad (3)$$

where:

OMC_{ASy} = Operation and maintenance annual costs of the AS in the year y of period p .

OMC_{BSy} = Operation and maintenance annual costs of the BS in the year y of period p .

with:

$$C3_{AS-BS} = \sum_{y=1}^p \frac{EC_{ASy} - EC_{BSy}}{(1+r)^y} \quad (4)$$

where:

EC_{ASy} = Annual costs from energy required of the AS implementation in the year y of period p .

EC_{BSy} = Annual costs from energy used in the BS for any year y of period p .

To obtain the net present value (NPV) of the incurred costs, we considered a discount rate (TD) of 12% and an analysis period of 20 years because it is equal to the useful life of the gasifier reactor.

3. Case Study: Corn Flour Production

3.1. Description of the Production Process

Healthy and clean corn grains are subjected to alkaline cooking and grinding to obtain nixtamalized corn flour [63]. This process, known as traditional nixtamalization, involves cooking the corn grains in a solution of calcium hydroxide $\text{Ca}(\text{OH})_2$ at a 1% concentration per kilogram of grain (w/w) dissolved in water at 90 °C for 40 min. The ratio is 2 L of water to each kilogram of grain [64]. This cooking softens and breaks the pericarp of the grain, increases its moisture content, and makes it easier to grind into a dough known as “nixtamal”. The term “nixtamalization” comes from the Nahuatl words “nextli” (ash lime) and “tamalli” (cooked corn dough) and refers to the process of alkaline cooking of corn grains.

After washing, the grain is crushed in a stone mill to obtain fresh dough with a moisture content ranging from 45% to 55%. It is then passed through a flash dryer at 260 °C for 4 s to obtain dehydrated dough as lumps with a 10% maximum moisture content [64]. The lumps are subsequently pulverized in a hammer mill, and the resulting flour is sieved through a 0.5 mm mesh. Once sieved, the flour is ready to be packaged and stored (see Figure 3).

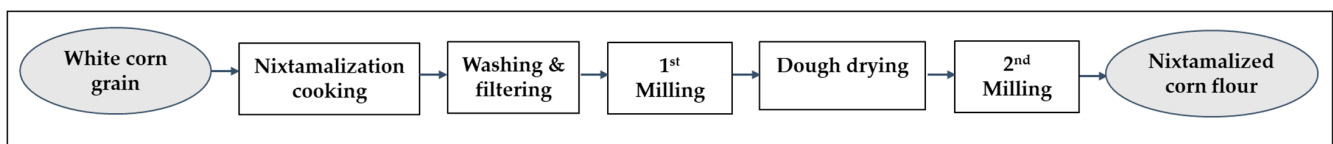


Figure 3. Stages in the manufacturing process of nixtamalized corn flour.

Electrical energy is required to provide mechanical energy through electric motors for pumping water, transporting cooked grain, washing and rinsing cooked grain, wet grinding of nixtamal, dry grinding of flour, sifting/sifting, and packaging flour. The thermal energy requirements are for the alkaline grain cooking and wet dough drying stages. Table 4 shows the average energy consumption per kilo of white corn grain.

Table 4. Average unit consumption of thermal and electric energy for the corn flour manufacturing process; CO₂ Emission Factors due to LPG combustion in boilers and electricity consumption from the grid of the Mexican Electric System (MES).

Process	Thermal Energy (kWh _t /kg Grain)	Electric Energy (kWh _e /kg Grain)	References
Cooking	0.273		[65]
Drying	0.402		[66]
Wet grinding—stones		0.041	[65]
Dry Grinding—hammers		0.075	[67]
Add energy	0.675	0.116	
CO₂ Emission Factors (kgCO₂/kWh)			
LPG	0.234		[68]
Electricity from MES		0.505	[69]

3.2. Base Scenario

The Base Scenario considers a small and medium-sized industry (SME) with the capacity to produce 1039 tons of nixtamalized white corn flour annually. This study assumes that this production is achieved by operating two shifts of eight hours per day, five days a week throughout the year (3840 h). According to [65], for every kilogram of white corn grain, 0.93 kg of flour is obtained. Using the unit values from Table 4, we determined the daily energy demand for this production, resulting in 3145 kWh_t/day of thermal energy and 540 kWh_e/day of electrical energy.

