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Biofuels in Latin America: Sustainability Assessment of Argentinian, Brazilian, Colombian, and Guatemalan cases

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Abstract:	This paper addressed production, land use, environmental impacts, and the energy balance associated with ethanol and biodiesel production in Argentina, Brazil, Colombia, and Guatemala, respectively. These countries were selected because they are a representative group of Latin America with a significant contribution to biofuels production and are considered as developing countries. We consider how public policies to stimulate the adoption of low carbon fuels, such as the Renovabio policy framework, might encourage biofuels production in these nations. In this context, official data for each country were used to quantify the production of biofuels and the land required for their production. To evaluate environmental impacts, a cradle-to-gate Life Cycle Assessment (LCA) was performed using the OpenLCA software. The ReCiPe Midpoint 2016 (H) approach was used to calculate the impacts. The results revealed that turning 5% of current pastures into arable land for raw materials could double biofuels production. Besides, the results indicated that increases in raw material productivity could significantly reduce the land demand, suggesting that efforts in this direction should be intensified. Hence, when ethanol and biodiesel production were compared to gasoline and diesel, considerable reductions in global warming and ozone layer depletion were observed, and most importantly, the Energy Ratio (ER) and Net Energy Balance (NER) revealed that biofuels production in these countries is energetically sustainable. Finally, public policies such as the Renovabio program may incentivize farmers, biofuels producers, and policymakers to improve the biofuel supply chain.
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To

Dr. Aoife Foley

Editor in Chief

Renewable Energy and Sustainable Reviews

We kindly ask you to consider the manuscript by Canabarro et al. “Biofuels in Latin America: Sustainability Assessment of Argentinian, Brazilian, Colombian, and Guatemalan cases” for publication. To our best knowledge, our study is the first analysis of biofuels sustainability and potential for expansion in Argentina, Brazil, Colombia and Guatemala that covers a life cycle analysis, land use and policies. Besides shedding light in the efficiencies of current production of biofuels and its effectiveness to decrease GHG emissions, we consider the study can help these countries achieve energy security and generation of wealth. Our results indicate where improvements are needed and evaluates the potential to double biofuels production in these regions. Also, our results indicate that current production of biofuels in these countries is energetically favorable and contributes significantly to reduce emissions. We believe our findings would appeal to a broad audience, such as the readership of Renewable Energy and Sustainable Reviews as a wide-reaching journal publishing original research on all aspects of Bioenergy, Life cycle Analysis and Policy.

Sincerely,

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Biofuels in Latin America: Sustainability Assessment of Argentinian, Brazilian, Colombian, and Guatemalan cases

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Highlights

- Latin America biofuels reduce 70% GHG
- 63 mtCO_2/yr avoided
- 5% pastureland to double biofuels

Keywords: bioenergy, biofuels, life cycle assessment, land use, climate change, Latin American countries, public policies.

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ABSTRACT

This paper addressed production, land use, environmental impacts, and the energy balance associated with ethanol and biodiesel production in Argentina, Brazil, Colombia, and Guatemala, respectively. These countries were selected because they are a representative group of Latin America with a significant contribution to biofuels production and are considered as developing countries. We consider how public policies to stimulate the adoption of low carbon fuels, such as the Renovabio policy framework, might encourage biofuels production in these nations. In this context, official data for each country were used to quantify the production of biofuels and the land required for their production. To evaluate environmental impacts, a cradle-to-gate Life Cycle Assessment (LCA) was performed using the OpenLCA software. The ReCiPe Midpoint 2016 (H) approach was used to calculate the impacts. The results revealed that turning 5% of current pastures into arable land for raw materials could double biofuels production. Besides, the results indicated that increases in raw material productivity could significantly reduce the land demand, suggesting that efforts in this direction should be intensified. Hence, when ethanol and biodiesel production were compared to gasoline and diesel, considerable reductions in global warming and ozone layer depletion were observed, and most importantly, the Energy Ratio (ER) and Net Energy Balance (NER) revealed that biofuels production in these countries is energetically sustainable. Finally, public policies such as the Renovabio program may incentivize farmers, biofuels producers, and policymakers to improve the biofuel supply chain.

1. Introduction

Concerns about climate change and its environmental impacts have driven a worldwide effort to reduce the use of fossil fuels. Energy security concerns are also incentives for countries to seek sustainable solutions for energy production [1–3]. Furthermore, increasing energy demands in developing countries to keep up with their economic and social growth have been drawing attention (*Appendix A*, Figure A.1). In this context, bioenergy has proven to play an important role in enabling for sustainable development strategies [4]. The COVID-19 pandemic has impacted the energy sector, and the global demand decreased 4% in 2020; however, the International Energy Agency (IEA) predicts a 4.6 % growth in energy consumption in 2021 [5]. Almost 70% of the projected global energy demand will occur in emerging markets and developing economies, which means the rising of Greenhouse Gas Emissions (GHG) in these regions. In this way, an evaluation of the potential of these emerging markets to produce bioenergy to replace fossil fuels in a sustainable way, as well as the environmental impacts related to these activities should be conducted.

Among all sectors of the energy matrix, the transport sector stands out in the consumption of fossil fuels, being responsible for about 60% of total oil demand [5]. Some initiatives to decarbonize the transportation industry have been launched [6], with liquid biofuels emerging as a feasible option [7,8]. Biofuel's production is increasing annually in the world (except for 2020) [9], and the Central and South American continents are responsible for around 27% of total biofuels production worldwide (Figure 1). Brazil, the second-largest global ethanol producer [10], accounts for around 90% of the total biofuels of Central and South American. In addition, Brazil has launched a new public policy for biofuels, the Renovabio program [11], which may be a good mechanism for incentive improvements in the sector. This program aims to promote sustainable bioenergy production and achieve the Paris Agreement's pledge on climate change. Also, other Latin American (L.A.) countries show significant potential in biofuels production, including Argentina [12–14], Colombia [15,16], and Guatemala [17].

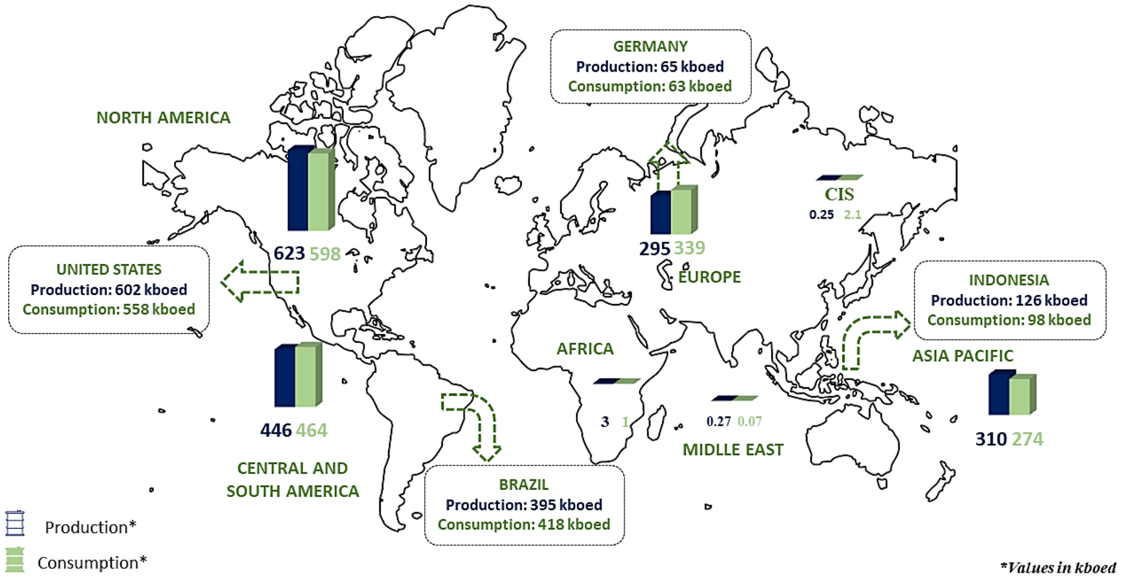

Figure 1. World consumption and production of liquid biofuels in 2020. Based on [18].

The share of energy consumed for the transportation sector in Argentina, Brazil, Colombia, and Guatemala is around 23%, 34%, 26%, and 8% (*Appendix A*, Figure A.2), respectively. Petroleum derivatives, such as gasoline and diesel, dominate the energy matrix of the transport sector, and the contribution of biofuels in the transport sector remains limited, with values equivalent to 9%, 23%, and 7% for Argentina, Brazil, and Colombia, respectively (*Appendix A*, Figure A.3). The Guatemalan situation is particularly unique since the government does not use biofuels in the transportation sector. Around 80 % of Guatemalan ethanol is exported to North America and Europe. In contrast, all the gasoline and diesel consumed in Guatemala are imported from the U.S (United States) [19]. Some studies have already argued about the Guatemalan ethanol paradox and have shown the main barriers to implementing biofuels blend mandates in the country [17,20], which include high costs of ethanol-gasoline blends relative to gasoline and lack of political support.

While biofuels have considerable potential to aid the transition to low-carbon energy systems, large-scale biofuels production has drawn attention due to the many aspects and complexities involved when dealing with land use for feedstock cultivation, land-use changes, and agriculture in general [21]. According to the International Renewable Energy Agency (IRENA) [22], biofuels production will account for 25% of total transport fuel consumption worldwide by 2050. Agriculture, forestry, and other land use (AFOLU) are second only to electricity production in terms of GHG emissions. In recent years, these activities have generated around 12 Gt $_{CO2eq}$ net GHG emissions [23]. Concerns were raised on biofuels sustainability, which has led to debates on food security, water resources, carbon soil, biodiversity, etc. Many efforts have been made to address the sustainability of the biofuels production process [24–26], as it is a critical concern for policymakers designing bioenergy-based policies.

Life cycle assessment (LCA) methods are considered a crucial tool for environmental sustainability assessment. It focuses on assessing the environmental impacts based on the entire life cycle of a product. It considers an analysis of impact categories such as global warming, acidification, eutrophication, ozone and water depletion, particulate matter formation, among others [7,24]. Previous studies have shown the advantages of biofuels utilization compared to fossil fuels [12,24,27–29], and the impact of public policies on the biofuels production chain [26,30]. However, there is a lack of a comprehensive outlook of biofuels production in emerging markets.

In the present study, an assessment of biofuels production in the Latin American countries Argentina, Brazil, Colombia, and Guatemala is performed to show their potential for biofuels production. Basic information on biofuels production in these countries and their effects on land-use change and agricultural indicators have been compiled to counterbalance the benefits and disadvantages of increasing biofuels production. LCA was carried out for ethanol and biodiesel production to assess the environmental impacts using the open-source software OpenLCA®. In addition, the environmental impacts for biofuels production were compared to those ones for gasoline and diesel oil. Lastly, an analysis of the consequences on revenues and GHG emissions of enacting a biofuels policy like Renovabio was also conducted. We suggest carrying out such an analysis at the early stages of biofuel mandates implementation to define strategies with the most potential.

2. Outlook of biofuel’s production in selected Latin American countries

Status analysis is organized in three sections where we define the potential of biofuel production in Argentina, Brazil, Colombia, and Guatemala. The first section presents the biofuels production *status quo* in these countries and the necessary raw materials for ethanol and biodiesel production. Besides, the existing regulations for biofuel blending were also examined. The second section addresses the impacts on land demand for the current biofuels production and effects caused by an eventual large-scale expansion of biofuels. The data were obtained from government reports and the Food and Agricultural Organization of United Nations (FAO) [31] (Argentina [32,33], Brazil [34], Colombia [35,36], Guatemala [37]). Furthermore, several agricultural indicators such as crop yields, crop production energy consumption, biomass energy, agricultural energy ratio, and biofuel yields were considered to assert the need for improvements in the process sustainability and strategies to boost the production of liquid biofuels. A detailed description of the methodology adopted to obtain the agricultural indicators is described in *Appendix A*, section 2. Due to the pandemic scenario, 2020 was an atypical year. For this reason, the data of 2019 were used in this analysis.

2.1 *Status quo* of biofuels production

Figure 2 shows the total amount of biofuels - ethanol and biodiesel - produced in 2019 and the respective raw materials for each country.

