27th ABCM International Congress of Mechanical Engineering
December 04-08, 2023, Florianópolis-SC, Brazil

COB-2023-1406
THE USE OF BIOETHANOL IN THE TRANSPORTATION SECTOR: AN OVERVIEW OF THE BRAZILIAN SCENARIO

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Abstract. *This article aims to estimate the current potential of bioethanol for powering the light vehicle fleet in Brazil. A general overview on bioethanol production and characteristics is here contemplated. With that said, the area of land needed to meet the Brazilian car fleet energy demand with sugarcane based bioethanol was be estimated. Results show that about 22% of the country's agricultural area would be necessary for powering the fleet with first generation bioethanol. Moreover, it was projected how much* CO_2 *equivalent emissions would be saved in that scenario. Results show that in comparison with a gasoline powered fleet, the use of first generation bioethanol would potentially represent a reduction in greenhouse gasses emissions of 72 %. In conclusion, as exemplified by the Brazilian case analysis, bioethanol could represent an important step towards the transition into a green energy economy, and, thus, should be a subject of great investment and studies in the foreseeable future.*

Keywords: *ethanol, transportation sector, Brazil,* CO_2 *emissions.*

1. INTRODUCTION

The sustainability of human development is a subject of increasing concern amongst governments around the world. The 2015 Paris Agreement (COP21) sets an important milestone in terms of global efforts against climate change. Currently with 194 signed parties, it aims for the decarbonization of the global economy, setting ambitious long-term goals in the direction of a net-zero emissions world (United Nations, 2015). Considering this, there is a critical need for research in the energy sector. For instance, in 2022, the global energy-related greenhouse gas (GHG) emissions were over 40 Gt of CO2eq (IEA, 2023), which roughly represents between 60 % and 70 % of all greenhouse gas emissions, according to IEA in 2021. The transportation sector is responsible for up to 28% of global energy consumption (IEA, 2022a), where high rates of GHG emissions prevail due to the historical predominance of fossil fuels. In 2019, road transportation alone was responsible for approximately 49% of world's oil consumption (IEA, 2019), and the sector contributed to the release of more than 5.8 billion tons of CO2eq into the atmosphere, just in 2021 (IEA, 2022b).

Reducing the impact of human activity on the transportation sector is crucial for decarbonizing the energy economy. Therefore, it is important to search for sustainable fuel alternatives for vehicles. Amongst the many alternatives, biofuels have presented themselves as renewable, sustainable options to substitute fossil fuels for vehicle use. In that regard, with the intent of reducing its dependence on oil derivatives, and as a response to the 1973 oil crisis, Brazil started in 1975 the "Pro-álcool" program, an initiative that leveraged the production of sugarcane-based bioethanol in the country (Moreira and Goldemberg, 1999). Bioethanol is a renewable fuel, made from biomass, and in terms of GHG emissions, has a much healthier life cycle than gasoline. Bioethanol production in Brazil has evolved from 555 million liters in the first year of the program (Dias, 2012), to more than 27 billion liters in 2022 (Conab, 2023a), globally ranking Brazil in second place in terms of ethanol production. Moreover, the introduction of flex-fuel vehicles (FFV), vehicles that can operate with any fraction of ethanol and gasoline, in 2003, allowed the further expansion of ethanol in the country, giving customers the power to choose as fuel prices fluctuated. In 2022, more than eighty percent of Brazil's new light vehicles were FFVs (Anfavea, 2023), while gasoline is sold with 27% of ethanol in volume in all Brazilian territory.

However, threats concerning ethanol's expansion involve indirect pressure on untouched ecosystems, due to the expansion of other crops and cattle into those areas, and land competition with food production (Goldemberg et al., 2008). The Brazilian Forest Code (Federal Law 12651), from 2012, establishes rules for the preservation of native vegetation on rural properties (EMBRAPA, 2021). Properties situated in the Legal Amazon must maintain 80% of native vegetation cover. That fraction is 35% for properties in Cerrado, and 20% for the rest of the country, where most of the sugarcane production is located. Improvements in agricultural practices, such as the integration with cattle and planted forests (EMBRAPA, 2016), can raise productivity, allowing further expansion without excessive increase in land use. Likewise, genetic improvements in sugarcane varieties and growth in bioethanol yields allow for higher fuel productivity per area, thus reducing land use pressures (Goldemberg et al., 2008).