The electricity supply in this scenario is from the Federal Electricity Commission (CFE, by its acronym in Spanish) distribution network, demanding a total necessary for an installed capacity of 33.7 kW_e, and all the required heat is supplied by the combustion of LPG to produce steam in a pyrotubular boiler with a capacity of 196.5 kW_t (equivalent to 20 BHP (Boiler Horsepower)) [70] and an efficiency of 82%. To perform the cost analysis of this BS scenario, we will use the information given in Table 5.

Table 5. Unit investment cost and investment cost of a 20 BHP boiler.

Equipment	Cost	Units	References
Unit investment cost 20 BHP boiler	USD 402.00	USD */W	[71]
Investment cost 20 BHP boiler	USD 79,011.89	USD	Own calculations with data from [71]

* Constant 2017 USD.

3.3. Alternative Scenario

This scenario considers the reuse of corn cob for the partial substitution of fossil fuels involved in the annual manufacturing of 1039 tons of nixtamalized corn flour. Corn cob is a residue of the corn agroindustry; for each ton of corn grain, 150 kg of corn cob is obtained [65]. See Figure 4, a scheme showing the integration of a biomass CHP gasifier to the nixtamalized white corn flour manufacturing process.

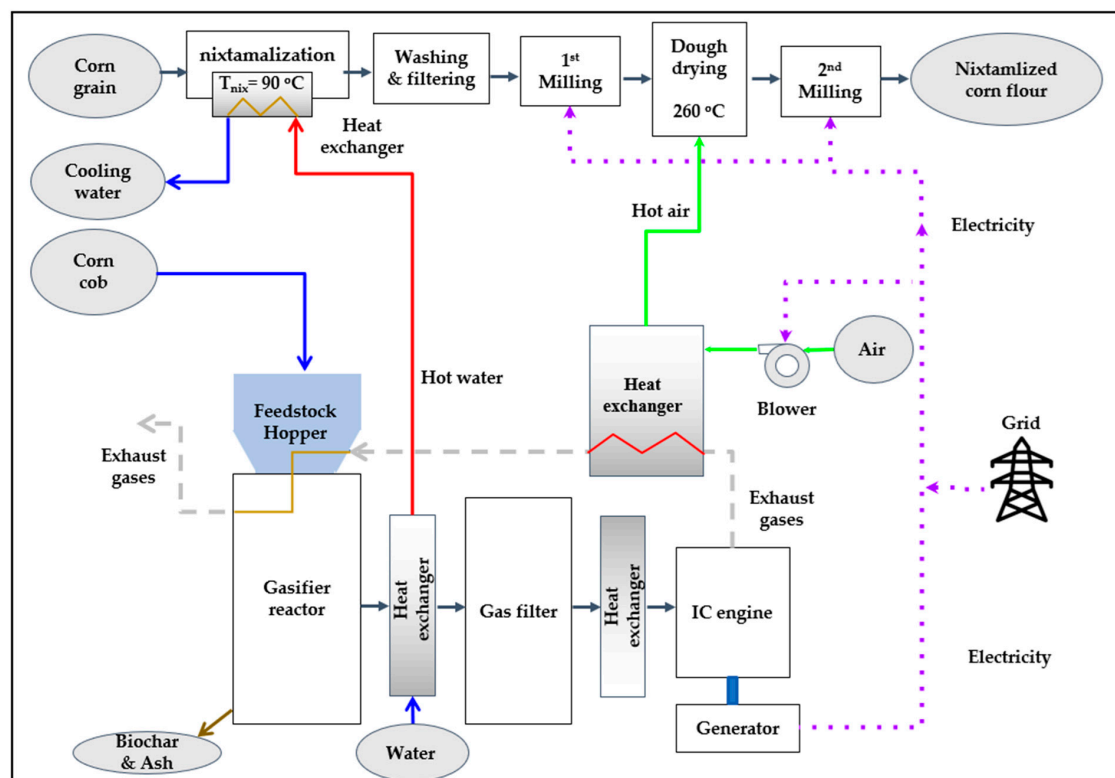


Figure 4. Scheme of the integration of a CHP gasifier, with its components disaggregated.