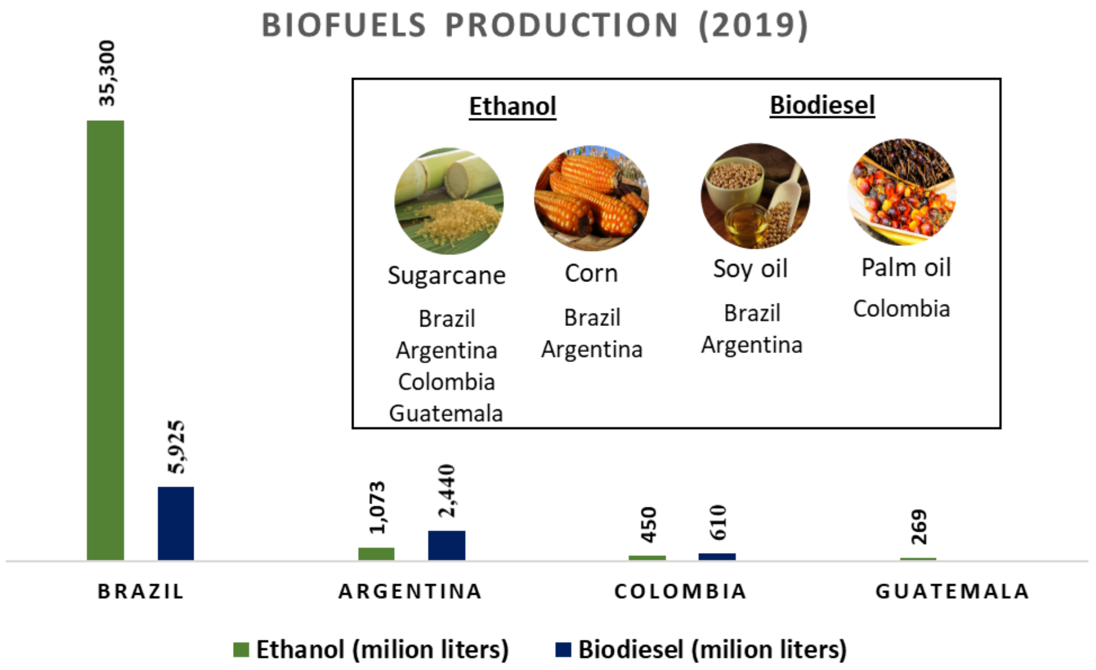

Figure 2. Production and main raw materials used to produce liquid biofuels [32,38]

Brazil produced approximately 36 billion liters of ethanol in 2019: 10.7 billion liters of anhydrous ethanol and 25.3 billion liters of hydrated ethanol. Anhydrous ethanol is blended into commercial gasoline (27% ethanol), while hydrated ethanol is sold separately as fuel for Otto cycle engines. Although sugarcane is the feedstock for more than 98% of Brazilian ethanol, corn ethanol production has increased steadily since 2013 [34]. The Brazilian Energy Research Agency (EPE) reports eight approved facilities in operation; corn ethanol production in Brazil increased from 11 million liters in 2013 to 1.3 billion liters in 2019 [11]. The Brazilian government has adopted biofuels policies and implemented a compulsory blend of at least 5% of anhydrous ethanol in the gasoline composition since 1931 [39]. Later, in response to the impacts caused by oil shocks during the 1970s, the Brazilian government launched the ‘*ProAlcool*’ program, which aimed to increase the ethanol blending level up to 25% in gasoline (E25) and introduce hydrated ethanol (approximately 95% ethanol and 5% water, E100) for use in light vehicles. For over 80 years, Brazilian cars have been using blends of ethanol and gasoline, which is currently 27% (E27) [39,40]. Currently, Brazil has at least 363 plants producing anhydrous and hydrated ethanol, corresponding to a production capacity of 129 thousand m³/day and 243 thousand m³/day, respectively [41].

Brazil is the third largest biodiesel producer in the world, behind the U.S. and Indonesia [42]; the production in 2019 was around 6 billion liters distributed in 50 biodiesel plants. At this point, it is worthwhile mentioning that about 45% of the biodiesel manufacturers' capacity is idle. The raw materials used in its manufacture were around 68 % soybeans, 11% tallow, 2% palm oil, and 19% others (*i.e.*, chicken and pork fat, cotton oil, used cooking oil, corn oil, and canola oil) in 2019 The biodiesel blend mandate (Law 11097/2005) is newer than ethanol. The biodiesel blend into diesel varied from 2% in 2008 to 5% in 2010, and gradually increased to 12% (B12) in 2020.

The ethanol production in Argentina was overa1 a billion liters in 2019. The Argentinian ethanol is made from sugarcane and corn, approximately 50% of each feedstock, according to the Ministry of Agriculture (MAGyP [32]). Argentina has at least 22 ethanol plants operating, corresponding to a production capacity of 1.65 billion liters. The sugarcane sector has 12 dehydrators and 16 distilleries, while the corn sector has five medium- to large-scale plants and 5-10 small plants that are used intermittently. Argentina produced around 2.5 billion liters of biodiesel from soybean oil in 2019. About 48% of the biodiesel was exported exclusively to Europe. Exports to the U.S. and Peru are hindered due to high import taxes. At least 33 biodiesel plants will be operating in Argentina in 2021, with a total capacity of 4.43 billion liters. The Argentinian government has launched a new public policy for biofuel blend mandates (New Biofuels Law 27640

– July 2021), which replaces Law 26093 from 2006 and establishes new criteria for blends of ethanol and biodiesel in fossil fuels. According to the new rules, the mandatory rate for mixing ethanol in gasoline is at least 12% (E12), while for biodiesel, the minimum percentage allowed is 5% (B5) [43].

In Colombia, ethanol and biodiesel production were noted to have reached 450 and 610 million liters in 2019, respectively [44]. There are seven distilleries and twelve biodiesel plants with a production capacity of 660 and 900 million liters of ethanol and biodiesel, respectively. Based on Law 693 of 2001 for ethanol, and Law 939 of 2004 for biodiesel, since 2002, the Colombian government has been implementing policies for biofuels. Aiming to reduce pollution, contribute to climate change commitments, and incentivize local production, the government established the highest ever blend mandates for ethanol and biodiesel, 10% (E10) and 12% (B12), respectively. However, due to the adverse effect caused by the ‘La Niña’ weather phenomena, the Colombian Ministry of Mines and Energy issued a resolution to decrease the ethanol blend mandate from 10% (E10) to 4% (E4) from April to July of 2021. As reported by the Colombian government, the ‘La Niña’ phenomena had a significant impact on national sugarcane production with consequences in mill operations [44].

In Guatemala, the current sugar industry comprises 12 sugar mills located in the Pacific Ocean coastal plain. In 2017, sugar was Guatemala’s second most valuable export, ranking top among agricultural products. In the 2016–2017 season, Guatemala harvested almost 25.8 million tonnes of sugarcane and produced 2,719 million tonnes of sugar, reaching a yield of 10.63 tonnes/ha. Guatemala has an installed capacity of 253.6 million liters per year of ethanol (fuel and other uses). All distilleries use molasses as feedstock and export to Europe and the United States around 80% of the total ethanol produced [19,45].

2.2. Crop yields and feedstock production efficiencies

Table 1 provides some agricultural indicators for primary raw materials used in biofuels production in Argentina, Brazil, Colombia, and Guatemala. Even for the same raw material, there were significant yield differences. Sugarcane productivity in Argentina and Colombia was 55.6 tonnes/ha and 120 tonnes/ha, while Brazil and Guatemala presented sugarcane yields of 75.4 and 115.7 tonnes/ha, respectively. The main factors affecting yields are climate and soil [46,47]. Seed quality, soil fertility, precipitation indices, sugarcane variety used, solar radiation, and other factors may cause these discrepancies. As expected, the sugary feedstocks are more productive than the starchy ones [48], as could be observed for Argentinian ethanol production. Despite having the lowest productivity compared to the other countries evaluated in this study, sugarcane is seven times more productive than corn in Argentina, which reached a productivity of 7.5 tonnes/ha. Palm is more productive than soy for the raw materials most used for biodiesel production. However, the specific conditions necessary for the development of palm (temperature and humidity) have limited its propagation, besides strong issues regarding deforestation associated with its cultivation, mainly in Asia [49]. For instance, in Brazil, soy cultivation is spread over several regions, while palm oil producers are located in the north of the country, where the climatic conditions are similar to those in Colombia and ideal for its cultivation[49].

Nonetheless, some efforts have been made to expand palm cultivation to other Brazilian regions, such as the Southeast and Midwest. According to Antonini and Oliveira (2021) [50], the climatic and soil characteristics in these regions allow the production of this oilseed as long as the water need is fulfilled by full irrigation. It is noteworthy that improving the productivity of the raw material will increase the energy contained in the biomass per hectare, which means obtaining higher values of agricultural ratio and, consequently, improving the biofuels production. Therefore, the efforts to discover new feedstocks phenotypes should be intensified, seeking to enhance yields, adapt to climate change soil limiting conditions such as low fertility.

Table 1. Agricultural indicators for primary feedstocks used for biofuels production in some Latin American countries

		Argentina			**Brazil**[d]		**Colombia**[e]		**Guatemala**[f]
Indicators	***Units***	*Corn*[b]	*Sugarcane*[b]	*Soybean*[c]	*Sugarcane*	*Soybean*	*Sugarcane*	*Palm Oil*	*Sugarcane*
Crop yield	(tonne/ha)	7.5	55.6	2.9	75.4	3.4	120	19.3	115.7
Crop production energy consumption	(GJ/ha)	4.4	10.8	8.5	11.8	6.8	10.6	12.2	120.2
Biomass Energy	(GJ/ha)	138.8	292.4	119.9	337.1	118.7	531.6	294	512.7
Agricultural energy ratio*	-	27.2	27.0	16.3	28.5	17.4	50.1	24.1	4.3
Biofuel yield[a]	(GJ/ha)	50.7	35.4	20.2	135.7	22.6	46.6	28.9	21.2

Based on:[a][25],[b][33], [c][32], [d][51], [e][35,36], and [f][37].

* The ratio between Biomass Energy and Crop production energy consumption.

3. Materials and methods

This section presents all the relevant information about the production of ethanol and biodiesel, as well as the guidelines used for the life cycle assessment to understand the impacts associated with the biofuels supply chain. Briefly, a detailed description of the system boundaries for each biofuel production process and the steps to carry out the life cycle impact assessment were described.

3.1 Systems boundaries

The scenarios assessed were (i) anhydrous ethanol production in Argentina, Colombia, Brazil, and Guatemala; (ii) biodiesel production in Argentina, Brazil, and Colombia. The Latin American countries selected employed a variety of feedstocks for biofuel production, implying a variety of biofuel production pathways (section 2.1). Considering the ethanol production from sugarcane, the supply chain production is composed of four main stages included in the system boundary: *(i) farming, (ii) juice extraction, (iii) sugar production, and (iv) ethanol production*. The corn-based ethanol produced in Argentina is divided into two main stages, as know *(i) farming and (ii) ethanol production*. Regarding biodiesel production, both production from soybean oil (Argentinian and Brazilian scenarios) and palm oil (Colombian scenario) are organized into four central systems: *(i) farming, (ii) oil extraction, (iii) oil refining, and (iv) oil transesterification*. A detailed scheme of these systems can be observed in Figures 3 and 4 for ethanol and biodiesel production, respectively. The general characteristics of each system are described below, and more detailed information about each system can be found elsewhere (*Sugarcane ethanol* [13,15,52], *Corn ethanol* [14,53], *Soybean biodiesel* [54,55], and *Palm oil biodiesel* [15,52,56]). As indicated in section 3.1.2, data for each country were obtained through a review of the specialized literature.

