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Article

Profitability of corn ethanol production in different plant scenarios

Lucratividade da produção de etanol de milho em diferentes cenários de usinas

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Abstract: Productive efficiency and production costs are factors that impact the economic success of sugar and ethanol plants. Ethanol is a highly demanded product and, during the off-season period of sugarcane, its residual production is insufficient to supply the market. This generates the need for imports and adversely affects the Brazilian trade balance. In this context, the ethanol produced from corn figures as a potential alternative to ensure the market supply, generating revenue and diluting plants' operational costs by expanding its operational period throughout the year. However, access to raw materials and implementation costs can affect the economic viability of this activity. In this study, the objective was to evaluate if the profitability of corn ethanol is feasible within the context of a sugarcane-only plant to be adapted to flex, located in the state of São Paulo. The increment in the marketing margin of this fuel and its co-products was used as an indicator, taking into account the difference between the costs of raw materials in two regions. The results demonstrate that the marketing margin of corn ethanol is negative in the state of São Paulo due to its distance from major corn supplies in Brazil. Although, when we considered the potential revenue from co-products, the loss scenario is converted into profitability. Thus, it is concluded that the profitability of the corn ethanol production in this scenario depends on the commercialization of its co-products in consumer markets, such as pig farming and biodiesel plants.

Keywords: biofuels; costs; margin; raw material; sugar and ethanol plants.

Resumo: A eficiência produtiva e custos de produção são fatores que impactam o sucesso econômico das usinas no setor sucroenergético. O etanol é um produto com elevada demanda e, nos períodos de entressafra da cana-de-açúcar, sua produção residual é insuficiente para abastecer o mercado, gerando a necessidade de importação, desfavorecendo a balança comercial brasileira. Nesse contexto, o etanol produzido a partir do milho figura como potencial alternativa para garantir o abastecimento do mercado, gerando receita e diluindo custos operacionais das usinas ao expandir seu período de operação. Entretanto, o acesso à matéria-prima e os custos de implementação podem afetar a viabilidade econômica dessa atividade. No presente estudo, o objetivo foi avaliar se há lucratividade associada à produção de etanol de milho no contexto de uma usina "full" a ser adaptada para "flex", localizada no estado de São Paulo, distante da oferta de milho. Foi utilizado como indicador os incrementos na margem de comercialização deste combustível e seus coprodutos, levando em conta a diferença entre os custos da matéria prima nas duas regiões. Os resultados obtidos demonstram que, em São Paulo, a distância da cadeia produtiva do milho encarece o custo da matéria prima, tornando sua margem de comercialização negativa. Porém, considerando a potencial receita com coprodutos, o cenário de prejuízo é convertido em lucratividade. Dessa forma, conclui-se que a lucratividade da produção de etanol de milho, no cenário estudado, depende da comercialização dos coprodutos desta atividade junto a mercados de consumo como, por exemplo, a suinocultura e usinas de biodiesel.
Palavras-chave: biocombustíveis; custos; margem; matéria-prima; usinas "flex".

1. Introduction

Brazil is the world’s largest producer of sugarcane and stands out in terms of efficient ethanol production[1]. Despite Brazil's notorious position as an ethanol producer, in 2018 and 2019 imports of this fuel were detrimental to the country’s trade balance[2]. Noteworthy, even though there are quarterly quotas of 150 million liters as a limit for tax exemption on ethanol imports, the trend of a negative trade balance for this fuel has been maintained by the Ministério da Agricultura, Pecuária e Abastecimento (MAPA). Thus, it is necessary to study the possibility of complementing the offer of this product by increasing the national production from alternative sources, instead of importing it from other countries.

Among these alternatives, the production of ethanol from corn during the sugarcane off-season is one of the ways to increase plants’ revenue, by building new distilleries able to ferment cornstarch the industry opens opportunity to increase production and reduce industrial fixed costs since it reduces the off-season without ethanol production[3].

The corn ethanol production has additional processes compared to sugarcane’s due to the steps of reception and storage of grains, grinding, liquefaction, saccharification and, after fermentation and separation, which are common for corn and cane ethanol, the drying step, from which industry obtains the Dried Distillers Grain (DDG)[4]. Hence, adapting the plant must consider the construction of a grain reception sector followed by a grinding and cooking space, in which the liquefaction and saccharification processes will be performed. There is also the infrastructure demanded by the separation process that involves the acquisition of centrifuges, floaters and dryers aiming to separate and obtain the subproduct that comes from corn ethanol[5].

By considering the synergy associated with production integration of both types of ethanol, corn and sugarcane, there is room for optimize the utilization of technical infrastructures, such as fermentation vats and distillation columns), and also other utilities as steam and electricity generation equipment[6]. Such synergies denote low necessary investments for the plant integration (sugarcane and corn) and, consequently, the generated steam and electricity can be applied within the grain processment which encourages the sugarcane ethanol plant to use corn also as a raw material[6].

In the sugar-energy sector, the regional delimitation is based on geoeconomical characteristics, with the South-Central region comprising the South and Southeast macro-regions (except for the North of the state of Minas Gerais) in addition to part of the Center-West, represented by parts of the states of Goiás, Mato Grosso and Mato Grosso do Sul[7], [8].

Data from the systematic survey of agricultural production by the Brazilian Institute of Geography and Statistics (IBGE)[9] indicate that 53% of the national corn production for the 2019 and 2020 harvests was concentrated in the Center-West region, with 60% of this total originating in the state of Mato Grosso, totaling 63 million tons. The region also has a large area planted with sugarcane, providing an excellent scenario for installing flex type plants capable of producing ethanol from both these raw materials[2], [10]. In the first half of February 2021, the volume of ethanol produced from corn was around 110.88 from a total of 133.57 million of liters produced in Brazil’s South-Central region[11].