All things considered, due to its sustainability, already established infrastructure, and well-known production techniques, bioethanol is a promising short-term alternative for replacing gasoline in Brazil and could represent a relevant step in the transition to a green energy economy. Considerable research has been done regarding improvements in productivity (Bechara et al, 2018), land use (de Souza and Horridge, 2014) and sustainability of bioethanol production (Goldemberg et al., 2008) (Maga et al., 2019), but few have estimated its potential for replacing gasoline in the national fleet of Brazil (Camargo et al., 2019), especially considering a first- and second-generation integration scenario. The current potential of bioethanol to feed the fleet is needed. In light of the aforementioned, this paper offers a preliminary overview of bioethanol's characteristics and production processes, from biomass to biofuel, focusing on the Brazilian status and perspectives. In addition, an estimation of the agricultural land needed to power the national light vehicle fleet with bioethanol will be contemplated. The CO_2 emissions savings in that scenario will also be estimated.

2. LITERATURE REVIEW

In order to highlight the potential of bioethanol as an alternative to fossil fuels, a general overview of the fuel's characteristics and production processes (focusing on the Brazilian case) is presented herein.

2.1 Fuel characteristics

Neat ethanol fuel used in engines, known as E-100, or hydrous ethanol, has 96 °GL (96% in volume). It has a lower heating value (LHV) of 6,300 kcal/kg, almost 30% less in comparison to 10,400 kcal/kg of neat gasoline (gasoline A). Common gasoline (gasoline C) sold in Brazil has 27% of anhydrous ethanol (99.7°GL) in volume, regulated by Federal Law nº 9.478 (Ministério de Minas e Energia, 2022), and a LHV of 9,400 kcal/kg. Even though bioethanol's LHV is lower than gasoline, ethanol has a higher octane number, allowing higher compression ratios.

2.2 Fuel production processes

Bioethanol production relies on extracting and fermenting the carbohydrates present in sugarcane. It involves crop, cultivation, and processing, aiming to extract the most out of the crop's energetic content. Sugarcane bioethanol production steps, from crop to fuel, are present herein.

2.2.1 Sugarcane production

In terms of primary crop, which are not processed after being harvested (FAO, 2023), sugarcane is the one most produced in the world, and Brazil is its largest producer, accounting for 40% of the total 1.9 billion tons produced globally in 2020 (FAO, 2020). Compared to other crops used for bioethanol production, sugarcane biomass productivity per hectare of land is significantly higher, reaching an average of 75 t/ha in a year, as opposed to 56.5 t/ha for sugar beet and 8.75 t/ha for corn (Manochio et al, 2017). Also, life cycle energy balance of bioethanol from sugarcane, defined as the ratio between the renewable energy produced and the fossil energy needed, is close to eight times higher than that of bioethanol from corn or sugar beet (Manochio et al, 2017). Recently, studies on new hybrid sugarcane varieties for energy applications (energy cane) have shown biomass productivities above 180 t/ha (Boschiero, 2023). Even though those varieties have lower sucrose content per ton of sugarcane (total recoverable sugars - TRS), and consequently more fibrous content, the great increase in productivity per hectare of land can provide higher kg of sucrose per hectare than traditional varieties. However, the high fibrous content makes processing in conventional units more difficult, and the lower juice purity is prejudicial to sugar production (Carvalho-Netto et al., 2014). For energetic applications, energy cane can represent a big step in terms of productivity.

2.2.2 Bioethanol production

Sugarcane's biomass can be converted to ethanol in two ways: (i) using the sucrose content present in the stalks to produce first-generation (1G) bioethanol; and (ii) using the lignocellulosic content present in the bagasse and straw to produce second-generation (2G) bioethanol. On average, one-third of sugarcane's energetic content is present in bagasse, while sucrose and tops and leaves contain the rest (Goldemberg J., 2008).