The corn cob will be the input for a cogenerating biomass gasifier. Using corn cob with the characteristics presented by [9] is considered (see Tables 1 and 2). Also, the gasifier–cogenerator equipment considered is that described in Section 2.2, which generates 25 kW_e of electrical energy and 50 kW_t of thermal energy with an input of 27.5 kg of biomass fuel per hour. However, the above annual production requires more than this cogeneration capacity. An extra heat generator, an LPG boiler of the same type as the one in BS, must be included to satisfy the thermal demand. Nevertheless, with a smaller capacity, 147.7 kW_t (15 BHP) [70], and to satisfy the electrical demand, the purchase of electricity from the grid is needed. To perform the cost analysis of this AS scenario, we will use the information given in Table 6.

Table 6. Unit investment cost and investment cost of a 15 BHP boiler and a CHP gasifier.

Equipment	Cost	Units	References
Unit investment cost CHP gasifier	USD 2376.0	USD/kW _e	[57]
Investment cost CHP gasifier 25 kW _e	USD 59,400.0	USD	Own calculations with data from [57]
Unit investment cost Boiler	USD 402.0	USD/kW _t	[71]
Investment cost 15 BHP boiler	USD 59,375.8	USD *	Own calculations with data from [71]

* Constant 2017 USD.

4. Results

4.1. Reduction of GHG Emissions

Based on the average unit consumptions provided in Table 4, the production of 270.8 kg of flour per hour, operating in two shifts per day, five days per week throughout the year to achieve a total production of 1039 tons per year of nixtamalized white corn flour, requires an installed thermal capacity of 196.5 kW_t and an electrical equipment capacity of 33.7 kW_e. We obtained the following emission scenarios by applying the CO₂ emission factors associated with the National Electric System and LPG, as summarized in Table 7 and Figure 5.

Table 7. Annual, cumulative, and avoided CO₂ emissions (tCO₂) in the Base Scenario (BS) and in the Alternative Scenario (AS), and the total emissions reduction.

	Annual tCO ₂	Accumulated over 20 Years tCO ₂	Cumulative Avoided Emissions AS-BS tCO ₂	% Cumulative Emissions Reduction (AS-BS)/BS
LPG emissions in BS	176.6	3531.4		
Grid electricity emissions in BS	<u>65.4</u>	<u>1307.0</u>		
Total BS emissions	241.9	4838.4		
LPG emissions in AS	131.6	2632.0	899.4	18.6%
Grid electricity emissions in AS	<u>17.5</u>	<u>349.0</u>	<u>958.0</u>	<u>19.8%</u>
Total AS emissions	149.1	2981.0		
Emissions avoided by energy substitution	92.9		1857.4	38.4%
Emissions avoided by storage in Biochar	<u>31.1</u>		<u>622.0</u>	<u>12.9%</u>
Total avoided emissions	124.0		2479.4	51.2%

Source: Own elaboration.