The Southeast region, on the other hand, comprises only 12.32% of the Brazilian corn production, with 24 million tons produced in 2019 and 2020, being the state of São Paulo accountable for 38% of this production, which corresponds to only 4.64% of the total national production[9]. However, the plants’ distribution on the Brazilian territory follows another pattern, where it is observed that in a total of 414 unities[12], 171 are located in the state of São Paulo and only 16 are in the state of Mato Grosso[2].

Therefore, while the South-Central geoeconomical region is limited in access to raw materials, the Center-West region is limited in installed capacity. From this, it is important to consider that the proximity of the production of alternative biomass sources, more specifically corn, can influence the viability of flex type plants. Additionally, the need for technical adaptation of the plants to produce ethanol from different biomass sources involves the acquisition of equipment and new structures, which should be taken into account.

Thus, the objective of this study was to evaluate whether the revenue generated from the production and commercialization of corn ethanol during the sugarcane’ off-season, given the associated costs, has the potential to increase the profit margins at plants in the state of São Paulo, or if this activity is restricted to particular cases where there are specific competitive advantages.

2. Material and Methods

In order to verify the non-supplied demand for ethanol during sugarcane off-season, data from the national production and consumption between 2017 and 2019 were collected. Those data were recovered from the

Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP) at the statistics data section for biofuels production, and also by the fuel's consumption section from the Sugarcane Observatory. From the information of those platforms, we were able to verify the deficit between production and consumption of ethanol in Brazil.

Furthermore, considering that the Sugarcane Observatory also provides data within ethanol imports in million on m³, we were also able to verify how internal demand, during the same time range, is supplied by external ethanol markets since imports have represented more than 20% of ethanol's availability between 2017 and 2019 (Figure 1).

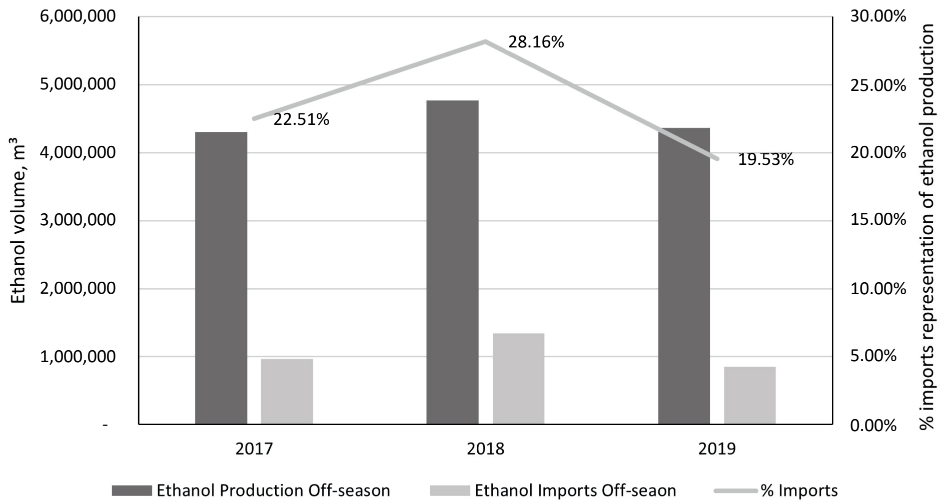

Figure 1. Ethanol import's share during sugarcane off-season (m³)

Source: Elaborated by the author based on statistical data of biofuels production[13] and fuel consumption history[14].

The profitability of corn ethanol production during sugarcane off-season was estimated considering two different scenarios regarding the following factors: proximity of major corn producing regions and previous infrastructure available for process and produce ethanol using corn as raw material. Hence, sugar and ethanol plants from the Center-West and Southeast regions provide an adequate contrast for the study.

In this study, the Center-West and Southeast regions of Brazil were represented by two plants at the states of Mato Grosso and Goiás (A Scenario) and one at the state of São Paulo (B Scenario), due to their relevance on corn grain and sugarcane ethanol production, respectively. The plants from the Center-West regionare denominated flex plants (i.e. are already adapted to produce ethanol from both corn and sugarcane), while the plant representing the Southeast region is a full plant (i.e. currently produces ethanol only from sugarcane).

To estimate the costs associated to converting a full plant into flex, the additional steps and necessary equipment were based on previous studies[15], [16] (Table 1), the prices of each necessary equipment will be exposed further in this study.

Table 1. Necessary equipment for adapting a full plant (sugarcane only) into flex (corn and sugarcane)

Extra step	Necessary equipment
Grain reception	Truck unloading system
	Grain pre-cleaning system
	Sample collector
	Truck unwinder
	Grain transport systems
	Silo
Grinding and cooking	Elevated metal silo
	Hammer mill
	Hydrolysis tank
	Motor pump
Separation	Tridecanter
	Dryer
	Flotter

Source: Adapted from Grippa[15]; Pereira[16].

The Capital Expenditure (CAPEX), defined by the total amount of money for acquiring the physical assets of infrastructure and present depreciation among time[17], were estimated considering the values provided by industry suppliers and the literature on this subject.

For estimation purposes, was considered that the capital for equipment acquisition would be obtained throughout the Agência Especial de Financiamento Industrial (FINAME) from Banco Nacional de Desenvolvimento Econômico e Social (BNDES), with a time horizon of the investment of ten years (120 months) which is the largest deadline provided by the bank, data regarding this financing program was obtained by using the total value funded through FINAME and BNDES as starting point to simulate the total cost. The simulation considering interest can be obtained by using the calculator available within FINAME webpage.