Ethanol production:

In brief, a traditional sugarcane ethanol plant consists of four systems, as mentioned above, and a combined heat and power unit. In Brazil, some mills manufacture ethanol from sugarcane juice, named ethanol dedicated plant (when both products, sugar, and ethanol are produced, the mill is referred to as Annexed, and around 70% of Brazilian mills are related to this configuration). On the other hand, 100% of the ethanol plants in Argentina, Colombia, and Guatemala produce sugar and ethanol. Therefore, this was the configuration adopted in this work. Brazil has 361 sugarcane ethanol plants and 8 corn ethanol plants, corresponding to a processing capacity of 745 million tonnes of sugarcane and 14 million tonnes of corn grain, respectively [34]. However, the share of corn in the production of Brazilian ethanol is still small, around 6% of the total ethanol produced. For this reason, corn ethanol production in Brazil was not considered in this study. A different scenario was observed in Argentina: there are 6 corn ethanol plants and 16 sugarcane ethanol plants operating and corresponding to a production capacity of around 950 thousand tonnes of ethanol per year [32]. In this case, the share of corn in the production of Argentinian ethanol is approximately 50%, reinforcing the importance to assess the process.

Sugarcane and corn cultivation (*cultivation system*) includes fertilizers application, harvesting, and transporting the raw material to the mill. In this stage were considered the use of fertilizers, herbicides, fuels, lime, etc. The distance transportation to the industry was assumed to be 30 km. The differences among fuel consumption are detailed in *Appendix A* (Tables A.4 to A.29) for each country. In producing ethanol from sugarcane, the cane is transported on a conveyor belt to the mill. At this stage, the sugarcane is chopped and cleaned, and its lignocellulosic fraction (bagasse) is separated from the liquid fraction (known as juice). The sugarcane juice is then transferred to a sugar and alcohol mill, where it is processed into sugar and ethanol. Sugar is obtained by evaporation, clarification, and crystallization of the sugar contained in the juice. The left-over juice forms a by-product with high concentrations of fermentable sugars, known as molasses, which are converted to ethanol by fermentation with yeast. This is the typical arrangement for the Annexed sugar/ethanol mills. Therefore, ethanol can be produced from sugarcane juice, molasses, or a mixture of both. In the fermentation step, the use of chemicals was also considered, and the information for each country was detailed in *Appendix A*. Besides, the sugarcane ethanol plants were considered energetically self-sufficient, which means the plant is supplied with enough energy generated by burning bagasse (electricity and steam) to feed all the systems and in and in some cases, with an electricity surplus sold to the grid.

On the other hand, there are two main systems for corn-based ethanol in Argentina. The farming steps are like those already described for sugarcane, where fertilizers, herbicides, fuels, and other chemicals are employed. The dry milling technology was used to assess corn-based ethanol in Argentina. This system is divided into four subsystems: grinding, liquefaction and saccharification, fermentation, and distillation. Firstly, corn grain is washed and finely ground. Then, the mashed corn grain is converted into fermentable sugars through enzymatic hydrolysis, which breaks the glycosidic bonds from starch macromolecules. Next, the output stream from the liquefaction process is combined with a recycled stream known as "backset" (liquid portion of stillage separated by centrifugation later in the process). The "backset" stream is significant to the fermentation step since it provides essential nutrients for the yeast. Besides, the glucose syrup is fermented into ethanol (9% v/v) and carbon dioxide by yeast action in this step. Finally, the ethanol obtained into the fermentation step is separated by distillation, originating the hydrated ethanol (95 wt%), and then it is separated with the use of molecular sieves to obtain anhydrous ethanol (99.8 wt%). A more detailed process description can be found elsewhere [14,53]. Unlike Brazil, corn ethanol plants in Argentina, as well as in the United States, are not energetically self-sufficient and use fossil fuels such as natural gas in their operations.

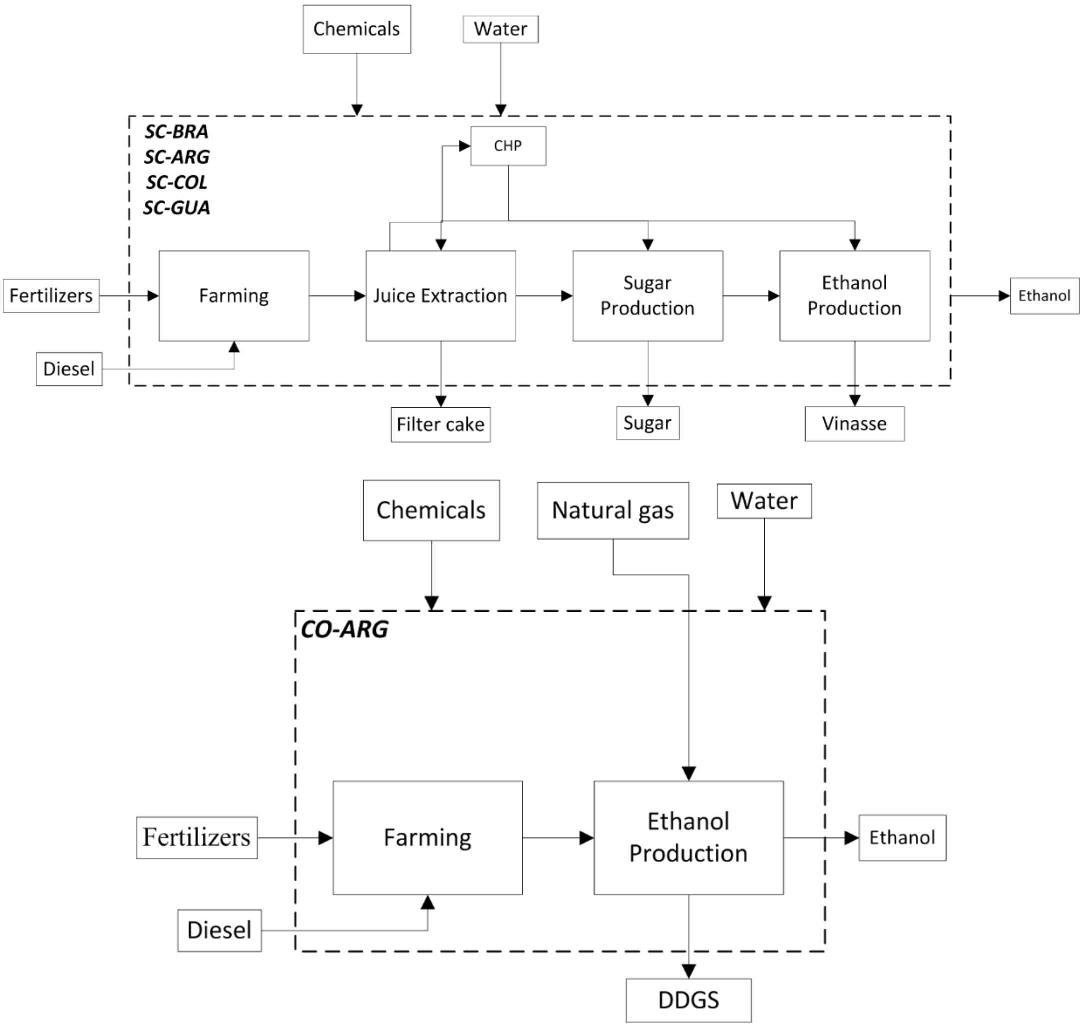

Figure 3. Systems diagrams for ethanol production from sugarcane and corn.

Biodiesel production:

Except for the combined heat and power plant in palm-based biodiesel production, the traditional soybean-based, and palm-based biodiesel facilities are similar and composed of four central systems. The farming system involves all soybean and palm planting, growing, and harvesting activities and feedstock transportation to mill. In this stage were considered the use of fertilizers, herbicides, fuels, chemicals, etc. The distance transportation to the industry was assumed to be 50 km. The differences among fuel consumption are detailed in *Appendix A* (Tables A.4 to A.29) for each country.

Regarding soybean-based biodiesel, after harvested and transported to the biodiesel plant, soybean is conditioned in silos, dried until it reaches final moisture around 11% d.b. (*dry base*), ground, and pressed to extract the soybean oil. In general, soybean oil extraction is performed with n-hexane and, from 1 tonne of soybean, around 180 kg of soybean oil (18%), 790 kg of soybean meal (79%), and 30 kg of residues (3%) are obtained. The soybean meal is removed for other uses and soybean oil is taken to the refining stage to remove impurities. After that, the refined oil is processed in a transesterification stage to obtain biodiesel. The process occurs through the methanation route and produces around 790 kg of soybean methyl ester and 106 kg of crude glycerin per tonne of soybean oil. It is worth mentioning that soybean-based biodiesel plants are not energetically self-sufficient, and electricity from the grid and heat from natural gas (Argentinian case) or forests residues (Brazilian case) are used.

On the other hand, palm-based biodiesel is energetically self-sufficient. At the oil extraction stage, the solid by-products, known as fiber and shells, are taken to combined heat and power units to produce electricity and heat, respectively. From 1 tonne of palm, around 200 kg of crude palm oil (CPO), 15 kg of crude kernel oil (CPKO), 25 kg of palm kernel cake (PKC), 220 kg of empty fruit bunches (EFB), 130 kg of fiber, 7 kg of shells, and 440 kg of palm oil mill effluents (POME) are obtained. The subsequent stages are similar to those already presented for soybean-based biodiesel, and the details can be accessed elsewhere [12,15,52,54]. The differences in life cycle inventory for each biodiesel pathway can be found in *Appendix A*.

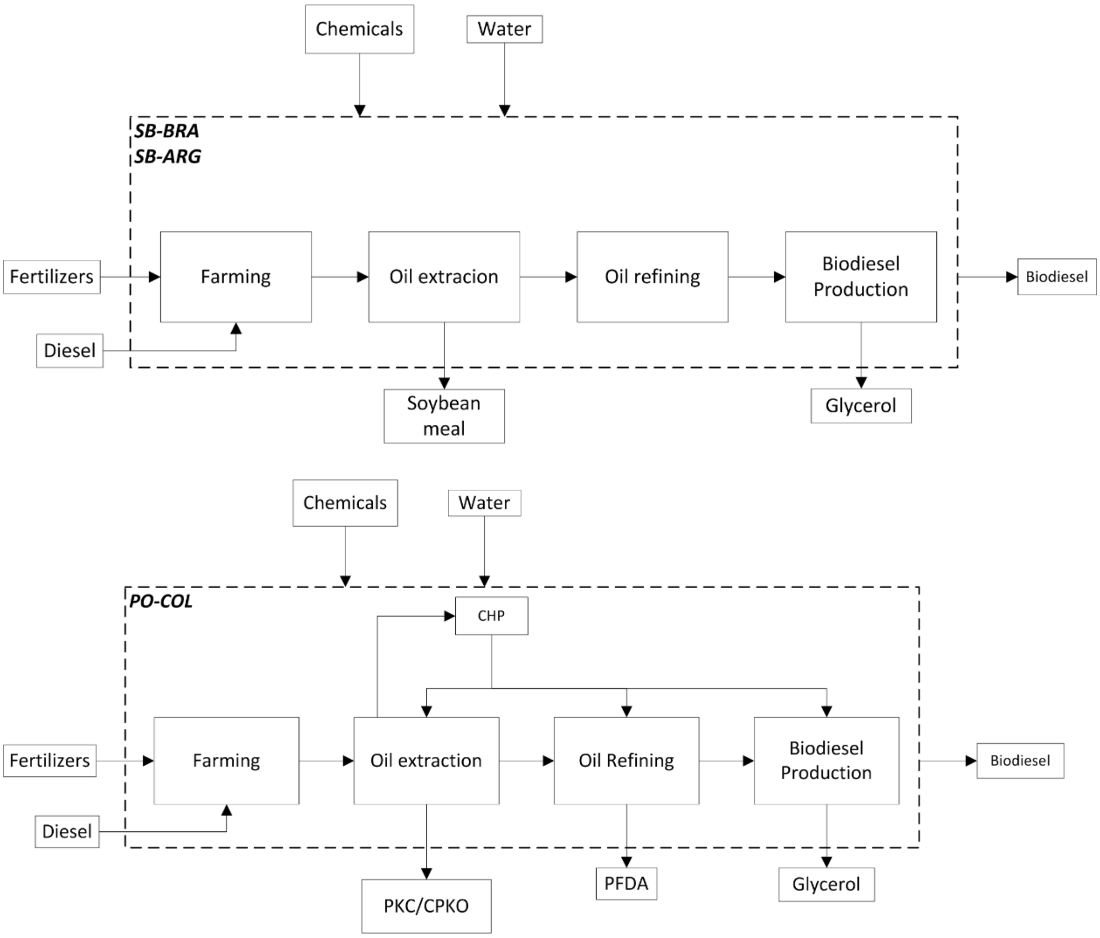

Figure 4. Systems diagrams for biodiesel production from soybean oil and palm oil.