First-generation (1G) bioethanol production is a well-established technology, being applied in industrial scale for decades (Moreira and Goldemberg, 1999). In Brazil, there are currently more than 350 production facilities, which together processed a total of 293 million tons of cane just in 2022 (ANP, 2023). The production process of first-generation bioethanol in Brazil is normally integrated with sugar production. Approximately half of the sugarcane produced in Brazil is used for sugar and half is used for ethanol production (Goldemberg J., 2008). The production process starts by cleaning the harvested sugarcane. Next, the juice is extracted by mills with the remaining bagasse being used as a fuel for cogeneration systems (Manochio et al, 2017). It is important to mention that the amount of bagasse produced by the milling process is enough such that these 1G cogeneration plants are self-sufficient in energy terms (Manochio et al, 2017). As for the juice produced, it can be converted into sugar or bioethanol. As well known, the production of bioethanol involves the fermentation of the extracted juice by yeasts (Manochio et al, 2017), where chemical reactions performed by the yeasts in the fermentation process convert sucrose into ethanol as shown below (Gnansounou and Dauriat, 2005),

$$C_{12}H_{22}O_{11} + H_2O \rightarrow C_6H_{12}O_6 + C_6H_{12}O_6 \quad (1)$$

$$C_6H_{12}O_6 \rightarrow 2\ CH_3CH_2OH + 2\ CO_2 \quad (2)$$

The result of the fermentation process is distilled producing hydrous ethanol. A following dehydration step can be added producing the so-called anhydrous ethanol (Manochio et al, 2017).

Second generation (2G) bioethanol production on an industrial scale has only recently become viable. Currently, there are only two industrial-scale facilities capable of producing second-generation ethanol in Brazil: Raizen's Piracicaba unit, an integrated 1G and 2G facility, and GranBio's São Miguel dos Campos unit, a standalone 2G facility (Maga et al, 2019). In an integrated 1G2G facility, the remaining bagasse from the traditional 1G unit is further processed. However, the 2G bioethanol producing process is more involved than the 1G since carbohydrates must be separated from the resulting biomass material and later broken down into fermentable sugars; more information on this process can be found in (Chang et al., 2017). Once sugars are formed, the resulting juice is distilled similarly to the 1G bioethanol (Maga et al, 2019). Needless to say that there is great interest in improving and expanding the utilization of 2G bioethanol since it increases the amount fuel produced per unit of area. An evolution in agricultural, industrial and technological aspects of 2G bioethanol production is expected, and economic viability should be achieved by 2025 (FAPESP, 2017).

3. METHODOLOGY

To better evaluate bioethanol as a feasible alternative fuel, from an energetic and land use standpoint, an estimation of the area of land needed to power the Brazilian car fleet with bioethanol is presented here. Starting from 1% of the agricultural land, going through sugarcane and bioethanol production, we estimated the number of cars this area of land could supply with bioethanol (E-100), per year. Then, with those results, the fraction of the agricultural land needed to power the whole light vehicle fleet is calculated. In addition, to assess the sustainability of bioethanol use, CO_{2eq} emissions savings in the same scenario will be estimated.

3.1 Crop area for bioethanol production

Brazil has a vast territory, with an extension of more than 8.5 million km². More than two thirds of that area is designated for protected and preserved vegetation (EMBRAPA, 2021). Also, 688,900 km² (68,890,000 ha), or about 8% of the national territory, compose the agricultural area - which can be used for cultivation (IBGE, 2020). As a comparison, 1% of the Brazilian agricultural land (688,900 ha) represents more than five times the extension of the city of New York.

Sugarcane productivity in Brazil has fluctuated between 67 and 78 tons of sugarcane per hectare of planted area in the last decade (Conab, 2023b). For 2023 harvest, a productivity of 75.75 tons per hectare is expected, based on the production so far (Conab, 2023a). Therefore, with the current data, the amount of sugarcane produced per year in an area of 1% of the country's agricultural land can produce is calculated by the following expression,

$$T = x \times A \times P \quad (3)$$

where T is the amount of sugarcane produced in a year (t/year), P is the sugarcane productivity per hectare year (t/hayear), A is the total agricultural land area (ha), and x is the percentage of the agricultural land used for the sugarcane production

Sugarcane conversion to ethanol by the first-generation process varies from 70 to 90 L/ton of sugarcane that enters the mills (Manochio et al, 2017). This value depends on the mass fraction of sucrose present in the sugarcane and the efficiency of the many steps. Assuming an 80 L/ton conversion factor, the amount of hydrous ethanol that could be produced based on the biomass calculated previously is estimated by the expression that follows,

$$Hy = (T \times c)/0.96 \quad (4)$$

where Hy is the amount of hydrous ethanol produced per year (L/year), T is the amount of sugarcane processed per year (t/year), and c is the average conversion factor of sugarcane to bioethanol (L/t).