The extra costs directly associated to corn ethanol production were estimated considering specialized studies by PECEGE[18], in which the costs in Brazilian real per metric cube (BRL m^{-3}) of ethanol production for two flex plants were calculated considering manpower, industry supplies, industrial maintenance and industrial expenses.

In order to understand the contribution of the raw material in the final cost of corn ethanol production, the prices in the states of São Paulo (SP) and Mato Grosso (MG) were obtained from the Companhia Nacional de Abastecimento (CONAB) at the agricultural price section, where the prices must be obtained by selecting the average monthly prices tab, after the period between January 2019 and January 2020 (for corn prices in both states) must be selected; for sugarcane prices the period considered is between January 2018 and January 2019 since it reflects an entire season for sugarcane. Thus, corn (or sugarcane) must be selected together with producer and SP and MT, the final values for average prices were calculated by using the average between the average monthly prices regarding both season and off-season periods separately.

The average cost of ethanol production in a scenario of a full sugarcane plant located in the SP was calculated from data obtained from a plant within this scenario, considering previous productive years. Since corn prices are provided considering a sack of 60 kilos (BRL $sack^{-1}$), the conversion of these values to BRL per tons (BRL ton^{-1}) was necessary (Equation 1).

$$Corn\ Cost_{BRL\ Ton^{-1}} = (BRL\ sack^{-1} \div 60\ kg) \times 1000\ kg \quad (1)$$

where, BRL $sack^{-1}$ is the cost of a 60 kilos sack of corn; 1000 is the equivalent in kilos for 1 ton.

Additional inputs needed for the conversion of raw materials (corn and sugarcane) into ethanol were obtained from the studies by Weschenfelder[19], Fabricio[20] and Oliveira et al.[21] The corn or sugarcane, in BRL ton^{-1}, necessary raw material for ethanol production process[22], [23] is labor (BRL), water (m^3), energy (kW h), yeast (kg), enzyme (kg), oil (L), chemicals (L), grease (kg) e diesel (L).

The unitary cost (BRL L^{-1}) of corn ethanol was calculated considering the total production during the expanded operational period of 160 days, which corresponds to the off-season of sugarcane[10]. The average daily production capacity was stipulated considering the total production informed by the ethanol plant used as reference in the study for 2019. Such capacity was divided by the total days of production also informed by the plant. The average daily production obtained was considered as a reference to the corn ethanol production during sugarcane off-season.

For raw material unit (BRL ton^{-1} sugarcane and BRL m^{-3} ethanol) conversion purposes, the average yield of sugarcane ethanol was considered, since the literature provides reliable reference values. Additionally, corn and sugarcane prices were obtained by consulting data regarding agricultural market prices CONAB[22], [23]. The following equations, demonstrate the units conversion according to the standard weight of the corn sack (Equation 2) and the ethanol yield of each raw material (Equations 3 and 4).

$$BRL\ ton^{-1}{}_{Corn} = (P_{corn} \div 60\ kg) x\ 1000\ kg \quad (2)$$

$$BRL\ m^{-3}{}_{Corn\ ethanol} = (BRL\ ton^{-1}{}_{Corn} \div 400)\ x\ 1000_{liters} \quad (3)$$

$$BRL\ m^{-3}{}_{sugarcane\ ethanol} = (P_{sugarcane} \div 80)\ x\ 1000_{liters} \quad (4)$$

where, P_{corn} is the price (in BRL) of a 60 kilos sack of corn; $P_{sugarcane}$ is the price (in BRL) of 1 ton of sugarcane registred by the market

By converting those units, it was possible to equalize and compare the final cost of ethanol from both sugarcane and corn. Based on estimated and provided costs for each plant scenario, the final production cost of corn ethanol (BRL m^{-3}) was calculated after dividing the total cost by the potential volume production within the extra 160 days processing corn during sugarcane off-season (Equation 5).

$$BRL\ m^{-3} = \frac{\left(\frac{\sum Adaptation\ costs}{120_{months}FINAME}\right)}{Produced\ volume\ during\ off{-}season_{m^3}} + \left(\sum Variable\ operating\ costs\right)_{BRL\ m^{-3}} \quad (5)$$

where, Adaptation costs are the costs of technically enabling the corn ethanol production where needed; Variable operating costs are the reference unitary costs regarding resources and raw materials necessary for corn ethanol production; Produced volume during off-season - is the potential volume that can be produced within the 160 additional days of operation, considering reference values provided by the plant involved in the study. Which means that the declared average daily production of 569 m^3 was used as a reference assuming that, during the 160 off-season days, the plant would produce the same volume of ethanol it usually produces during sugarcane season but using corn as a raw material instead.

The potential volume was multiplied by the average price of ethanol to the producer, obtained through the monthly price indicators provided by Centro de Estudos Avançados em Economia Aplicada (CEPEA), the necessary parameters for obtaining the average price of ethanol in both sugarcane season and off-season were obtained by selecting the following options: “Indicador Mensal do Etanol Hidratado Combustível CEPEA/ ESALQ - São Paulo” and the period between January 1st and December 31th of 2019, such parameters provide the monthly average prices of ethanol from which both season and off-season ethanol prices were calculated. This multiplication provides the estimative for potential revenue regarding ethanol production.

The plant’s productive capacity during sugarcane off-season was applied to estimate also the quantity of corn ethanol co-products generated regarding its yields per ton of corn, which generates approximately 280 kilos of DDG[24] and 13.4 liters of crude oil[18]. Since these co-products can be commercialized and transformed into extra revenue, the market prices for such co-products were considered within the total profit of the adapted plant. These prices were obtained considering studies[25] and market surveys[26].