3.2 Life cycle assessment (LCA)

LCA methodology was performed to investigate the environmental impacts of ethanol and biodiesel production in Argentina, Brazil, Colombia, and Guatemala. This methodology is structured according to ISO 14040 guidelines (ISO 14040 2006), and it was based on a compilation of life cycle inventories obtained in the literature [15,52–56].

3.2.1 Goal and scope

A "*cradle-to-gate*" comparative life cycle assessment was proposed to estimate the environmental impacts of first-generation ethanol and biodiesel production in Argentina, Brazil, Colombia, and Guatemala. The functional unit of 1.0 MJ of biofuel produced was defined, and the co-products were managed by energy allocation.

3.2.2 Life cycle inventories – LCI

Each country's inventories for each biofuel production pathway (ethanol and biodiesel) were built through a comprehensive revision from the specialized literature. All inventories are presented in *Appendix A* (*Tables A4 to A29*, Section 5).

3.2.3 Life cycle impact assessment (LCIA)

The process was modeled using the software OpenLCA$^{®}$v.1.10.3 (Green Delta, Germany, 2021) to create the process trees and compile the results based on the ReCiPe 2016 midpoint Hierarchist method for the characterization of the impacts. The Ecoinvent database v3.7 was used to obtain the main inputs' environmental profile, adapted to each country's conditions. The results obtained in this work were divided into eighteen midpoint categories (*Appendix* A), emphasizing a more detailed discussion for three well-known impact categories: *global warming, terrestrial acidification, and ozone depletion*.

3.2.4 Life cycle energy performance indicators

The *Energy Ratio (ER)* and *Net Energy Ratio (NER)* were used to analyze the life cycle energy efficiency and have been described in equations 1 and 2 below:

$$\mathrm{ER} = \frac{\mathrm{Bioenergy_{output}}}{\mathrm{Fossil\ energy\ input_{input}}} \tag{1}$$

$$\mathrm{NER} = \frac{(\mathrm{Biofuel\ energy_{output}} - \mathrm{Fossil\ energy\ input_{input}})}{\mathrm{Biofuel\ energy_{output}}} \tag{2}$$

$\text{Bioenergy}_{\text{output}}$ represents the energy contained in the final product and its by-products, $\text{Fossil fuel}_{\text{energy}}$ is the fossil energy used in the production system, and $\text{Biofuel energy}_{\text{output}}$ represents the energy contained in the biofuel produced.

3.2.5 Sensitivity analysis

Sensitivity analysis allows us to assess how performance indicators vary with the change of critical parameters [24,57]. A sensitivity assessment was performed considering all scenarios evaluated in this research. As decision-makers adopt GHG emissions to assess environmental impacts, changes in the global warming impact category were assessed. Thus, a Monte Carlo analysis was performed with 10,000 interactions and normal distribution with a 95% confidence interval ($p = 0.05$). The parameters considered in the analysis were determined according to the LCIA result and ranged between 25 and 100% of the LCI value.

3.3 Incentives and Policies for biofuels: The Renovabio case

The impact of public policies on biofuels production in Latin American countries was assessed, assuming that the four countries under investigation in this research could adopt a public policy for biofuels like Brazilian Renovabio. In 2017, Brazil launched RenovaBio (Law 13,576/2017), a state policy recognizing the strategic role of all types of biofuels in Brazil's energy matrix, both for energy security and for mitigation of greenhouse gas emissions. This new law is in effect since 2020 and has a global carbon intensity reduction target, established in 95.5 million CBIOs in 2029 (1 CBIO = 1-tonne CO_2eq). RenovaBio provides a market-based incentive by issuing GHG emissions reduction certificates, named "CBIO," which is sold in the stock market (1 CBIO = US$ 10) [41].

4. Results and discussion

4.1 Life cycle assessment

4.1.1 Life cycle impact assessment (LCIA) – Recipe Midpoint

The life cycle impact assessment for the four countries analyzed for biofuels production was evaluated in all eighteen mid-point categories from the ReCiPe Midpoint H method as shown in Figure A4 (*Appendix A*, section 3). The results reveal discrepancies among the mid-points categories evaluated per MJ of biofuels produced by the different countries. The discussion was focused on global warming, terrestrial acidification, and ozone depletion categories. For simplicity, all impact categories were presented in terms of farming and industrial phases.

4.1.2 Global warming potential (GWP)

The global warming potential (GWP) is the most well-known LCIA midpoint category and, generally, it is used as a parameter to measure the impact of human activities on natural resources. For this reason, special attention was given to this category. The values for the GWP category for liquid biofuels (ethanol and biodiesel) are shown as compared with fossil fuels (gasoline and diesel), in Figures 3 and 4. In the case of sugarcane ethanol production (Figure 5), a comparative analysis for the different scenarios showed a considerable reduction in the global warming potential (GWP) category. Contrasting with the GWP for gasoline, the GWP category values were 66%, 70%, 74%, and 81% lower for Guatemala, Argentina, Brazil, and Colombia, respectively. On the other hand, the production of corn ethanol in Argentina has less impact on climate change, reducing the value of the GWP category by only 37% compared to gasoline. This is due to a large amount of natural gas used in the production of corn ethanol, as this process does not have a combined heat and energy plant attached for the self-production of steam and bioelectricity. Farming activities contribute to global warming in all cases studied, ranging from 39.1% to 80.9% of GHG emissions. Our work corroborates the results of Gabisa et al. (2019) [24]. They conducted a LCA for ethanol production from sugarcane molasses and showed that sugarcane farming significantly contributes to GHG emissions in Ethiopia's ethanol production. In the same way, the study performed by Carvalho et al. (2021) [30] showed that the use of nitrogen is responsible for half of the GHG emissions during the ethanol production life cycle in Brazil.

The results obtained for biodiesel production (Figure 6) were like those observed for ethanol production. Although the life cycle assessment was performed for different raw materials, compared to diesel, all the pathways analyzed in this work showed a reduction of the emissions. In descending order, the GHG emissions reductions were 84%, 79%, and 68% of biodiesel compared to diesel for Colombia, Argentina, and Brazil. It is worth noticing the significant decrease in GHG emissions presented in the Colombian case. Different systems influenced GHG emissions in different ways for each investigated country. Except for the Argentinian case, which has a significant contribution from the industrial phase (70%), the significant contribution to Colombian and Brazilian emissions from biofuels came from the farming system (70% for both). Significant contributions to GHG emissions are related to fertilizers and fossil fuels such as diesel oil and natural gas. In the production of fertilizers, around 5% of the natural gas produced in the world is consumed [58]. The replacement of this fuel by biogas could be an alternative to reduce greenhouse gas emissions in the production of biofuels. For both ethanol and biodiesel production, the GWP values were lower than those for gasoline and diesel, respectively. Our study indicates there is room for improvement and opportunities for developments to further benefits associated to liquid biofuels production in Argentina, Brazil, Colombia, and Guatemala. For example, a strategy that could improve sustainability metrics and reduce GHG emissions would be to adopt an integrated ethanol and biodiesel production system. According to Ocampo Battle et al. (2021) [52], palm oil biodiesel and sugarcane ethanol integrated production processes proved energetically and economically efficient. However, the authors also highlighted the need to improve the conversion technologies, the tax incentives based on reducing the use of fossil fuels and achieving higher conversion yields.

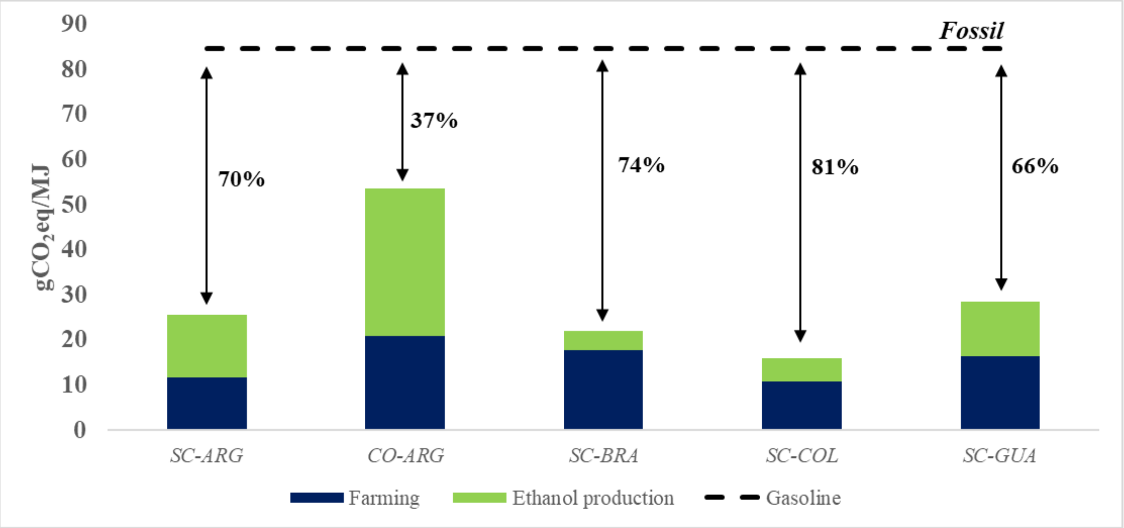

Figure 5. Climate change impact (GWP 100) for ethanol production compared to gasoline use for the countries investigated in this study (Recipe Midpoint, H).

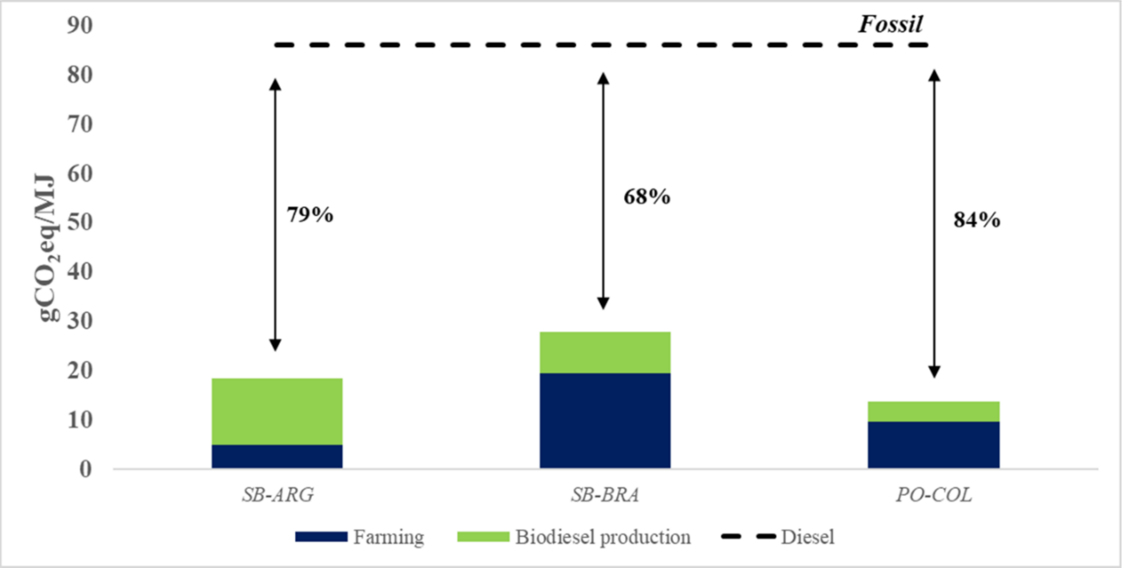

Figure 6. Climate change impact (GWP 100) for biodiesel production compared with diesel use for the countries investigated in this work (Recipe Midpoint, H).

4.1.3 Terrestrial acidification (TAP)

For the ethanol production process, the terrestrial acidification category was considerably affected by the Argentinian and Guatemalan cultivation system and also by the ethanol production system in the Brazilian and Colombian cases (Table 2). The TAP impact category of Argentina and Guatemala scenarios were strongly affected by applying fertilizers (70.8% for Argentina) and diesel use (64.9% for Guatemala) in the cultivation phase. The results presented in this study agreed with the study conducted by Amores et al. (2013) [13]. They indicated that the NO_X emissions from burning sugarcane straw and the use of fertilizers accounted for 90% of terrestrial acidification. The increased use of nitrogen fertilizers contributes to increasing soil acidity through the release of H^+ ions due to the oxidative reaction of ammonium compounds, which consequently decreases the soil pH [59].