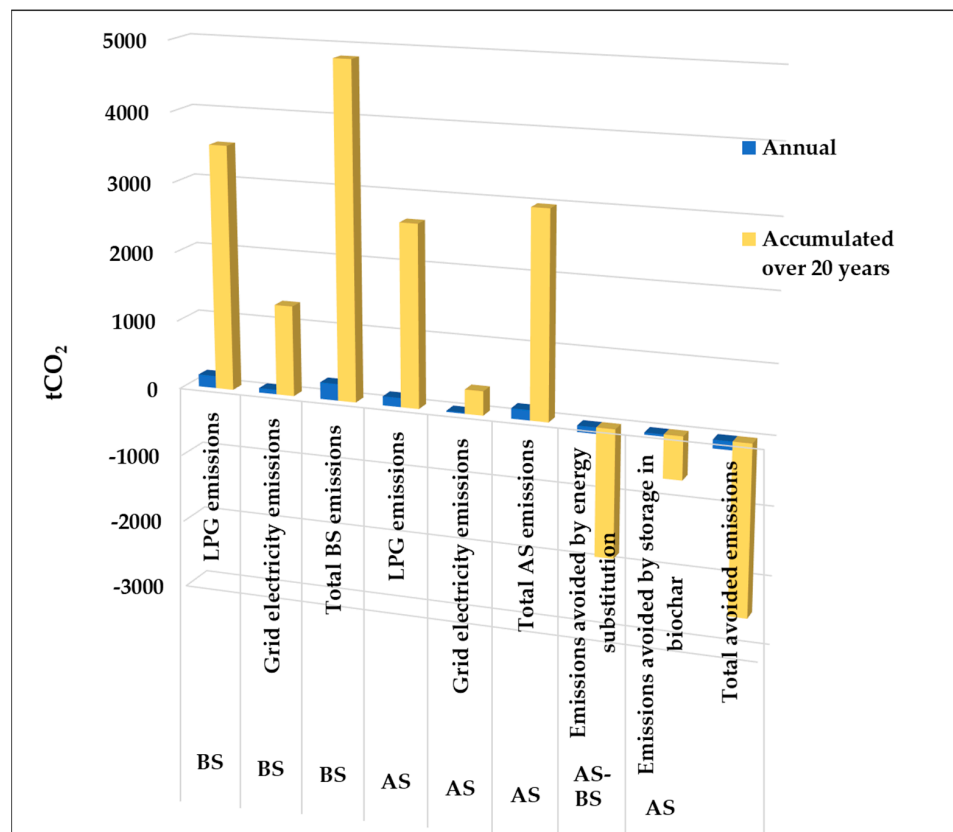


Figure 5. Cumulative CO₂ emissions in tons. In the traditional BS, and avoided emissions in the AS due to the use of a smaller size LPG boiler and integration of a corn cob gasifier that produces heat, electricity, and biochar.

In the Base Scenario, we observe that all thermal energy is supplied by a 196.5 kW_t boiler fueled by LPG, while all the electricity consumed is sourced from the CFE network. The annual emissions in this scenario amount to 241.9 tons of CO₂, with 73% attributed to thermal demand and 27% to electricity demand.

In the Alternative Scenario, we introduce a gasifier that utilizes corn cob as fuel, providing 27.5 kg/h. This gasifier generates 50 kW_t of thermal energy and cogenerates 25 kW_e of electricity. Additionally, heat generation is complemented by a 146.5 kW_t boiler, and an additional electricity requirement of 8.7 kW is purchased from the CFE network to meet the same energy demand as in the Base Scenario. The Alternative Scenario results in annual emissions of 149.1 tons of CO₂, with 88% corresponding to the thermal demand of the boiler and 12% to the electrical demand.

Thanks to the integration of corn cob gasification, which accounts for 25.4% of heat generation and 74.2% of electricity generation, a reduction of 92.9 tCO₂ per year is achieved compared to the Base Scenario. This reduction corresponds to a decrease of 38.4% relative to the Base Scenario. Furthermore, as mentioned in Section 2.2, corn cob gasification also generates biochar as a by-product, with an average production of 80 g per kilo of corn cob, equivalent to 2.2 kg of carbon per hour, which further translates to 8.1 kg of CO₂/h. Over a year, this amounts to 31.1 tons of avoided CO₂ emissions, assuming the biochar is a soil improver and restorer. Importantly, the biochar remains stored in solid form for extended periods, effectively removing CO₂ from the atmosphere. This additional atmospheric removal represents a further reduction of 12.9% compared to the Base Scenario. When combined with the reduction mentioned above, the total avoided emissions reach 124.0 tons per year, summing up to 2479.4 tCO₂ in all the analyzed period, corresponding to a total reduction percentage of 51.2% compared to the Base Scenario. The contribution

to emission reduction from corn cob gasification, which partially substitutes LPG and electricity, accounts for 18.6% of thermal and 19.8% of electrical energy.

When comparing the two scenarios of corn flour production in relative terms, we verified that the total energy consumption per mass product unit is the same in both scenarios, as we initially assumed (0.791 kWh/kg corn flour). Nevertheless, introducing a corn cob gasifier into the manufacturing process significantly reduced CO₂ emissions per product unit. Specifically, emissions decreased from 233 grCO₂/kg corn flour in the BS to 114 grCO₂/kg corn flour in the AS, representing a substantial overall reduction of 51.2% per product unit.