3. Results

3.1 Potential demand for corn ethanol

Due to storage issues of the raw material, the production of ethanol from sugarcane is limited to this crop’s season, given between April and November for South-Central region of Brazil and November to April for both North and Northeast regions[27]. Although having complementary months of season, the volume produced by each region does not present the same proportion, which affects ethanol availability during the off-season period in Southeast region (Figure 2).

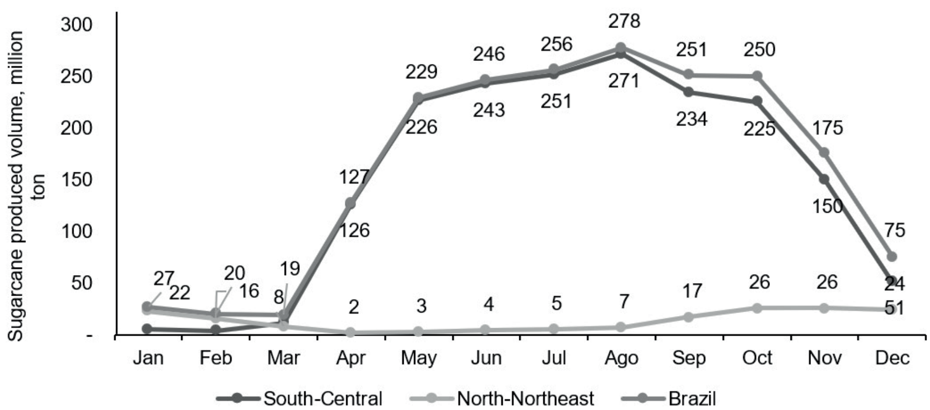

Figure 2. Harvest calendar for sugarcane during the season years of 13/14, 14/15 and 15/16
Source: Elaborated by the author based on CONAB data[28], [29], [30].

Brazil has an average monthly harvest of 163 million tons of sugarcane, of which 92% comes from the South-Central region and only 8% is from the North and Northeast regions combined (Figure 2). Data from the Brazilian supply and demand for ethanol during sugarcane's off-season in South-Central region make clear the problem generated by the shortfall of raw material (Figure 3).

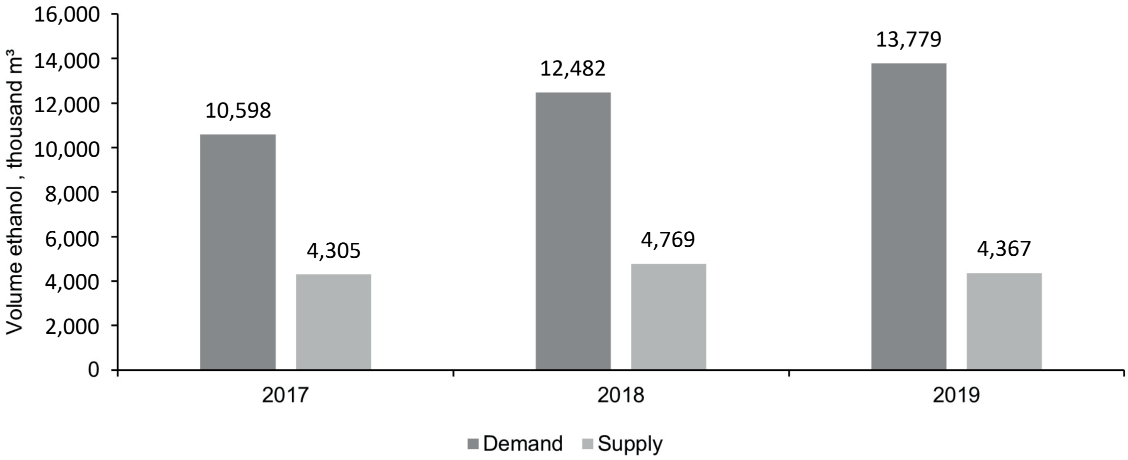

Figure 3. Total ethanol (anhydrous and hydrous) supply and demand for off-season months at Brazil's South-Central region

Source: Elaborated by the author based on statistical data of biofuels production[13] and fuel consumption history[14].

On average, during season years from 2017 to 2019, both anhydrous and hydrous ethanol production during sugarcane off-season months were responsible for supplying only 37% of the national demand in the same period. Therefore, between November and April, the residual production of the South-Central ethanol plants, added to the volume produced by the North-Northeast plants, remains insufficient for attending the total demand for this biofuel, generating the need for imports of ethanol during this period (Figure 4).

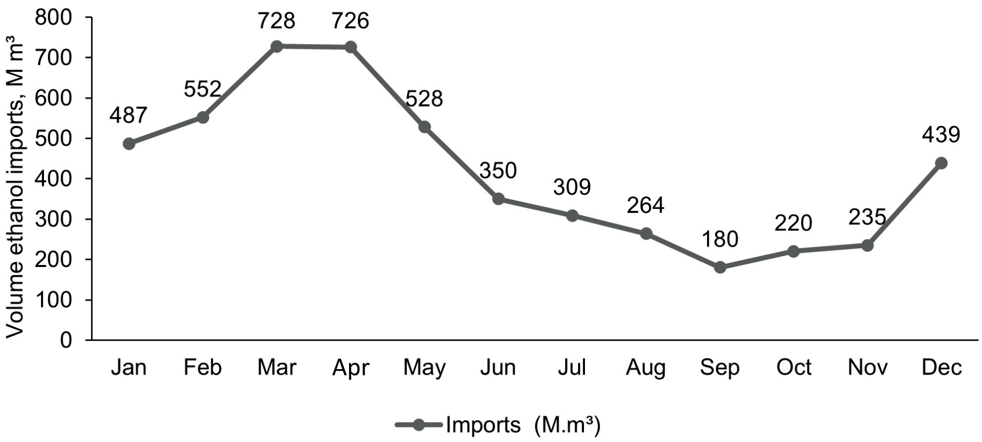

Figure 4. Brazilian average ethanol imports from 2017 to 2019

Source: Elaborated by the author based on original monthly imports data for Brazil for season year and civil year[31].