In the Brazilian and Colombian cases, the TAP category was strongly affected by NO_X and SO_X emissions associated with burning biomass in the cogeneration system. According to Eugster and Haeni (2013) [60], emissions generated from biomass burning can increase the impact of the TAP category in two ways, namely, dry or wet deposition. The first deals with the formation of fog and, consequently, the deposition of SO_X and NO_X. On the other hand, wet deposition occurs through the oxidative reaction between sulfur and nitrogen oxides and ozone, resulting into sulfuric acid and nitric acid, respectively. In general, the dissociation of these acids into H^+ ions result in acid precipitation and, consequently, an increase in TAP.

Looking at biodiesel production (Table 3), for the Argentinian and Brazilian scenarios, the farming system is responsible for significant contribution to the TAP impact category, based on the same fact already observed and discussed for the ethanol cases. The palm oil extraction system significantly influenced terrestrial acidification in the Colombian scenario due to the high NO_X emissions during the burning of palm by-products in the cogeneration system. When a comparison is performed with fossil fuels such as gasoline and diesel, a cradle-to-gate LCA showed a lower impact of fossil fuels on the TAP category than ethanol and biodiesel, respectively. However, both diesel and gasoline have sulfur in their composition. This inherent characteristic of fossil fuels will probably increase the TAP impact category used in Otto cycle engines. The study conducted by Cavalett et al. (2013) [7] evaluated seven different LCIA models (CML 2001, Impact 2002+, EDIP 2003, Econ-indicator 99, TRACI 2, ReCiPe midpoint (H), and Ecological Scarcity 2006). The results found in this work corroborate with those obtained by Cavalett et al. (2013) [7], showing the higher impact of ethanol on the TAP category (5.34×10^{-4} kg SO_2eq) in comparison with the gasoline (1.99×10^{-4} kg SO_2eq).

Table 2. Process contribution of terrestrial acidification impact category (TAP100) for ethanol production in the different scenarios evaluated (Functional unit = 1 MJ).

Terrestrial acidification (kg SO_2eq/MJ)				
Scenarios	**Farming**	**Industrial phase***	**Total**	**Gasoline**
SC-ARG	5.3×10^{-4}	2.2×10^{-4}	7.5×10^{-4}	1.3×10^{-4}
CO-ARG	2.8×10^{-4}	1.0×10^{-4}	3.8×10^{-4}	1.3×10^{-4}
SC-BRA	1.5×10^{-4}	5.9×10^{-2}	7.4×10^{-2}	1.3×10^{-4}
SC-COL	1.8×10^{-4}	5.8×10^{-2}	6.0×10^{-2}	1.3×10^{-4}
SC-GUA	2.4×10^{-4}	1.2×10^{-4}	3.6×10^{-4}	1.3×10^{-4}

*It represents all the steps dedicated to converting fermentable sugars into ethanol (LCI on Appendix A).

Table 3. Process contribution of terrestrial acidification impact category (TAP100) for biodiesel production in the different scenarios evaluated (Functional unit = 1 MJ).

Terrestrial acidification (kg SO_2eq/MJ)				
Scenarios	**Farming**	**Industrial phase***	**Total**	**Diesel**
SB-ARG	3.6×10^{-5}	1.3×10^{-5}	4.9×10^{-5}	1.1×10^{-4}
SB-BRA	1.3×10^{-4}	4.9×10^{-5}	1.8×10^{-4}	1.1×10^{-4}
PO-COL	8.0×10^{-5}	1.8×10^{-3}	1.9×10^{-3}	1.1×10^{-4}

*It represents all the steps dedicated to extracting and converting vegetal oil into biodiesel (LCI on Appendix A, Section 5).

4.1.4 Ozone depletion

The results obtained for the ozone depletion (ODPinf) impact category can be observed in Tables 4 and 5. For ethanol production, the evaluated scenarios presented ODPinf values ranging from $1.9 \times 10^{-9}$to 7.9×10^{-9} kgCFC-11_{eq} and, except for corn ethanol in Argentina, all other sugarcane ethanol production processes showed a significant contribution from the farming system. The share of the sugarcane farming system in the ODPinf impact category was 94.3%, 63.6%, 68.8%, and 90.2% for the Argentinian, Brazilian, Colombian, and Guatemalan cases, respectively. Agricultural activities, such as the production and application of fertilizers, are responsible for the results found. The large amounts of natural gas and diesel oil used to produce and apply fertilizers were responsible for almost all impacts reported in the ozone layer depletion category. The work carried out by Gabisa et al. (2019) [24] also reports the significant contribution (~46%) of fertilizer production and use in the ODP impact category. For corn ethanol in Argentina, as discussed in *section 4.1.2*, the large amount of natural gas utilized in the ethanol production system accounted for 33.8% of the ODP impact category.

Pieragostini et al. (2014) [14] performed LCA for corn ethanol production in Argentina and showed a substantial contribution of natural gas in the ozone layer categories.

According to the authors, the natural gas use and heat supply accounted for 58% of the impact caused by the ozone layer depletion category.

Furthermore, compared to gasoline, all ethanol production scenarios analyzed in this paper performed better in the ODP impact category. The results for the biodiesel production scenarios support the observations that have previously been made for the ethanol scenarios. Table 5 shows that all biodiesel production cases have lower ODP values than diesel oil.

Table 4. Process contribution of ozone depletion and particulate matter formation impacts categories for ethanol production in the different scenarios evaluated (Functional unit = 1 MJ).

Ozone depletion (kg CFC-11eq/MJ)				
Scenarios	**Farming**	**Industrial phase***	**Total**	**Gasoline**
SC-ARG	3.8×10^{-9}	0.02×10^{-9}	4.1×10^{-9}	1.5×10^{-8}
CO-ARG	2.2×10^{-9}	3.3×10^{-9}	5.5×10^{-9}	1.5×10^{-8}
SC-BRA	2.0×10^{-9}	1.1×10^{-9}	3.1×10^{-9}	1.5×10^{-8}
SC-COL	1.3×10^{-9}	0.6×10^{-9}	1.9×10^{-9}	1.5×10^{-8}
SC-GUA	7.2×10^{-9}	0.7×10^{-9}	7.9×10^{-9}	1.5×10^{-8}

Table 5. Process contribution of ozone depletion and particulate matter formation impacts categories for biodiesel production (Functional unit = 1 MJ).

Ozone depletion (kg CFC-11eq/MJ)				
Scenarios	**Farming**	**Industrial phase***	**Total**	**Diesel**
SB-ARG	2.0×10^{-9}	2.8×10^{-9}	4.8×10^{-9}	1.6×10^{-8}
SB-BRA	0.8×10^{-9}	0.5×10^{-9}	1.3×10^{-9}	1.6×10^{-8}
PO-COL	0.1×10^{-9}	1.4×10^{-9}	1.5×10^{-9}	1.6×10^{-8}

4.1.5 Life cycle energy indicators

The life cycle energy indicators energy ratio (ER) and net energy balance (NEB) were estimated for all the investigated countries, and the results are presented in Figure 7 (A) for ethanol production and in Figure 7 (B) for biodiesel production, respectively. The NEB values for all biofuels production ranged from 0.51 $MJ_{net\ energy}/MJ_{biofuel}$ to 0.96 $MJ_{net\ energy}/MJ_{biofuel}$, while for ER, it ranged from 2.5 $MJ_{bioenergy}/MJ_{fossil}$ to 9.3 $MJ_{bioenergy}/MJ_{fossil}$. NEB values greater than zero indicate that all biofuel production pathways produce more energy than is needed to produce the fuel, and this is an essential criterion for energy sustainability for biofuels in the transport sector. Among the investigated ethanol production systems, it is worth highlighting the NEB values for the cases of Colombia and Guatemala. In the first case, the NEB value was the lowest found in this work (NEB = 0.51), while the second had the higher NEB value (NEB = 0.96). Although ethanol is produced from molasses in both cases (Colombian and Guatemalan), the differences in product and co-product yields influenced NEB values. According to Chum et al. (2014) [8], increased co-production of electricity (and other co-products) increases NEB values. An analysis of the LCI data (*Appendix A*, tables A.4 to A.29) reveals a significant discrepancy between the amounts of bioelectricity, ethanol, and sugar produced in each country. These differences in LCI showed the specificity for each country on the production of ethanol even when a similar pathway was employed (Argentina, Colombia, and Guatemala produce ethanol from molasses). The results obtained for Biodiesel production showed NEB values ranging from 0.24MJ$_{\text{net energy}}$/MJ$_{\text{biofuel}}$ to 0.69 MJ$_{\text{net energy}}$/MJ$_{\text{biofuel,}}$ and just as for ethanol, all NEB values were higher than zero. Comparing raw materials used for biodiesel in these countries allows understanding the differences found in this work. When soybean was used for biodiesel production (Argentinian and Brazilian cases), there was no electricity co-production, as the soybean meal is used for human consumption or animal feed. As for biodiesel production from palm oil (in the Colombian case), the co-products were destined for the co-production of electricity, contributing to the increase in bioenergy production [8,61].

Regarding renewable energy per unit of fossil fuel used, the ER energy indicator presents significant variability for the countries evaluated in this work, as depicted in Figures 7 (A) and (B). The use of significant amounts of natural gas in the manufacture of ethanol from corn results in lower ER values than those obtained in the sugarcane ethanol production process, which uses energy generated at the plant. The differences for sugarcane systems depend on the yield of ethanol and co-products and the NEB values discussed above. For the biodiesel production systems, the ER values obtained for Argentinian and Brazilian cases were higher than those obtained for the Colombian case. The co-production of electricity and electricity consumption from the grid or other alternative sources justifies these values. For the Colombian case, in the palm oil extraction stage, large amounts of electricity produced from the grid and diesel were used for each tonne of fresh fruit bunches, contributing to the decrease in ER values. In the Argentinian and Brazilian case, compared with the Colombian case, a lower amount of electricity from the grid (per tonne of soybean) was used in the biofuel cradle-to-gate lifecycle. In general, it is possible to observe that all biofuel production systems evaluated here positively impact energy sustainability.