4.2. Cost Analysis

Data from Tables 5 and 6, Figure 6, and Table 8 show the resulting costs in net present value, considering a discount rate of 12% and an analysis period of 20 years due to the useful life of the gasifier [56]. Although the investment and O&M costs are 33% and 54% higher in the AS, respectively, considerable savings are obtained in LPG and electricity, although its price reduction is expected, see Figure 2. A notable saving is in electricity, which, in the AS, costs approximately only a quarter of the BS. Furthermore, the NPV of the cash flow is negative, which indicates that this investment will not only be recovered but will also yield benefits.

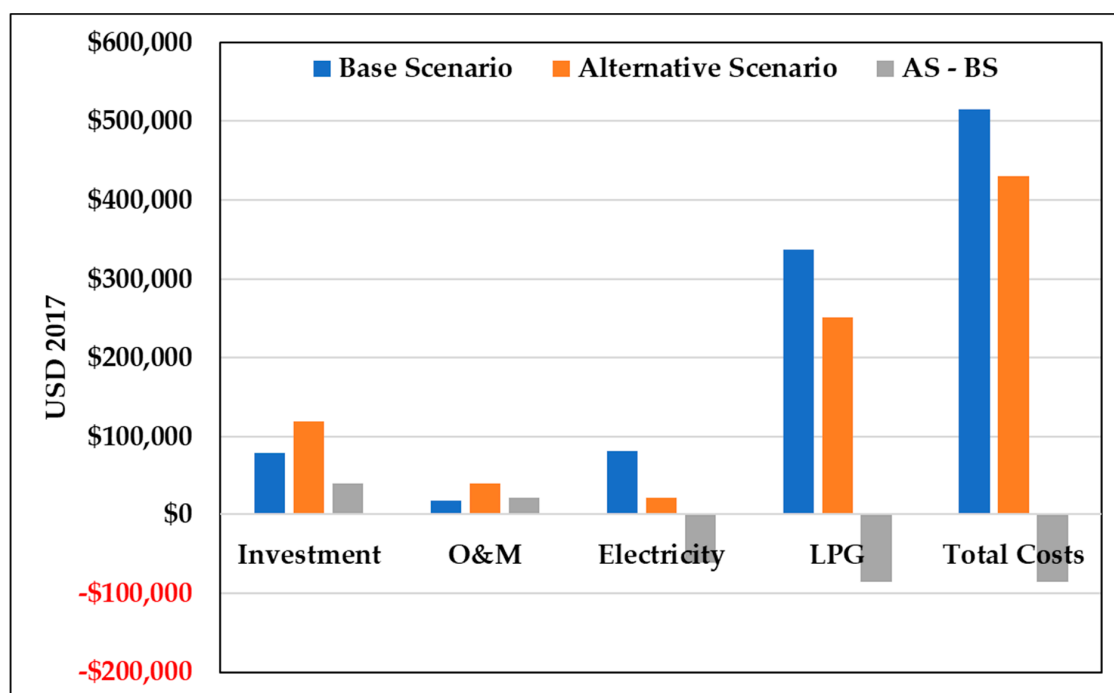


Figure 6. Net present value of investment, O&M, and energy costs in the Base and Alternative Scenarios.

Table 8. Net present value of investment, O&M, and energy costs and the total costs in the BS, the AS, and the difference between the two scenarios.

	BS	AS	AS – BS
Investment	USD 79,012	USD 118,776	USD 39,764
O&M	USD 17,705	USD 38,817	USD 21,112
Electricity	USD 81,776	USD 21,187	USD –60,589
LPG	USD 336,833	USD 251,145	USD –85,688
Total costs	USD 515,326	USD 429,925	USD –85,401

Source: Own elaboration.

The levelized cost of energy (LCOE) for each scenario (BS and AS) was estimated by annualizing the total costs presented in Table 8 and considering the annual thermal and electrical energy requirements, using kWh units, thus obtaining that for the Base Scenario the LCOE is USD 7.80 cents/kWh while for the Alternative Scenario it is USD 6.51 cents/kWh, which indicates that the energy cost for the AS is 17% lower than that found for the BS, which reiterates that it is economically viable to use corn cob as an option to mitigate climate change.