From Figures 2 and 4, it is possible to apprehend that imports volume increase specifically during sugarcane's off-season in South-Central region (November to April). During this period, imports volume for 2017, 2018 and 2019 were registered as 528 10^3 m^3, against 309 10^3 m^3 during sugarcane season (from May to October). Considering the total volume imported during those 3 years, Brazil has bought approximately 5,018 10^3 m^3 from other countries (Figure 4). According to data for 2020, until April, the Brazilian ethanol imports were estimated in 741 10^3 m^3, bought mostly from United States of America[31]. At the same time, there is a non-supplied annual volume of 7.8 10^6 m^3 when it comes to national production during sugarcane's off-season (Figure 4), which brings the possibility to meet this demand by producing corn ethanol.

3.2 Production scenarios regarding type of plant and geographic position

To better illustrate the cost associated to produce ethanol from both corn and sugarcane, it is important to contextualize the distinct types of plants generally installed in each Brazilian region.

Although being viable in some of Brazil's regions, corn ethanol production has highest processing costs when compared to sugarcane's and the energy balance for the conversion of corn into ethanol presents negative results, while for sugarcane it is positive[32]. For each liter of ethanol produced from corn, 1.29 kcal are consumed, while for the same volume of ethanol produced from sugarcane, 3.24 kcal are generated. Nevertheless, corn presents better yields since it generates 400 liters per ton processed, while sugarcane generates around 70 to 85 liters per ton processed[33]. Considering those values, it is supposed that the highest production cost of corn ethanol is compensated by higher yields.

The corn ethanol production in Brazil is concentrated on Midwest plants, which are geographically close to the major supplies of this raw material, making this activity profitable in this context. Therefore, the logistics costs of sending the raw material from the Midwest to the Southeast region (here represented by the state of São Paulo) is a key factor to be considered to evaluate the economic viability of corn ethanol production at the state of São Paulo, since transportation represents 64% of logistics costs and 4.3% of a company's revenue[34].

São Paulo's ethanol production is marked by the usage of sugarcane as a biomass source and a beter distributed infrastructure in comparison to other regions of Brazil, which reduces the final price of this product[35]. The dependence of a highway network is another key factor that harms the competitiveness of corn ethanol in the state of São Paulo, since this modal is associated with costs ten times higher than other alternatives[36]. Such aspect increases unitary costs, as proved by the difference between the average price of the corn sack in the states of Mato Grosso (BRL 25.00 per 60 kg sack) and São Paulo (BRL 35.83 per 60 kg sack) [22], [23], with an extra 43.30% in BRL ton^{-1} for the latter, in 2019.

These prices, as well as the price per ton of sugarcane, must be expressed in the same units for profitability comparison purposes. Table 2 exposes the raw material costs already converted into BRL m^{-3} and BRL ton^{-1} considering the respective yields per ton of processed raw material calculated through equations 2, 3 and 4.

Table 2. Raw Material yields for ethanol production and unitary costs in the states of São Paulo (SP) and Mato Grosso (MT)

Indicator	Sugarcane SP	Corn SP	Corn MT
Industrial yield (L ton^{-1})	80	400	400
Raw material cost (BRL ton^{-1})	72.25	597.10	416.69
Production cost of ethanol (BRL m^{-3})	903.13	1,492.76	1,041.73
Unitary cost of ethanol (BRL L^{-1})	0.90	1.49	1.04

Source: Elaborated by the author based on original data from CONAB[22]; Freitas and Miura[33].

After comparing the cost (BRL L^{-1}) to produce corn ethanol in São Paulo and Mato Grosso, an increase of 0.45 BRL L^{-1} is observed, which represents an additional cost of 43%. On the other hand, when comparing the unitary cost of sugarcane ethanol produced in São Paulo with the corn ethanol produced in Mato Grosso, the difference is reduced to 0.14 BRL L^{-1}, or a 15% increment. This result indicates that the large offer of corn grain in Mato Grosso represents an advantage when it comes to acquisition prices of raw material by ethanol plants in this state and, at the same time, demonstrate the reflex of transportation costs over the corn ethanol produced in São Paulo[18] (Table 2).

The object of this study was a full sugarcane ethanol plant located in the state of São Paulo (B Scenario). It has a monthly average grinding capacity of 291,542 tons of sugarcane, with an operation period of 186 days per year, and an average daily production of 569 m^3 of ethanol (Table 3). During sugarcane off-season, the plant performs its industrial maintenance processes. Furthermore, the plant also has a monthly energy production capacity of 7 MWh from the sugarcane bagasse, of which 70% are surplus that can be sell as an extra source of revenue. Alternatively, the surplus sugarcane bagasse could be used to generate energy and steam for corn ethanol production, creating synergy between these activities.

Table 3. Production parameters of the full sugarcane plant located at the state of São Paulo, used as reference for the study (B Scenario)

Plant production parameters	Annually	Monthly average
Milled tons of cane in 2019	2,332,335	291,542
Production months year^{-1}	8	-
Operating days in 2019*	186	N/A
Milling tons day^{-1}	12,539	N/A
Ethanol (L)**	105,869,505	13,233,688
Sugar (ton)	153,791	19,224
Superficial water capture (m^3)	Not provided data	195,779
Recycled water	Not provided data	4,736,335
Water needed for processes	Not provided data	4,932,114
Total energy produced (kWh)	224,445,308	28,055,664
Energy consumption (kWh)	69,195,061	8,649,383
Exportable energy surplus (kWh)	155,250,247	19,406,281

Notes: *23.25 average days of producing days within the months considering pauses; ** based on a declared average daily production of 569 m^3 of ethanol.