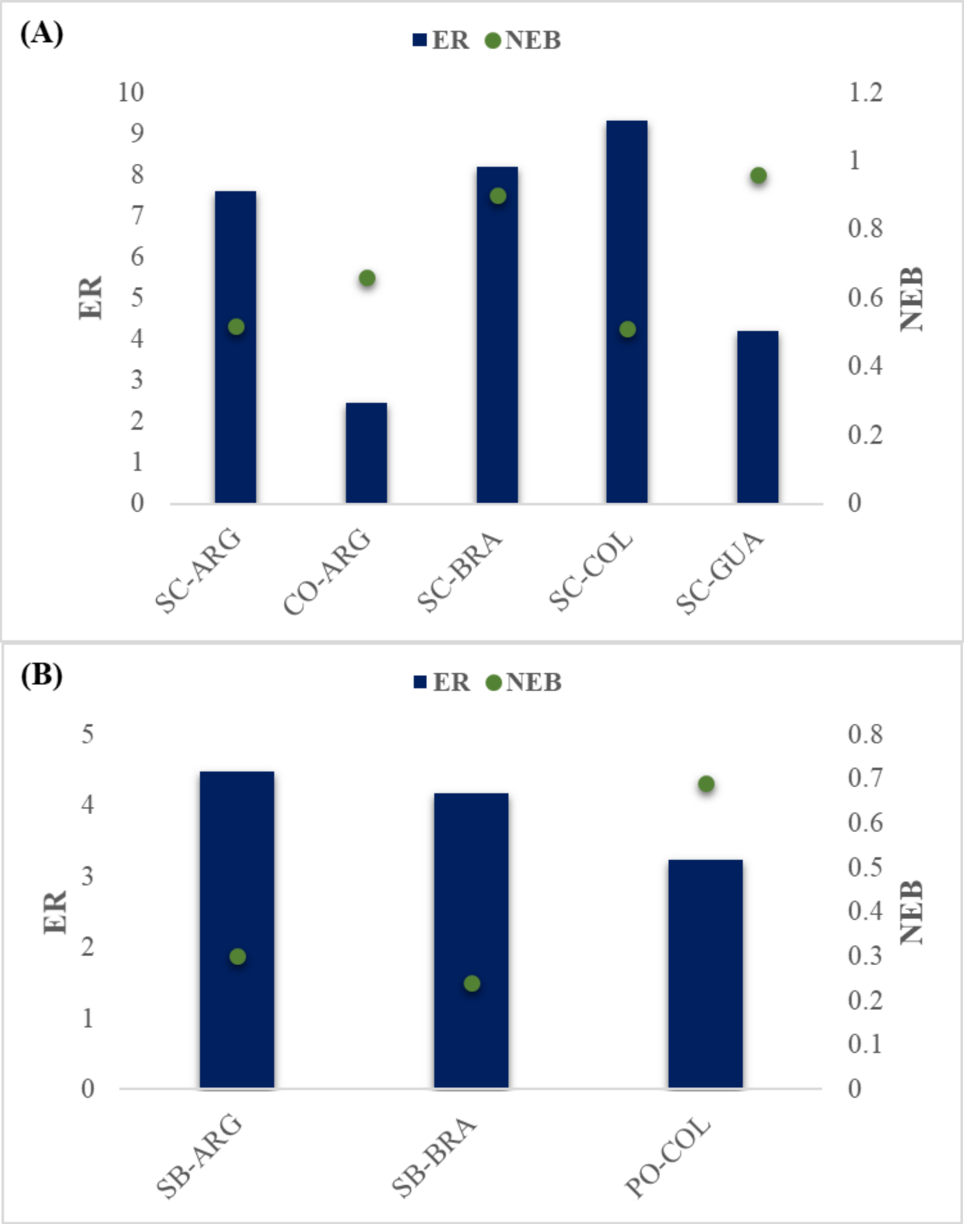

Figure 7. Energy ratio (ER) and Net energy balance (NEB) for ethanol (A) and biodiesel (B) production in selected countries. CO-ARG* - Values provided by [53].

4.1.6 Sensitivity analysis

Among all the impact categories assessed, climate change (GWP100) has caught much attention and is generally used to evaluate many environmental impacts. Figures 8 (A) and (B) show the sensitivity analysis for the global warming potential category in

Brazilian ethanol and biodiesel production, respectively. The sensitivity analysis for all other scenarios evaluated in this work can be found in *Appendix A* (Figure A.5 (A-C) and Figure A.6 (A-B)).

For the Brazilian ethanol production scenario (Figure 8A), greenhouse gas emissions were highly sensitive to fertilizer application and use activities. As mentioned in item 4.1.2, the fertilizer production chain uses natural gas, and its application is also directly linked to diesel oil consumption. Therefore, it is worth noticing that the activities involving fertilizers production and application were responsible for the changes observed in the GWP100 impact category. The biodiesel production scenario in Brazil (Figure 8B) shows a considerable influence of diesel consumption in the impact category GWP100. As shown in section 2.3, soybean productivity is the lowest compared to other raw materials used to produce biofuels analyzed in this study. It can explain the outstanding contribution of the diesel consumption in the results since it needed a large area to produce the raw material. In descending order, the production and use of fertilizers, pesticides, and methanol were the other elementary streams that showed sensitivity for the GWP100 impact category. The sensitivity analysis for Argentinian, Colombian and Guatemalan scenarios followed the same pattern observed for Brazilian ones, and the results can be found in *Appendix A*.

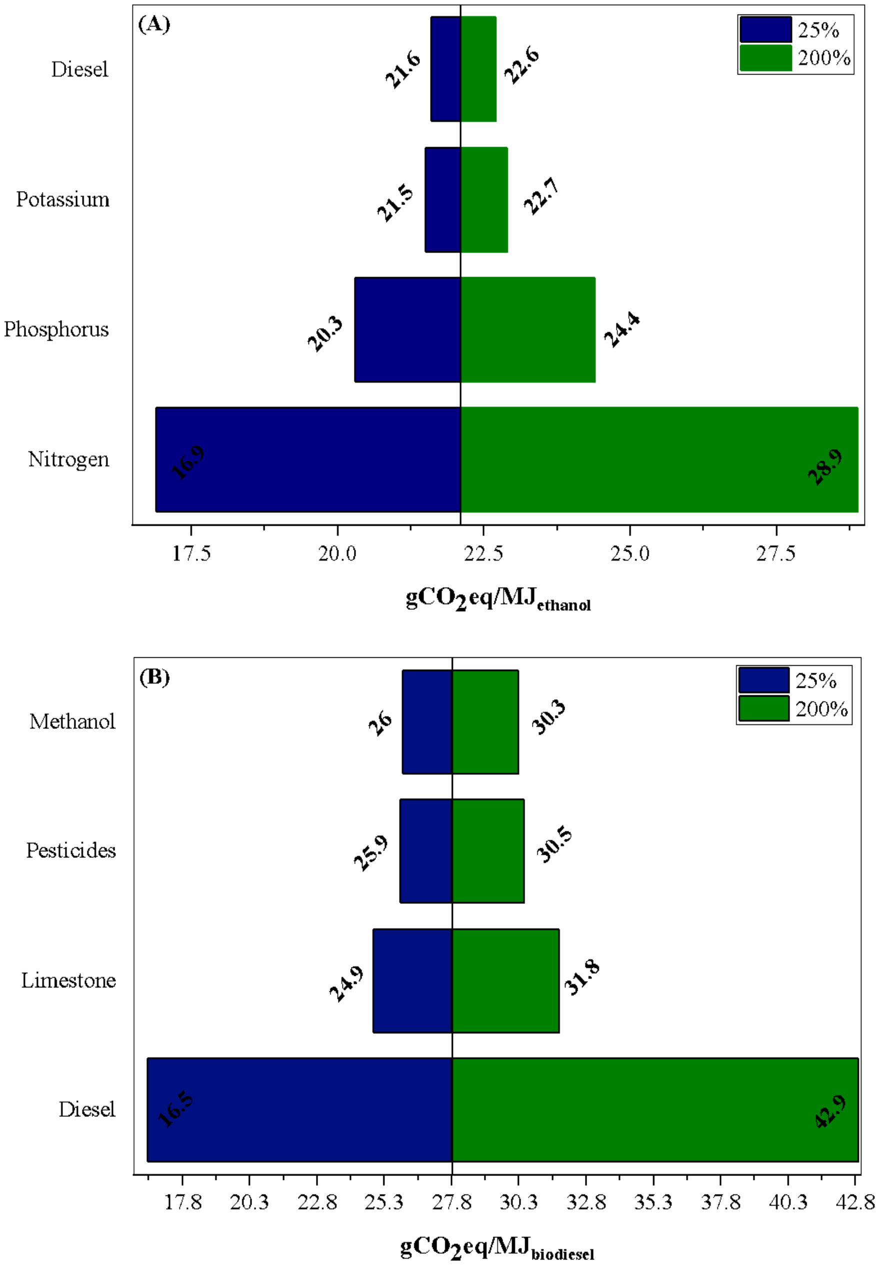

Figure 8. Sensitivity analysis for global warming potential (GWP100) impact category in Brazilian ethanol (A) and biodiesel (B) production. Where 25% and 200% are the minima and maximum values obtained from LCI values.

4.2 Incentives and policies

The GHG emissions obtained in the LCIA were used to demonstrate the impacts caused by the adoption of public policies for biofuels. The data in Tables 6 and 7 show the results obtained assuming that all four countries adopted a public policy for biofuels like the Brazilian Renovabio (described in *section 3.4).*

Table 6. Total and avoided GHG emissions if gasoline were replaced by ethanol in selected Latin American countries per year.

Scenarios	Annual Production (Billion L)	GHG emissions ethanol (Gg CO_2eq)	GHG emissions Gasoline[1] (Gg CO_2eq)	Emissions avoided by replacing gasoline by ethanol[2]		Value of CBIOs issued (Mi US$)[3]
				(%)	Mtonnes (CO_2eq)	
SC-ARG CO-ARG	1.07	910	1989	54.2	1.08	10.8
SC-BRA	35.3	16544	65427	74.7	48.8	448.8
SC-COL	0.45	148	834	82.3	0.68	6.8
SC-GUA	0.27	0	499	0	0	0

[1]GHG for gasoline 87.4 gCO_2eq/M.J.;[2]Assuming all countries has a public policy like Renovabio; [3]1 CBIO = US$ 10.

Table 7. Total and avoided GHG emissions if diesel were replaced by biodiesel in selected Latin American countries per year.

Scenarios	Annual Production (Billion L)	GHG emissions Biodiesel (Gg CO_2eq)	GHG emissions Diesel[1] (Gg CO_2eq)	Emissions avoided by replacing diesel with biodiesel[2]		Value of CBIOs issued (Mi US$)[3]
				(%)	Mtonnes (CO_2eq)	
SB-ARG	2.4	1284	6013	78.6	4.73	47.3
SB-BRA	5.9	5483	16508	66.8	11.02	110.2
PO-COL	0.6	283	1706	83.4	1.42	14.2

[1]GHG for diesel 84.3 gCO_2eq/M.J.;[2]Assuming all countries have a public policy like Renovabio; [3]1 CBIO = US$ 10.

As shown in Table 6, the ethanol production for Argentina, Brazil, and Colombia is environmentally highly sustainable, allowing a reduction of 54.2%, 74.7%, and 82.3%, respectively, in total emissions compared with gasoline. Due to political issues, Guatemala has not adopted blend mandates for biofuels, and policymakers have already discussed this possibility [62]. According to Cutz et al. (2020) [17], Guatemala has an adequate installed capacity to implement E10 (10 % ethanol-gasoline blend), which corresponds to 240 million liters of ethanol produced in 2019. As shown in Table 6, Guatemala has produced 270 million liters of ethanol, corroborating with Cutz et al. (2020) [17] findings and reinforcing the potential that Guatemala has to replace gasoline with ethanol. If Guatemala implemented a public policy like Renovabio, the country would avoid GHG emissions by 6% by implementing a blending of gasoline and ethanol. Considering biodiesel production, the data presented in Table 7 pointed out a potential reduction in GHG emissions of 78.6%, 66.8%, and 83.4% when diesel was replaced by biodiesel in Argentina, Brazil, and Colombia, respectively. If a ton of CO_2 was negotiated at US$ 10 the Brazilian biofuel producers would receive US$ 599.1 million per year, while for Argentinian, Colombian and Guatemalan producers, the annual profit would be around US$ 58.1, US$ 21.1, and US$ 3.3 million, respectively, considering their respective productions as seen in 2019. The issuing of decarbonization certificates could be an important mechanism to incentivize practices aimed at reducing GHG.

4.3. Land currently used for biofuels production and potential for expansion

The worldwide pressure for changes that may lead to lower GHG gas emissions reflected in recent years in the increasing of biofuels production and use due to the implementation of blending regulations (as stated in *section 2.1*) and a shift to low-carbon energy systems. Land-use changes related to the production of biofuels is a central issue [21] that deserves a systematic analysis since it depends on several factors. Data on the land demand to produce ethanol and biodiesel in the Latin American countries selected in this study are presented in Tables 8 and 9, respectively.

Brazil has the largest areas in use for biofuels when compared with the other Latin American countries analyzed in this study, as shown in Table 8. The sugarcane harvested area in 2019, compared to the 2017/2018 sugarcane harvest season, decreased by 1.1%, 3.2%, and 1.9% in Brazil [51], Colombia [31], and Guatemala [31], respectively. The reduction in the harvested area in Brazil was caused by the return of leased areas, sugarcane replacement by other crops, fewer new greenfield projects, and the shutdown of existing production units. On the other hand, in Argentina [32], the harvested area increased by 6.8% and 4% for corn and sugarcane between seasons 2017/2018 and 2018/2019. It is important to note that an increase in the harvested area does not always imply an increase in biofuels production, as the feedstock use for production may fluctuate depending on global sugar and corn grain prices as well as crop yields. Soy production in Brazil [51] and Argentina [32] dropped by 2.3% and 0.9%, respectively, at the 2018/2019 season, compared to the previous season. In Colombia [35], there was a reduction of 5.3% in palm crop yields between 2017/2018 and 2018/2019.