The mitigation cost of the partial substitution of a conventional LPG boiler for a cogenerator gasifier with a smaller size boiler in the small and medium-sized nixtamalized corn flour industry in Mexico, resulting from the ratio of the NPV of the cash flow between the avoided emissions, was $\text{USD } -85,688/2479 = \text{USD } -34.44/\text{tCO}_2$. Being negative, this value means that these expenses and investments result in a benefit in the long term. Another indicator of this investment's convenience is the investment's payback period; considering an additional investment cost of USD 39,764 divided by the annual equivalent value of the savings obtained, USD 16,757, the resulting payback period is 2.4 years. Table 8 presents the net present value of the investment, O&M, energy costs, and the resulting total cost. The calculations were performed considering the BS, the AS, and the difference between them.

5. Conclusions

This article analyzes the GHG mitigation potential and the technical–economic feasibility of a small-scale industry manufacturing 1039 tons of corn flour annually. The industry considers the integration of a gasifier with cogeneration capacity, which will be fueled by corn cobs, one of the major agricultural residues in Mexico. The gasification process produces synthesis gas, which can generate electricity when burned in an internal combustion engine coupled to a 25 kWe power generator. In addition, heat recovery from the engine's exhaust gases can produce up to 50 kWt of thermal energy, used in the corn flour manufacturing process jointly with the electricity that is generated initially. Moreover, biochar is obtained as a by-product of corn cob gasification, which will be used for soil restoration, CO₂ removal, and underground carbon sequestration. Due to this carbon removal plus the avoided emissions from heat and electricity generation from corn cob gasification, a low-carbon technology is harnessed in small-scale industries. This option represents an overall cumulative reduction related to the Base Scenario of 2479 tCO₂, which represents a 51.2% reduction in GHG emissions compared to the conventional system. In relative terms, the emissions decreased from 233 grCO₂/kg corn flour in the BS to 114 grCO₂/kg corn flour in the AS, representing a substantial overall reduction of 51.2% per product unit.

Finally, the mitigation cost of the partial substitution of a conventional LPG boiler for a cogenerator gasifier with a smaller size boiler in the small and medium-sized nixtamalized corn flour industry in Mexico, resulting from the ratio of the NPV of the cash flow between the avoided emissions, was $\text{USD } -34.44/\text{tCO}_2$, and since this value is negative, it means that these expenses and investments result in a benefit in the long term. Additionally, according to our results, the LCOE for the BS is USD 7.80 cents/kWh and the LCOE for the AS is USD 6.51 cents/kWh. This means that the energy cost for the Alternative Scenario is 17% lower than that found for the Base Scenario. Therefore, it is economically feasible to use corn cobs as an option to mitigate climate change.

This work shows, for the first time in the literature on gasification, the environmental and economic advantages of including a gasifier–cogenerator that takes advantage of a residue from the corn grain industry in the manufacturing industry of nixtamalized white corn flour in Mexico.

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Abbreviations

°C	Degrees Celsius
AS	Alternative Scenario
BHP	Boiler Horsepower
BS	Base Scenario
C	Carbon
Ca(OH) ₂	Calcium Hydroxide
CFE	Federal Electricity Commission (CFE, by its acronym in Spanish)
CH ₄	Methane
CHP	Combined Heat and Power
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
GHG	Greenhouse gas
GJ	Gigajoule
GWh	Giga watt hour
H	Hydrogen
H ₂ O	Water
IPCC	Intergovernmental Panel on Climate Change
kg	Kilogram
kW	Kilowatts
kW _e	Kilowatt electric
kWh	Kilowatt hour
kWh _e	Kilowatt hour electric
kWh _t	Kilowatt hour thermal
kW _t	Kilowatt thermal
LCOE	Levelized cost of energy
LPG	Liquefied Petroleum Gas
MES	Mexican Electric System
MJ/kg	Megajoule/Kilogram
mm	Millimeters
N	Nitrogen
NPV	Net present value
O	Oxygen
O&M	Operation and Maintenance
S	Sulfur
SME	Small and medium-sized enterprise
tCO ₂	Tons of Carbon Dioxide
USD	US Dollar
w/w	% Weight concentration

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