Considering the parameters mentioned (Table 3), the plant operates with the following cost structure and industrial processes (Table 4).

Table 4. Costs associated to industrial processing of sugarcane to produce ethanol in a full plant located at the state of São Paulo (B Scenario)

Resource	Category	Total cost ---------(BRL)---------	Cost ---(BRL ton^{-1})---	Cost ----(BRL m^{-3})----
Sugarcane*	Raw material	21,063,900	72.25	903.13
Labor**	Labor	Not provided data	5.45	68.13
Water				
Electrical energy				
Yeast				
Chemicals	Fuels and raw materials	6,307,667	21.64	270.44
Oil				
Grease				
Diesel				
Maintenance[25]	Off-season maintenance	Not provided data	4.20	52.50
Total			103.54	1,294.19

Notes: *Based on original data from CONAB[22]; **PECEGE[25].

Detailed budget for plant's adaptation is provided bellow (Table 5).

Table 5. Necessary budget for purchasing the equipment needed to adapt a full sugarcane plant (B scenario) into flex (sugarcane and corn)

Step	Equipment	Supplier/Reference	Cost ------(BRL)------
Grain Reception	Truck unloading system		
	Sample collector	SAUR	1,450,000
	Truck unwinder		
	Grain pre-cleaning system	Pereira[16]*	2,548,037
	Grain transport systems		
	Silo	Grippa[15]*	4,430,760
Cooking and Grinding	Elevated metal silo		4,430,760
	Hammer mill	Grippa[15]*	2,268,459
	Hydrolysis tank		1,020,847
	Motor pump	Equipe bombas	77,265
			39,237
Separation	Tridecanter - centrifuge	Grippa[15]*	2,126,764
	Floater		
	Dried distillers grain dryers	Sutil máquinas	19,600,000
Total			**37,992,129**

Note: *Values updated to present value through the General Market Price Index (IGMP).

The total cost estimated for adaptation was BRL 37,992,129.00, funded within 120 months through FINAME[37] considering an interest rate of 1.11% per year over the Constant Amortization System (SAC), in which the installment of the money funded is constant while the fees decrease and are applied over the debit balance[38]. The total value that must be paid considering interests is BRL 26,159,027. For simplification purposes, the installments were represented as an average of all the installments, that is, the total financing value (BRL 64,151,156), considering interests, divided by the 120 months of financing term (BRL 534,593).

For corn ethanol production costs during sugarcane off-season, the Manpower cost as BRL 19.74 m^{-3} of ethanol produced, while the raw material costs (such as steam, energy, fuels, chemicals, enzymes as well as intrinsic to industrial maintenance) were pointed out as BRL 363.86 m^{-3} of ethanol produced[18].

Considering the 160 extra productive days when integrating corn as raw material for ethanol production, and considering the average daily production claimed by the reference plant (569 m^3), the total additional volume of ethanol produced is estimated to be 91,071 m^3 (Table 6).

Table 6. Simulation of corn ethanol production values during sugarcane off-season in a full sugarcane plant adapted to flex in the state of São Paulo (B Scenario)

Resource	Category	Cost	
		------------(BRL ton^{-1})------------	------------(BRL m^{-3})------------
Corn	Raw material*	597.10	1,492.75
Labor	Labor**	7.90	19.74
Water			
Electricity			
Yeast			
Chemicals	Fuels and raw materials**	145.54	363.86
Oil			
Grease			
Diesel			
Total		758.44	1,876.35

Notes: *Based on original data from CONAB[22]; **Based on original data from PECEGE[18].

Considering these costs, a cost of 1.88 BRL L^{-1} of corn ethanol is obtained, while sugarcane ethanol for season period is 1.29 BRL L^{-1}. On the other hand, the value associated with corn ethanol production in the state of Mato Grosso is 1.71 BRL L^{-1} (Table 7).

Table 7. Comparison of ethanol production costs considering different plant scenarios and raw materials

Plant scenario	Raw material	Cost	
		----(BRL ton^{-1})----	------(BRL m^{-3})------
B	Corn	1,876.35	1.88
B	Sugarcane	1,294.19	1.29
A	Corn*	1,709.01	1.71
A	Sugarcane*	1,789.40	1.79

Notes: *Based on original data from PECEGE[18]; A – flex Plant in the state of Mato Grosso; B – full plant adapted to flex in the state of São Paulo.

The 31% higher production cost associated with the liter of corn ethanol when compared to sugarcane ethanol is a consequence of both the larger sugarcane availability in the state of São Paulo and the transportation costs of corn from other regions (mainly in the state of Mato Grosso). Not to mention the better developed technological environment of São Paulo plants among sugarcane ethanol production.

On the other hand, by considering both corn and sugarcane ethanol production in the state of Mato Grosso, the difference between production costs is only 0.08 BRL L^{-1}. This small difference indicates a fertile scenario for corn ethanol in the Midwest, since the sugarcane cultivated area in this region represents only 2.55% of the total area cultivated with this crop in Brazil (8,442 hectares) during 2019/2020 season, according to the monitoring of Brazilian sugarcane harvest[23]. At the same time, the monitoring of Brazilian grains harvest pointed out that corn cultivation area in the Midwest region presented an increase of 9.1%, with an extra 7.4% volume produced, which is equivalent to near 54,000 tons of corn[39].

Additionally, corn storage capacity generates opportunities for the negotiation of contracts in futures trading, in which fixed prices protect the traders against market fluctuations[18].