The land use data represents an estimate of the amount of land currently used to produce feedstocks for liquid biofuels based in the official data and an estimate on the amount of pasture that would be needed to double biofuels production. Pastures generally have low productivity and are generally underutilized. However, proper fertilization, rotational grazing, and integrated livestock-forestry or crop-livestock-forestry systems could improve land productivity [63]. The data presented in Tables 8 and 9 show that even for countries with a small territorial extension, the use of small portions of pastureland indicates a significant potential for biofuels feedstocks expansion. In Brazil, the results show that around 3.1% of pastureland is enough to duplicate the ethanol production, while for Argentina and Colombia, the use of 0.15% and 0.2% of pastureland would be necessary to achieve the same goal (Figure 9A). Guatemala is the smallest of the countries that would need 10% of pastures turned into agricultural land to produce raw materials for biofuels, to achieve a doubling of the volume of ethanol produced in the country.

For biodiesel production (Table 9), Argentina depicted a scenario in which around 4.5% of the pasture area would be sufficient to double biodiesel production, while for Brazil and Colombia the use of 3.3% and 0.05 of pastureland would be enough to reach the same goal. Therefore, using a small portion of pastures can significantly increase the production of biofuels and, consequently, increase the participation of biofuels in blending regulations. The differences are even more remarkable when compared with the total land devoted to agriculture (including crops and livestock). This leads us to believe that if the land were efficiently managed and if best practices were used [64], the expansion of biofuels production would not be a problem for these countries. In decreasing order, compared to total agricultural land, the share of land for biofuels (ethanol and biodiesel) was around 4.7%, 4.5%, 3.2%, and 0.2% for Brazil, Guatemala, Argentina, and Colombia, respectively (Figure 9B). Besides, according to the roadmap performed by IEA (2021) [23], if land-use remains at the same level until 2050, the share of bioenergy would be 10% lower. Furthermore, the productivity of feedstocks and biofuels are strongly related to land use, but not only, and it can vary significantly throughout the world, even for similar biofuels.

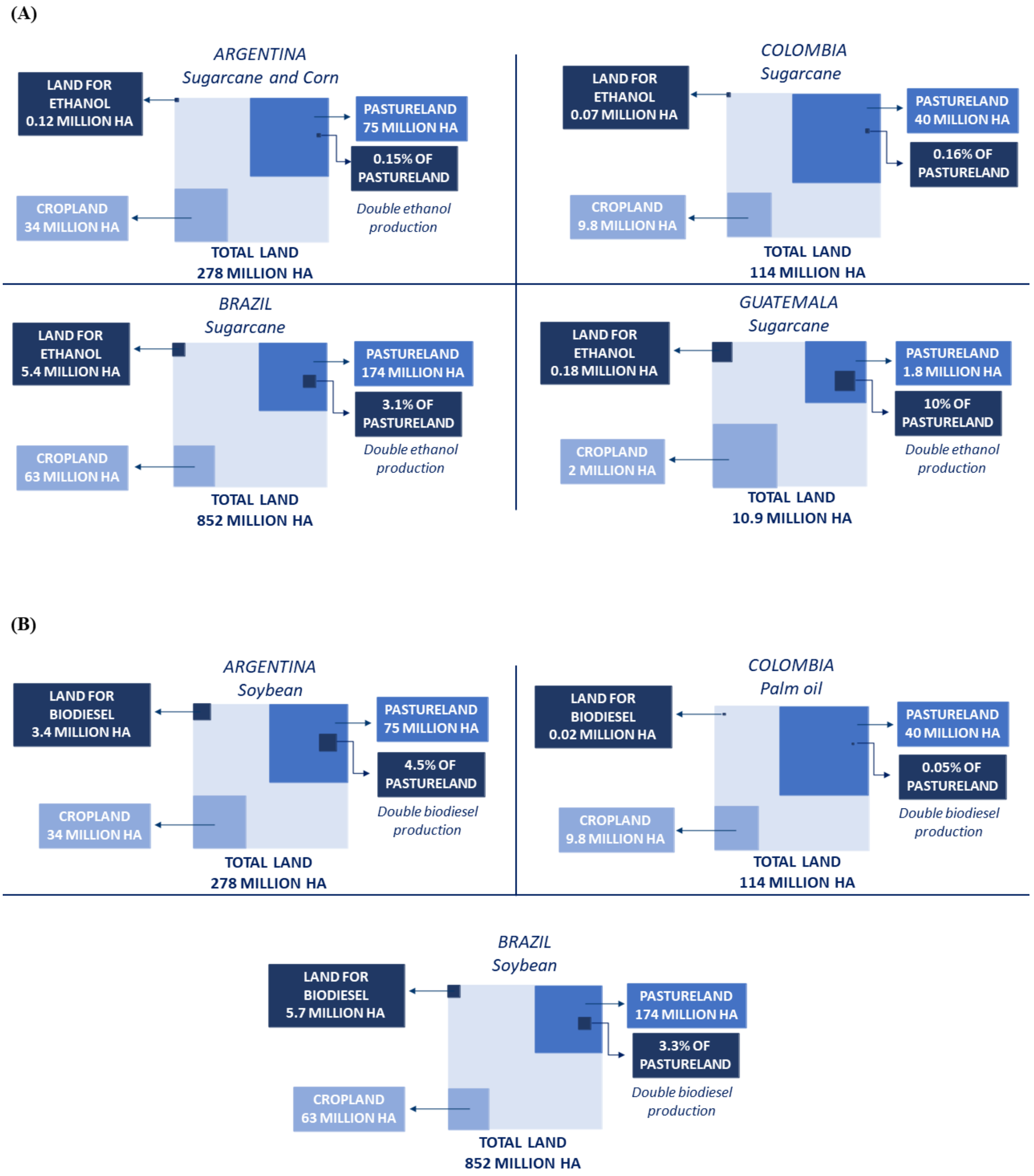

Figure 9. Current land used for biofuels (ethanol (A) and biodiesel (B)) and land demand to double the production.

Table 8. The feedstock used for ethanol production in 2019 (SC: sugarcane; CO: corn).

	Harvested area (million ha)	Use in biofuel (million tonnes)	Biofuel area (million ha)	Pastureland (million ha)	Share of land to duplicate biofuel production (%)	Agricultural land (billion ha)
SC-BRA	8.6	418	5.4	173.6	3.1	237
SC-ARG	0.5	3.1	0.1	74.7	0.13	108
CO-ARG	7.2	1.5	0.02		0.02	
SC-COL	0.2	17.5	0.07	39.8	0.2	50
SC-GUA	0.26	18.1	0.18	1.8	10	4

Source: (EPE, 2021 [65]; Argentina Biofuels Report (June 2021) [32]; FEPA Colombia 2021 [66]; Cengicaña statistical report [37], 2020; FAO, 2021 [31])

Table 9. The feedstock used for biodiesel production in 2019 (SB: soybean; PO: palm oil).

	Harvested area (million ha)	Oil used in biofuel (million tonnes)	Biofuel area (million ha)	Pastureland (million ha)	Share of land to duplicate biofuel production (%)	Agricultural land (billion ha)
SB-BRA	35.9	3.7	5.7	173.6	3.3	237
SB-ARG	16.6	2.2	3.4	74.7	4.5	108
PO-COL	0.5	0.3	0.02	39.8	0.05	50

Source: (EPE, 2021 [65]; Argentine Biofuels Report (June 2021) [32]; Fedepalma Colombia 2021 [35]; FAO, 2021 [31])

5. Conclusions and recommendations

The expansion of liquid biofuels production in Argentina, Brazil, Colombia, and Guatemala proves feasible and could support the transition to a low-carbon energy system in the transport sector. Biofuels produced in these countries significantly reduce emissions, are energetically favorable and have the potential to bring profit to producers through low-carbon biofuel certification schemes and carbon credit negotiations. Constraints on land demand are of little significance as seen by comparing the pastureland available in these countries, which can partially be converted to biofuel feedstock, with the potential to doubling the production of biofuels. Even though adopting a similar process to obtain biofuels, significant differences in the productivity of biofuels and yield of raw materials were found for the selected countries. Therefore, the need to encourage investments in breeding, biotechnology, soil nutrition, and conversion technologies must be emphasized since such actions can help improve the general performance of biofuel production in the region. Although fossil fuels perform better in terrestrial acidification, biofuels can drastically reduce impacts related to GHG emissions and the depletion of the ozone layer. Except for corn ethanol in Argentina, agricultural activities had the largest share in the GHG emissions and ozone layer depletion for ethanol production, mainly due to the production and use of fertilizers. The opposite was verified for biodiesel production in the Argentinian and Colombian cases, which seems to be drastically impacted by industrial activities mainly due to the use of natural gas in some processes. The sensitivity analysis confirms the significant relationship between GHG emissions and the usage of fertilizers and fossil fuels. Therefore, reducing the amount of fertilizer used and replacing natural gas with renewable fuels such as biogas would be an alternative to minimize emissions. The adoption of public policies for biofuels, which generate decarbonization certificates, presents itself as an excellent alternative to encourage the reduction of GHG emissions. The exchange of CBIOs can encourage farmers and biofuel producers to adopt good practices to reduce GHG emissions throughout the entire biofuel production chain.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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Appendix A.

References

[1] Junqueira TL, Chagas MF, Gouveia VLR, Rezende MCAF, Watanabe MDB, Jesus CDF, et al. Techno-economic analysis and climate change impacts of sugarcane biorefineries considering different time horizons. Biotechnol Biofuels 2017;10:50. https://doi.org/10.1186/s13068-017-0722-3.

[2] Kylili A, Christoforou E, Fokaides PA. Environmental evaluation of biomass pelleting using life cycle assessment. Biomass and Bioenergy 2016;84:107–17. https://doi.org/10.1016/j.biombioe.2015.11.018.

[3] Sun C-H, Fu Q, Liao Q, Xia A, Huang Y, Zhu X, et al. Life-cycle assessment of biofuel production from microalgae via various bioenergy conversion systems. Energy 2019;171:1033–45. https://doi.org/10.1016/j.energy.2019.01.074.

[4] Souza GM, Victoria RL, Joly CA, Verdade LM. Bioenergy & sustainability: bridging the gaps. Scientific Committee on Problems of the Environment (SCOPE); 2015.

[5] International Energy Agency. Global Energy Review 2021 - Assessing the effects of economic recoveries on global energy demand and CO2 emissions in 2021 2021:36.

[6] Zhang R, Zhang J. Long-term pathways to deep decarbonization of the transport sector in the post-COVID world. Transport Policy 2021;110:28–36. https://doi.org/10.1016/j.tranpol.2021.05.018.

[7] Cavalett O, Chagas MF, Seabra JEA, Bonomi A. Comparative LCA of ethanol versus gasoline in Brazil using different LCIA methods. Int J Life Cycle Assess 2013;18:647–58. https://doi.org/10.1007/s11367-012-0465-0.

[8] Chum HL, Warner E, Seabra JEA, Macedo IC. A comparison of commercial ethanol production systems from Brazilian sugarcane and US corn. Biofuels, Bioprod Bioref 2014;8:205–23. https://doi.org/10.1002/bbb.1448.

[9] BP. Statistical Review of World Energy 2021.

[10] de Souza NRD, Fracarolli JA, Junqueira TL, Chagas MF, Cardoso TF, Watanabe MDB, et al. Sugarcane ethanol and beef cattle integration in Brazil. Biomass and Bioenergy 2019;120:448–57. https://doi.org/10.1016/j.biombioe.2018.12.012.

[11] National Agency for Petroleum, Natural Gas and Biofuels - RenovaBio Biofuels Certification Dynamic Panel. Renovabio Panel 2021.

[12] Panichelli L, Dauriat A, Gnansounou E. Life cycle assessment of soybean-based biodiesel in Argentina for export. Int J Life Cycle Assess 2009;14:144–59. https://doi.org/10.1007/s11367-008-0050-8.

[13] Amores MJ, Mele FD, Jiménez L, Castells F. Life cycle assessment of fuel ethanol from sugarcane in Argentina. Int J Life Cycle Assess 2013;18:1344–57. https://doi.org/10.1007/s11367-013-0584-2.

[14] Pieragostini C, Aguirre P, Mussati MC. Life cycle assessment of corn-based ethanol production in Argentina. Science of The Total Environment 2014;472:212–25. https://doi.org/10.1016/j.scitotenv.2013.11.012.