An integrated 1G2G facility productivity varies from 85 to 129 L/ton of sugarcane processed (Bechara et al, 2018). An average 107 L/ton of cane was adopted, and the amount of hydrous ethanol a 1G2G facility could produce with the amount of biomass calculated previously can also be estimated by Equation (4).

To estimate the number of cars that could be supplied by this bioethanol production, first, it is necessary to obtain the demand for a single car. The new car registration records in Brazil show that until May, Chevrolet's Onix were the best-selling vehicles in the automobile category (Fenabrave, 2023). Therefore, this car model will be used in the further analysis. It has a fuel economy of 9.4 km/L of bioethanol, for a commuting in the city (INMETRO, 2023). Considering that a Brazilian car, in average, drives 12,900 km in a year (KBB Brasil, 2019), it is possible to estimate how many liters of bioethanol a car consumes per year using the following expression,

$$lc = Q/fe \qquad (5)$$

where lc is the year demand in liters of bioethanol of the model car (L/year), Q is the average amount of km driven per year by a Brazilian (km/year), and fe is the fuel economy of the chosen model car (km/L)

According to data from March of 2023, Brazilian light vehicle fleet was of 69,891,693 vehicles (Ministério da Infraestrutura, 2023). Considering a hypothetical fleet composed by the model car, the fraction of cars that could be powered by the bioethanol produced using only 1% of the nation's agricultural area can be calculated by the expression that follows,

$$Pc = (Hy \times 100)/(lc \times f) \qquad (6)$$

where Pc is % of the car fleet (%), Hy is Liters of hydrous ethanol produced per year (L/year), lc is the demand in liters of bioethanol of a modal car in a year(L/year), and f is the number of light vehicles in the national fleet (cars).

3.2 CO2 savings estimation

To better evaluate bioethanol's sustainability in the same scenario presented above, an estimation of CO2eq emissions savings is presented herein. To obtain the difference in emissions resulting from using bioethanol instead of gasoline to power the fleet, first, it is necessary to estimate the emissions of a modal car running with each fuel. For each liter of first generation bioethanol consumed, during the fuel's lifecycle, an average of 0.4 kg of CO2eq is emitted (Maga et al, 2019). Knowing the amount of liters consumed by a car per year, the amount of CO2eq emissions can be estimated by the following expression,

$$ee = 0.96 \times lc \times el \qquad (7)$$

where ee is the emissions of a model car powered by ethanol per year (kg CO_2 eq/ano), lc is the year demand in liters of bioethanol of the model car (L/year), and el is the emissions of CO2eq per L of anhydrous ethanol used (kg of CO_2 eq/L). Regarding 1G2G bioethanol, the emissions also can be calculated using Eq. 7, but in this case, el=0.6 (kg of CO_2 eq/L) (Maga et al, 2019)

Regarding the emission using gasoline C as fuel, and considering the same model car, using Eq. 5 and fe=13.3 km/L (INMETRO, 2023) the gasoline demand per year can be estimated. Gasoline's life cycle emissions are assumed to be 0.07507 (kg CO2 eq/MJ) (EPE, 2022). Using a LHV of 39.292 MJ/kg and a density of 0.75425 kg/L, the emissions of a model car running on gasoline per year can be estimated using the following expression,

$$eg = lc \times ej \times LHV \times d \qquad (8)$$

where eg is the emissions of a model car powered by gasoline per year (kg CO_2 eq/year), lc is the year demand in liters of gasoline of the model car (L/year), ej is the emissions of CO2eq per MJ of gasoline used (kg of CO_2 eq/MJ), LHV is gasoline's LHV (MJ/kg), and d is gasoline's density (kg/L).

4. RESULTS AND DISCUSSION

Using the described methodology, the amount of sugarcane that 1% of the agricultural area can produce in a year was estimated. Results are shown in Table 1. Using current data of sugarcane yields, a production of 52.18 million tons of the crop was estimated. Brazil's 2022/2023 harvest production was of 610,131,400 million tons (Conab, 2023a).

According to our estimates, 11.7% of the agricultural area is needed to reach that production, which is close to the 12.2% currently in use for that end.

Tables 2 summarizes the results of bioethanol production and potential number of cars fed by using 1% of the agricultural area, obtained using the described methodology. It can be observed that with only 1% of the agricultural land, first-generation sugarcane bioethanol production is estimated to be capable of yielding more than 4.3 billion liters of ethanol per year, feeding 3.2 million cars yearly. That represents 52% of the automobile fleet of São Paulo city, Brazil's most populous city with more than 12.2 million citizens. For 1G2G integration production, 5.8 billion liters and 4.2 million cars are the yearly estimations, using only 1% of the agricultural land. That represents 69% of the São Paulo fleet. Results show that for each 1% of agricultural land used, 1G2G integration represents an increase of 1.1 million cars fed per year, when compared to the 1G case.

Table 1. Sugarcane production estimations based on 1% of the agricultural land area.

Area of land (ha)	**Sugarcane productivity (t/ha)**	**Sugarcane yield (10^6 t/year)**
688,900[(1)]	75.75	52.18

(1) 1% of the agricultural land area.

Table 2. Fuel production and powering of the fleet estimations based on 1% of the agricultural land area.

Yields	**1G**	**1G2G**
Bioethanol, billion L/year	4.3	5.8
Number of cars powered, millions	3.2	4.2
% of the light vehicle fleet	4.5	6.1

Figure 1 illustrates the potential of bioethanol for powering the vehicle fleet in terms of the fraction of the agricultural land. Taking the agricultural area currently in use for sugarcane cultivation (8,410,340 ha, or 12% of the total agricultural area) (Conab, 2023a), 54% is the fraction of the fleet potentially powered by first-generation bioethanol. This value could increase to 73% if 1G2G bioethanol were used. It is important to note that those fractions correspond to the scenario where all the sugarcane produced in that area is destined for bioethanol production. In Brazil, though, bioethanol production shares the total sugarcane feedstock with sugar industry, allowing the producer to choose the better distribution for the feedstock according to market prices. Considering that half the sugarcane yield from those 12% of agricultural land would be used for sugar production, still, 1G production would be able to supply more than a quarter of the national fleet (27%), and 1G2G production would be able to supply more than a third (36%). This is the amount of bioethanol needed to feed that fraction of the fleet, not including the amount present in gasoline in the remaining fraction.

Figure 2 illustrates the emissions of the hypothetical fleet when powered by 1G bioethanol, 1G2G bioethanol, and gasoline. It also shows the potential emission savings of 1G and 1G2G when compared to gasoline. If 30% of the national fleet previously powered by gasoline instead becomes powered by first generation bioethanol, the emission of up to 32.8 million tons of CO_{2eq} would be saved per year, a reduction of roughly 72%. The 1G2G integrated case produced more emissions than the 1G case. That happened because the assumed value of 0.6 kg of CO_{2eq}/L considered in the analysis accounts the carbon footprint of using natural gas as a way to feed the needed energy in the processes, previously fully provided by bagasse burning in the 1G route. As mentioned by (Maga et. Al., 2019), from a GHG emissions perspective, the fraction of bagasse that goes either to cogeneration or to second generation ethanol production in a 1G2G plant should be balanced in a way that the plant becomes energy self-sufficient, avoiding the need for using extra fossil energy.

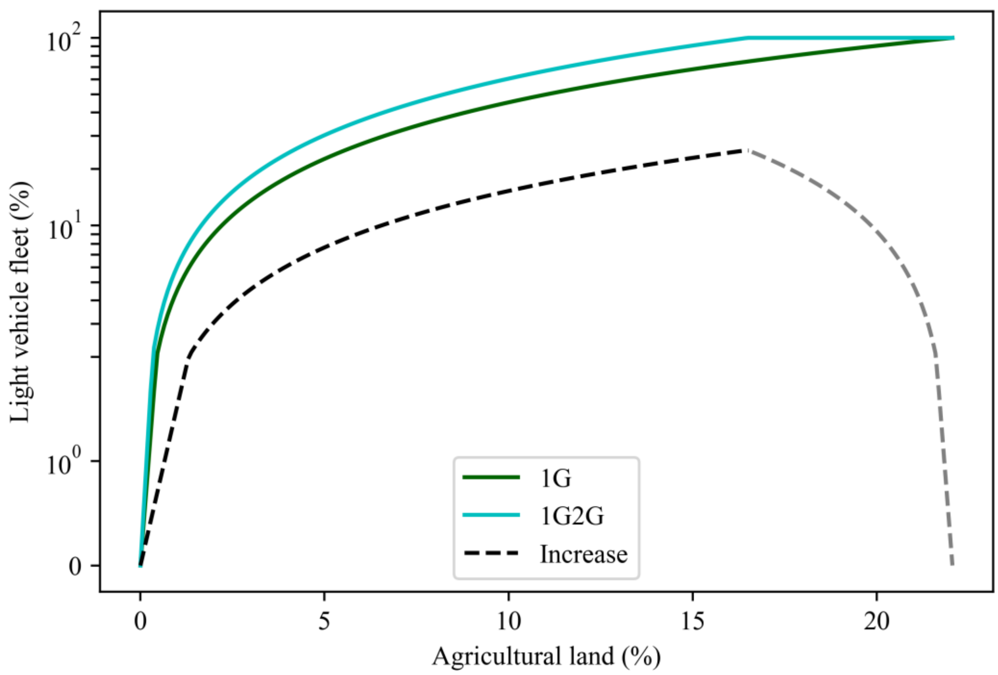

Figure 1. Area needed to power the Brazilian car fleet with sugarcane based bioethanol.

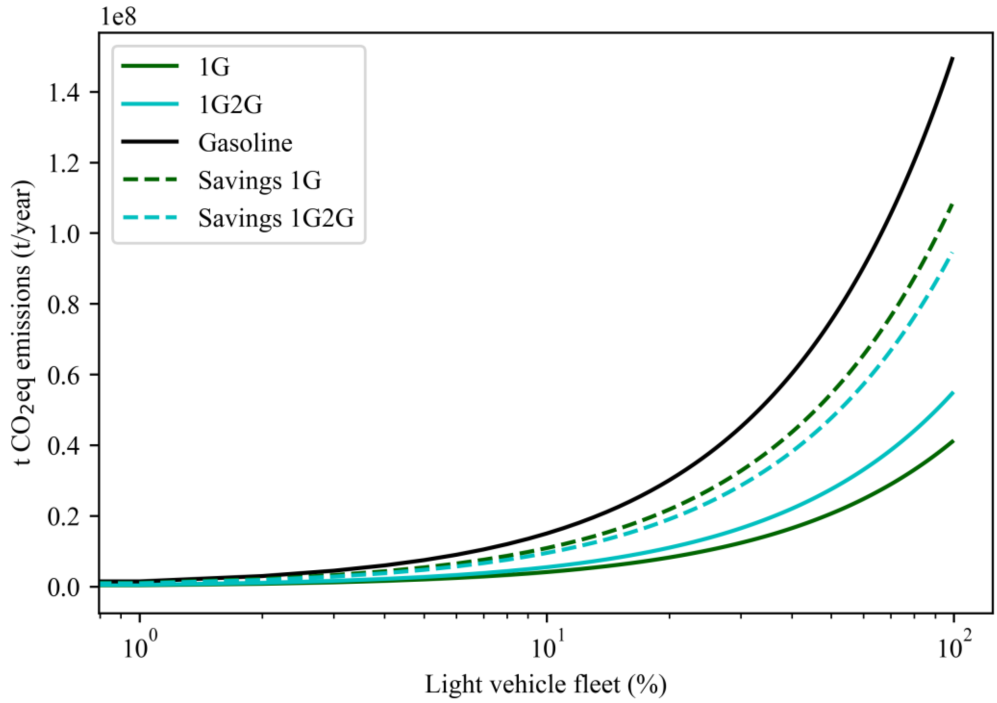

Figure 2. CO_{2eq} emissions comparison.

5. CONCLUSIONS

The results show that with current productivity data, and without excessive increase in land use, bioethanol could be used to replace a large fraction of the gasoline currently in use in Brazil, especially when envisioning the expansion of integrated 1G2G facilities. More specifically, results indicate that over half of the Brazilian car fleet could be entirely powered by ethanol while considering the current farmable land in use today. In addition, reductions of up to 72% in GHG emissions could be achieved if bioethanol is used as a replacement for gasoline under non-optimistic scenarios. Besides the scalability and environmental advantages, the Brazilian sugarcane-based bioethanol production can be economically competitive with gasoline. The results are even more promising with the development of the so-called second-generation technology, which has the potential to further increase bioethanol production per unit of farmed area, hence, mitigating the use of land and the impacts on it. Therefore, due to its sustainability, already established infrastructure, well-known production techniques and great potential of the evolving production technologies, sugarcane bioethanol could be the optimal short-term alternative to fossil-based fuels in Brazil, and, thus, should be subject of great investment and study in the foreseeable future.

6. ACKNOWLEDGEMENTS

The authors are grateful for the financial support provided by CNPq under project # 405859/2022-8.

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