There will be 15 corn ethanol plants on the production pipeline until 2030 in the Midwest region of Brazil, from which 5 will be flex plants, while 10 will be full corn plants[2]. Since full plants are overcoming the flex ones is the Midwest region, it can be said that there is a trend of migration to plants using corn as raw material for ethanol production, once the scenario favors this source.

Table 8. Parameters and reference values for estimating the cost of corn ethanol and sugarcane ethanol produced in a full plant converted into flex in the state of São Paulo (B Scenario)

Parameter corn ethanol	Value
Average daily volume (m^3)	569.19
Additional days per year	160
Additional volume (m^3) - off-season	91,071.54
Adaptation costs (BRL)	64,151,156
Adaptation unit cost (R$ m^{-3}) [A]	5.87
Production costs (R$ m^{-3}) [B]	1,876.35
Total (R$ m^{-3}) [A] + [B]	1,882.22
Sugarcane ethanol	
Average daily volume produced (m^3)	569.19
Production days per year	186
Total volume produced (m^3) – sugarcane season	105,869.51
Total adaptation costs (BRL)	64,151,155
Unitary adaptation cost (BRL m^{-3}) [A]	5.05
Unitary production cost (BRL m^{-3}) [B]	1,294.19
Total BRL m^{-3} [A] + [B]	1,299.24

Considering the dilution of adaptation costs over 120 months of the investment funding, and including both sugarcane season and off-season periods, there was a small impact over the final cost (BRL L^{-1}) of corn ethanol (5.87 BRL m^{-3}), which corresponds to 0.31% of the final production costs (1,882.22 BRL m^{-3}). However, by considering such cost dilution over the sugarcane season, it is also necessary to calculate the impact over the final value of the ethanol produced from sugarcane during this period (Table 8).

The impact of adaptation costs over the unitary value (BRL m^{-3}) of the sugarcane ethanol produced is of 0.32%. Although this value is higher than the impact of the adaptation costs over the production costs of corn ethanol, the absolute value (BRL m^{-3}) is lower, since there is a 16% higher volume of sugarcane ethanol produced during the crop season in comparison to the off-season. The extra volume of corn ethanol produced during sugarcane off-season (91,071 m^3) represents an 86% increase in the biofuel that could be sold by the plant, creating a relevant new source of revenue.

There are also other opportunities of increasing plants' revenue when considering the co-products of corn processing, which could be used to create new supply chains to other markets[6]. For the plant in the B scenario, the co-products considered were the DDG, which has an yield of 280 kg ton^{-1} of corn processed[24], and also the crude corn oil, that has an yield of 13.4 L ton^{-1} of corn processed[18]. Thus, for the 91,071 m^3 of corn ethanol produced during sugarcane off-season, and also considering the average industrial corn yield (4000 L ton^{-1} of corn processed), the co-products generated could be estimated (Table 9).

Table 9. Estimation of the co-products generated during corn processing in a full sugarcane plant converted into flex in the state of São Paulo (B scenario)

Parameter	Volume
Total corn processed (ton)	227,676
Dried distillers grain yield (kg ton^{-1})	280
Crude corn oil yield (L ton^{-1})	13.4
Estimated total dried distillers grain (kg)	63,749,379
Estimated total crude corn oil (L)	3,050,863

The high price of DDG in the market is related to its large applications for animal nutrition[3]. During the second fortnight of august 2020, DDG prices oscillated between 950 and 1,226.27 BRL ton^{-1} considering a 32% total protein concentration[26]. The market for such co-products is in trend, since the prices for soybean meal have been rising. At the same time, North American exports of DDG for the Mexican (17%) and Asian (39%) markets[40] highlights the potential of this co-product as an extra revenue from the corn ethanol production.

Furthermore, crude corn oil production also opens doors for biodiesel markets, in which some plants use this co-product for biodiesel production[40]. The crude corn oil prices registered during the season of 2018/2019 have reached 2,164.20 BRL m^{-3} (2.16 BRL L^{-1})[18]. Table 10 exposes a revenue simulation from corn's co-products and compares it with corn ethanol production costs in B scenario.

Table 10. Revenue simulation from the co-products generated during corn ethanol production in a full sugarcane plant converted into flex in the state of São Paulo (B Scenario)

Product/Co-product	Volume	Total cost ---------(BRL)---------	Unitary price --------(BRL L^{-1})--------	Total revenue ---------(R$)---------
Ethanol (L)	91,070,542		1.79*	163,016,270
Dried distillers grain (kg)	63,749,379	171,414,798	1.56**	99,264,158
Crude corn oil (L)	3,050,863		2.16***	6,602,678
Total	157,870,784	171,414,798	1.70****	268,883,107
Profit (R$)				97,468,308

Notes: *Based on original data from CEPEA[41]; **Average weighted from the values surveyed in August 2020, based on original data from Scot Consultoria[26]; ***Based on original data from PECEGE[18]; ****Average weighted from prices of products and co-products.

By considering only corn ethanol trades in the B scenario, without considering the revenues provided by its co-products, there was a negative margin, since its unitary cost exceeds by 0.9 BRL the market price for the producer during sugarcane off-season. By considering an entire year of production, with both sugarcane and corn ethanol in season and off-season respectively, the average profit margin is considered to be 0.18 BRL L^{-1} of ethanol (Table 11). Such margin is 44% inferior from the one that can be obtained by trading the ethanol produced only from sugarcane. This leads to a first conclusion that to keep the plant non-operational during sugarcane off-season is financially better, considering only ethanol production perspective and not accounting on extra revenues from co-products such as DDG and crude corn oil.

Table 11. Profit estimation for a full sugarcane plant converted into flex in the state of São Paulo (B scenario) considering only the sugarcane and corn ethanol trades

Parameter	Season (Sugarcane)	Off-season (Corn)	Total
Volume produced per year (L)	105,869,505.00	91,070,541.94	196,940,046.94
Production cost (BRL m^{-3})	1,299.24	1,882.22	1,568.83*
Unitary cost (BRL L^{-1})	1.30	1.88	1.57
Average price of ethanol (BRL L^{-1})**,***	1.71	1.79	1.75
Total revenue (R$)	181,036,853.55	163,016,270.06	344,053,123.61
Total cost (R$)	137,549,847.61	171,414,798.47	308,964,646.09
Marginal profit (R$ L^{-1})	0.41	- 0.09	0.18
Profit (R$)	43,487,005.94	- 8,398,528.40	35,088,477.54

Notes: *Average weighted by volume of ethanol produced in season and off-season; **Based on original data from CEPEA[41]; ***Product originally from the state of São Paulo, regarding its destiny (no freight or taxes included).

Source: Original results from the research.

On the other hand, once the revenues from the trading of corn ethanol's co-products are taken into consideration, there is a considerable change in the economic viability of this activity (Table 12).

Table 12. Unitary costs and profit margins with and without corn ethanol's co-products trading in a full sugarcane plant converted into flex in the state of São Paulo (B scenario)

Trading of co-products	Unitary cost [C]	Ethanol price in period [P]	Margins [C] - [P]	Total cost (BRL)	Total revenue	Profit
	-------------------- (BRL L^{-1})	--------------------		-------------------- (BRL)	--------------------	
No	1.88	1.79*	-0.09	171,414,798	163,107,341	-8,307,458
Yes	1.09	1.70**	0.70	171,414,798	268,696,075	97,281,277

Notes: *Based on original data from CEPEA[41]; **Average prices weighted by volume of ethanol and co-products produced.

Considering only the corn ethanol trades, the profit margin is negative, which means there is no financial advantage of using corn as a raw material for ethanol production during sugarcane off-season. Even though ethanol prices are higher during this period, the unitary price does not compensate for the unitary cost of its production.

After including the potential profit from corn ethanol's co-products, the financial loss scenario is converted into profitability, since the revenues with DDG and crude corn oil would incorporate 105 million BRL against the 8.3 million BRL losses when considering only the trading of corn ethanol. Such scenario would provide a total profit of 97 million BRL. However, it is noteworthy that having geographical proximity with markets for such co-products is strategic for capturing its profitability potential.

Brazil's Midwest region presents advantages when it comes to potential markets for DDG, since it concentrates the majority of Brazilian cattle[6]. Data from IBGE[42] have shown that 34.58% of cattle herd (approximately 74 million), are located at Midwest region, being 41% of this total (32 million) in the state of Mato Grosso. Although not only cattle farming has a potential demand for the co-products of corn processing such as DDG. Another interesting study indicated that swine feeding with 30% of corn co-product had no negative effects in animal performance[43]. For broilers, the inclusion of DDG in the diet in percentages from 7.44% to 11.02%, have also not shown negative effects on meat quality[44].

In parallel, the Southeast region of Brazil has 38.88% of broilers, being the state of São Paulo responsible for 56% of this total, with 53 million broilers[42]. Swine production, on the other hand, has a greater concentration in the South region, as it holds 49.69% of the national herd, with 7 million heads in the state of Santa Catarina, 6 million in the state of Paraná and 5 million in the state of Rio Grande do Sul[42]. Thus, an eventual DDG production in flex plants located in São Paulo could be absorbed by other agricultural markets.

There are also market opportunities for the crude corn oil as a raw material for biodiesel production. In North American markets, 45% of crude corn oil generated from corn ethanol production is used to produce biodiesel[45]. In 2019, from a total 6 million m^3 of biodiesel produced in Brazil, 40.6% was originated in the South region, while 8.5% was from the Southeast region[46]. Considering the biodiesel market, the state of Rio Grande do Sul (South region) figures as the largest seller, while the state of São Paulo (Southeast region) is the greatest consumer[46].

4. Conclusion

Corn ethanol profitability strongly relies on raw material availability. Geographical proximity from corn supply chains confers greater competitiveness as it generates large impact on the final price of the product. The disparities between the corn sack prices in the states of São Paulo and Mato Grosso exposes such dependence. When analyzing a full sugarcane plant adapted to flex in the state of São Paulo, corn ethanol production costs are much higher when compared to the sugarcane ethanol, which generate a negative profit margin. However, after including the potential revenues originated by commercialization of corn co-products (DDG and crude corn oil), the profit margins become positive, demonstrating that, although there is a competitive advantage associated with raw material geographic proximity, feasibility of corn ethanol production in the state of São Paulo can be achieved by including the revenues from the marketing of co-products to other supply chains (biodiesel plants, swine, and poultry). In conclusion, this study demonstrates that the corn ethanol production alone, limits the profitability of this activity to regions where corn is largely cultivated. In other locations, such as the state of São Paulo, the profitability of corn ethanol production during sugarcane off-season is only achieved by marketing the co-products of corn processing. Otherwise, it is more viable to maintain productive idleness for ethanol plants during sugarcane off-season period.

Though there might be an opportunity cost associated to the non-commercialization of the energy surplus from the sugarcane ethanol production, it was not considered in the study since it involves bureaucratic matters that would extend the scope of this work. The financing costs for adapting the plant to a flex type, able to produce both corn and sugarcane ethanol, are diluted in the price calculated for both fuels, since the installments must be paid monthly disregarding the raw material that is generating revenue.

Future studies must also consider the sensibility of other variables in order to verify impacts in a scenario that does not take ceteris paribus in consideration, demonstrating that such market relies not only in final prices of ethanol or its co-products.

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