[15] Valencia MJ, Cardona CA. The Colombian biofuel supply chains: The assessment of current and promising scenarios based on environmental goals. Energy Policy 2014;67:232–42. https://doi.org/10.1016/j.enpol.2013.12.021.

[16] Ramirez-Contreras NE, Munar-Florez DA, Garcia-Nuñez JA, Mosquera-Montoya M, Faaij APC. The GHG emissions and economic performance of the Colombian palm oil sector; current status and long-term perspectives. Journal of Cleaner Production 2020;258:120757. https://doi.org/10.1016/j.jclepro.2020.120757.

[17] Cutz L, Tomei, J, Nogueira, L.A.H. Understanding the failures in developing domestic ethanol markets: Unpacking the ethanol paradox in Guatemala. Energy Policy 2020:13. https://doi.org/doi.org/10.1016/j.enpol.2020.111769.

[18] BP Statistical Review of World Energy - 2021 n.d.

[19] Lorenzo, A, Melgar, M, Nogueira, LAH. Sugarcane ethanol in Guatemala. Sugarcane Bioenergy for Sustainable Development, Taylor & Francis; 2018.

[20] Tomei J, Diaz-Chavez R. Guatemala. In: Solomon BD, Bailis R, editors. Sustainable Development of Biofuels in Latin America and the Caribbean, New York, NY: Springer New York; 2014, p. 179–201. https://doi.org/10.1007/978-1-4614-9275-7_8.

[21] Weng Y, Chang S, Cai W, Wang C. Exploring the impacts of biofuel expansion on land use change and food security based on a land explicit CGE model: A case study of China. Applied Energy 2019;236:514–25. https://doi.org/10.1016/j.apenergy.2018.12.024.

[22] International Renewable Energy Agency. World Energy Transitions Outlook: 1.5°C Pathway 2021:312.

[23] International Energy Agency. Net Zero by 2050 - A Roadmap for the Global Energy Sector 2021:224.

[24] Gabisa EW, Bessou C, Gheewala SH. Life cycle environmental performance and energy balance of ethanol production based on sugarcane molasses in Ethiopia. Journal of Cleaner Production 2019;234:43–53. https://doi.org/10.1016/j.jclepro.2019.06.199.

[25] Hans Langeveld, John Dixon, Herman van Keulen. Biofuels Cropping Systems: Carbon, Land and Food. 1st ed. Routledge; 2018.

[26] Klein BC, Chagas MF, Watanabe MDB, Bonomi A, Maciel Filho R. Low carbon biofuels and the New Brazilian National Biofuel Policy (RenovaBio): A case study for sugarcane mills and integrated sugarcane-microalgae biorefineries. Renewable and Sustainable Energy Reviews 2019;115:109365. https://doi.org/10.1016/j.rser.2019.109365.

[27] Collotta M, Champagne P, Tomasoni G, Alberti M, Busi L, Mabee W. Critical indicators of sustainability for biofuels: An analysis through a life cycle sustainabilty assessment perspective. Renewable and Sustainable Energy Reviews 2019;115:109358. https://doi.org/10.1016/j.rser.2019.109358.

[28] Pereira LG, Cavalett O, Bonomi A, Zhang Y, Warner E, Chum HL. Comparison of biofuel life-cycle GHG emissions assessment tools: The case studies of ethanol produced from sugarcane, corn, and wheat. Renewable and Sustainable Energy Reviews 2019;110:1–12. https://doi.org/10.1016/j.rser.2019.04.043.

[29] Murali G, Shastri Y. Life-cycle assessment-based comparison of different lignocellulosic ethanol production routes. Biofuels 2019:1–11. https://doi.org/10.1080/17597269.2019.1670465.

[30] Carvalho JLN, Oliveira BG, Cantarella H, Chagas MF, Gonzaga LC, Lourenço KS, et al. Implications of regional N2O–N emission factors on sugarcane ethanol emissions and granted decarbonization certificates. Renewable and Sustainable Energy Reviews 2021:10.

[31] Food and Agriculture Organization of the United Nations. https://www.fao.org/faostat/en/#data n.d.

[32] MAGyP - Informe biocombustibles (Junio 2021) n.d.

[33] Institute for the Promotion of Sugar and Alcohol of Tucumán. https://www.ipaat.gov.ar/ 2021.

[34] Brazilian Energy Research Office. Análise de Conjuntura dos Biocombustíveis – Ano 2020 2020:87.

[35] Colombian National Federation of Oil Palm Growers. https://web.fedepalma.org/ 2021.

[36] Colombian Sugarcane Research Center. https://www.cenicana.org/ 2021.

[37] Guatemalan Sugarcane Research and Training Center. https://cengicana.org/ 2021.

[38] Global Agriculture Network Information. United States Department of Agriculture 2021.

[39] Nogueira LAH, Seabra JEA, Best G, Leal MRLV, Poppe MK. Sugarcane based bioethanol: energy for sustainable development. Banco Nacional de Desenvolvimento Econômico e Social; 2008. https://doi.org/10.13140/2.1.3774.1122.

[40] Global Agricultural Information Network (GAIN). Biofuels Annual São Paulo - Brazil 2021.

[41] ANP. National Agency for Petroleum, Natural Gas and Biofuels 2021.

[42] McDonald G, Rahmanulloh A. Biofuels Annual Indonesia Biofuels Annual Report 2019 2019.

[43] Global Agricultural Information Network (GAIN). Biofuels Annual Buenos Aires - Argentina 2021.

[44] Global Agricultural Information Network (GAIN). Biofuels Annual Bogotá - Colombia 2021.

[45] Cortez LAB, Leal MRLV, Nogueira LAH, LACAf Project, Universidade Estadual de Campinas, editors. Sugarcane bioenergy for sustainable development: expanding production in Latin America and Africa. London ; New York: Routledge, Taylor & Francis Group; 2019.

[46] Bordonal R de O, Carvalho JLN, Lal R, de Figueiredo EB, de Oliveira BG, La Scala N. Sustainability of sugarcane production in Brazil. A review. Agron Sustain Dev 2018;38:13. https://doi.org/10.1007/s13593-018-0490-x.

[47] Schultz N, Pereira W, de Albuquerque Silva P, Baldani JI, Boddey RM, Alves BJR, et al. Yield of sugarcane varieties and their sugar quality grown in different soil types and inoculated with a diazotrophic bacteria consortium. Plant Production Science 2017;20:366–74. https://doi.org/10.1080/1343943X.2017.1374869.

[48] Long S, Karp A, Buckeridge M, Davis S, Jaiswal D, Moore P, et al. Feedstocks for Biofuels and Bioenergy. Bioenergy & Sustainability: bridging the gaps, Scientific Committee on Problems of the Environment (SCOPE); 2015.

[49] Müller AA, Viégas I. A cultura do dendezeiro na amazônia brasileira. Embrapa; 2001.

[50] Antonini JC, Oliveira AD. Potencial de cultivo da palma de óleo irrigada nas condições do errado 2021.

[51] Brazilian National Supply Company 2021.

[52] Ocampo Batlle EA, Escobar Palacio JC, Silva Lora EE, Da Costa Bortoni E, Horta Nogueira LA, Carrillo Caballero GE, et al. Energy, economic, and environmental assessment of the integrated production of palm oil biodiesel and sugarcane ethanol. Journal of Cleaner Production 2021;311:127638. https://doi.org/10.1016/j.jclepro.2021.127638.

[53] Hilbert JA, Galbusera S, Jonatan Manosalva. Huella de carbono, Hídrica y Tasa de retorno energética de la Producción de Bioetanol y co-Productos ACABIO Coop. Limitada 2017 2018 2018. https://doi.org/10.13140/RG.2.2.30121.44641.

[54] Brondani M, Hoffmann R, Mayer FD, Kleinert JS. Environmental and energy analysis of biodiesel production in Rio Grande do Sul, Brazil. Clean Techn Environ Policy 2015;17:129–43. https://doi.org/10.1007/s10098-014-0768-x.

[55] Hilbert JA, Galbusera S, Jonatan Manosalva, Carballo S, LeilaSchein, Castro V. Calculo de la reducción de emisiones del biodiesel Argentino 2018. https://doi.org/10.13140/RG.2.2.22550.86080.

[56] Archer SA, Murphy RJ, Steinberger-Wilckens R. Methodological analysis of palm oil biodiesel life cycle studies. Renewable and Sustainable Energy Reviews 2018;94:694–704. https://doi.org/10.1016/j.rser.2018.05.066.

[57] Ong HC, Mahlia TMI, Masjuki HH, Honnery D. Life cycle cost and sensitivity analysis of palm biodiesel production. Fuel 2012;98:131–9. https://doi.org/10.1016/j.fuel.2012.03.031.

[58] Sutton M, Bleeker A, Howard CM, Bekunda M, Grizzetti B, Vries W de, editors. Our nutrient world: the challenge to produce more food and energy with less pollution ; Edinburgh: Centre for Ecology & Hydrology; 2013.

[59] López-Aparacio S, Guerreiro C, Viana M, Reche C, Querol X. Contribution of agriculture to Air Quality problems in cities and in rural areas in Europe 2013:30.

[60] Eugster W, Haeni M. Nutrients or Pollutants? Nitrogen Deposition to European Forests. Developments in Environmental Science, vol. 13, Elsevier; 2013, p. 37–56. https://doi.org/10.1016/B978-0-08-098349-3.00003-7.

[61] Macedo IC, Seabra JEA, Silva JEAR. Green house gases emissions in the production and use of ethanol from sugarcane in Brazil: The 2005/2006 averages and a prediction for 2020. Biomass and Bioenergy 2008;32:582–95. https://doi.org/10.1016/j.biombioe.2007.12.006.

[62] Aida Lorenzo. Personal Communication. Assocíación de Combustibles Renovables 2021.

[63] Baulcombe et al. Reaping the benefits science and the sustainable intensification of global agriculture. London: The Royal Society; 2009.

[64] Cherubin MR, Carvalho JLN, Cerri CEP, Nogueira LAH, Souza GM, Cantarella H. Land Use and Management Effects on Sustainable Sugarcane-Derived Bioenergy. Land 2021;10:72. https://doi.org/10.3390/land10010072.

[65] Brazilian Energy Research Office. https://www.epe.gov.br/pt 2021.

[66] FEPA. Fondo de Estabilización de Precios del Azúcar 2021.

NOMENCLATURE

List of abbreviations	
GHG	Greenhouse gas emissions
LA	Latin America
US	United States
POME	Palm oil mill effluents
PKC	Palm kernel cake
GWP	Global Warming potential
ODPinf	Ozone depletion
ER	Energy ratio
NEB	Net energy balance
LCI	Life cycle inventory
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
IEA	International energy agency
IRENA	International renewable energy agency
TAP	Terrestrial acidification
CPO	Crude palm oil
CPKO	Crude kernel oil
EFB	Empty fruit bunches
EPE	Brazilian energy research office
MAGyP	Ministry of Agriculture, Livestock, and Fisheries of Argentina
AFOLU	Agriculture, forestry, and other land use
CO-ARG	Corn-based ethanol in Argentina
SC-ARG	Sugarcane-based ethanol in Argentina
SB-ARG	Soybean-based biodiesel in Argentina
SC-BRA	Sugarcane-based ethanol in Brazil
SB-BRA	Soybean-based biodiesel in Brazil
SC-COL	Sugarcane-based ethanol in Brazil
PO-COL	Palm-based biodiesel in Brazil
SC-GUA	Sugarcane-based ethanol in Guatemala
CBIO	Decarbonization credit
ProAlcool	Brazilian Alcohol Program

NO_X	Nitrogen oxides
SO_X	Sulfur oxides
	Units
kboed	Kilogram of barrel of oil equivalent
ha	Hectare
%v/v	Volume concentration
MJ	Megajoule
km	kilometer
kg	kilogram
g	gram
ton	tonne
L	liter
US$	American dollar
wt%	Weight percent
d.b.	Dry basis
g CO_2eq	Grams of carbon dioxide equivalent
kg CFC-11 eq	Kilogram of trichloromonofluoromethane equivalent
kg SO_2eq	Kilogram of sulfur dioxide equivalent

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Declaration of interests

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: