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Sustainability assessment of ethanol and biodiesel production in Argentina, Brazil, Colombia, and Guatemala

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ABSTRACT

This study assessed the production, land use, environmental impacts, and energy balance associated with ethanol and biodiesel production in Argentina, Brazil, Colombia, and Guatemala. These countries are considered developing economies and produced 97% of biofuel in Latin America, achieving production of 46 billion liters in 2019. The implementation of public policies (*ie.* RenovaBio, LCFS frameworks) to stimulate the adoption of low-carbon fuels may encourage biofuel production. Hence, the official data for each country were used to quantify the biofuel production and land required for their production. To evaluate the environmental impacts, a cradle-to-gate attributional life cycle assessment (ALCA) was performed. The results revealed that transforming 5% of current pastures into arable land for raw materials could double biofuel production. The findings also showed that increases in raw material productivity could significantly reduce land demand, suggesting that efforts in this direction should be intensified. When ethanol and biodiesel production were compared to gasoline and diesel production, considerable reductions in global warming (up to 84%) and ozone layer depletion were observed; most importantly, the positive energy ratio (ER, 2.5–9.3 MJbioenergy/MJfossil) and net energy ratio (NER, 0.51–0.96 MJnet energy/MJbiofuel) indicated energy sustainability of biofuel production in these countries. In addition, water use and biodiversity impacts were presented based on previous studies. Finally, the impact of public policies such as the RenovaBio program, expected to incentivize farmers, biofuel producers, and policy-makers to improve the biofuel supply chain, were evaluated in the context of these countries.

1. Introduction

Concerns regarding climate change and its environmental impacts have inspired global efforts to reduce the use of fossil fuels. Energy security concerns are also incentives for countries seeking sustainable solutions for energy production [1–3]. Further, increasing energy demands in developing countries to match their economic and social growth have garnered significant attention (*Appendix A*, Figure A1). Thus, bioenergy plays an important role in enabling sustainable development strategies [4]. The COVID-19 pandemic impacted the energy sector, and the global demand decreased by 4% in 2020. However, the International Energy Agency (IEA) predicted a 4.6% increase in energy consumption in 2021 [5]. Almost 70% of the projected global energy demand was expected to occur in emerging markets and developing economies, indicating an increase in greenhouse gas emissions (GHG) in these regions. Thus, the potential of these emerging markets to produce bioenergy to replace fossil fuels in a sustainable way and the environmental impacts related to these activities should be evaluated.

Among all sectors of the energy matrix, the transportation sector is the main fossil fuel consumer, accounting for ~60% of the total oil demand [5]. Some initiatives to decarbonize the transportation industry have been launched [6], and liquid biofuels have emerged as feasible options [7,8]. Global biofuel production increases annually (except in 2020) [9], and the Central and South American continents are responsible for ~27% of the total global biofuel production (Fig. 1). Brazil, the second-largest global ethanol producer [10], accounts for ~90% of the total biofuels in Central and South America. In addition, Brazil has launched a new public policy for biofuels, the RenovaBio program [11], which may be a suitable mechanism for incentivizing improvements in

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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
NER	Net Energy Ratio
LCI	Life Cycle Inventory
ALCA	Attributional 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 Colombia
PO-COL	Palm-based biodiesel in Colombia
***SC*-GUA**	Sugarcane-based ethanol in Guatemala
DDGS	Distiller's dried grains with solubles
CHP	Combined heat and power unit
CBIO	Decarbonization credit
Pro-Álcool	Brazilian Alcohol Program
NO_X	Nitrogen oxides
LCFS	Low Carbon Fuel Standard
SO_X	Sulfur oxides

Units

kboed	Thousands of barrel of oil equivalent a day
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

the sector. This program promotes sustainable bioenergy production to achieve the Paris Agreement on climate change. Other Latin American countries, such as Argentina [12–14], Colombia [15,16], and Guatemala [17], exhibit significant potential for biofuel production. Argentina, Brazil, Colombia, and Guatemala account for 97% of the total biofuels produced in Latin America [9]. Hence, these countries can be considered the main players in incentivizing the increase in biofuel consumption and supporting the transition to low-carbon energy systems.

The transportation sectors in Argentina, Brazil, Colombia, and Guatemala consume approximately 23%, 34%, 26%, and 8% of energy (*Appendix A*, Figure A2), respectively. Petroleum derivatives such as gasoline and diesel dominate the energy matrix of the transportation

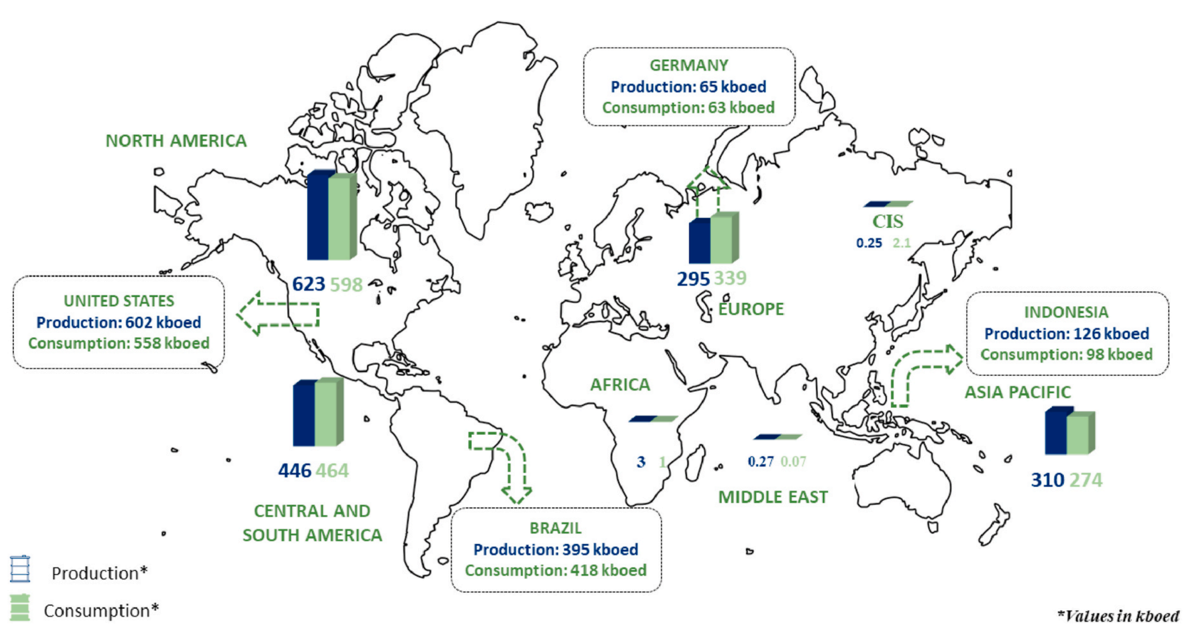

Fig. 1. World consumption and production of liquid biofuels in 2020. Based on [18]. Production and consumption of biofuels in Africa, Asia, Central and South America, CIS, Europe, the Middle East, and North America are shown. The values of production and consumption of the primary producers of each of the regions are highlighted in boxes. (kboed: thousands of barrel oil equivalent per day; CIS: Commonwealth of Independent States).

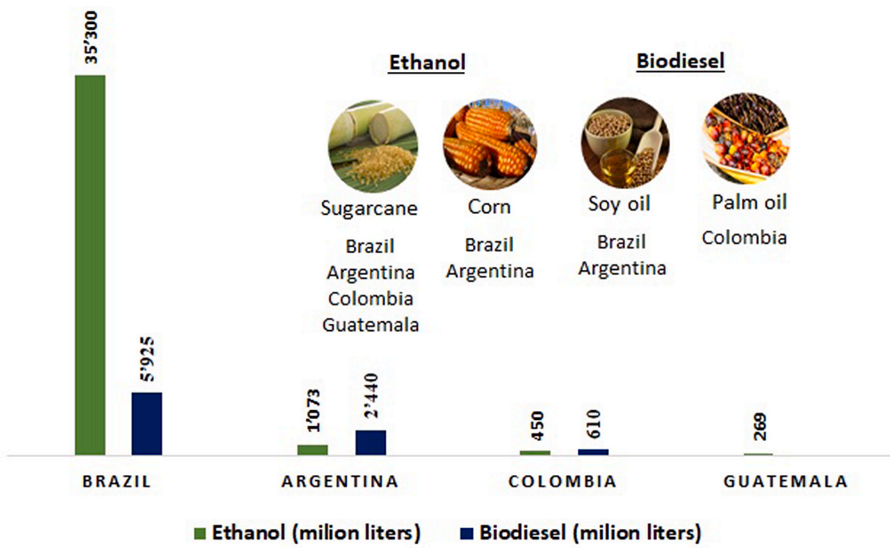

Fig. 2. Biofuels production in 2019. Production of sugarcane ethanol (Brazil, Colombia and Guatemala), corn ethanol (Argentina), soy biodiesel (Argentina and Brazil), and palm biodiesel (Colombia) [39,45].

sector, whereas biofuels have limited contribution, exhibiting values of 9%, 23%, and 7% for Argentina, Brazil, and Colombia, respectively (*Appendix A*, Figure A3). The situation in Guatemala is unique because the government does not use biofuels in the transportation sector. Approximately 80% of Guatemalan ethanol is exported to North America and Europe. In contrast, all gasoline and diesel consumed in

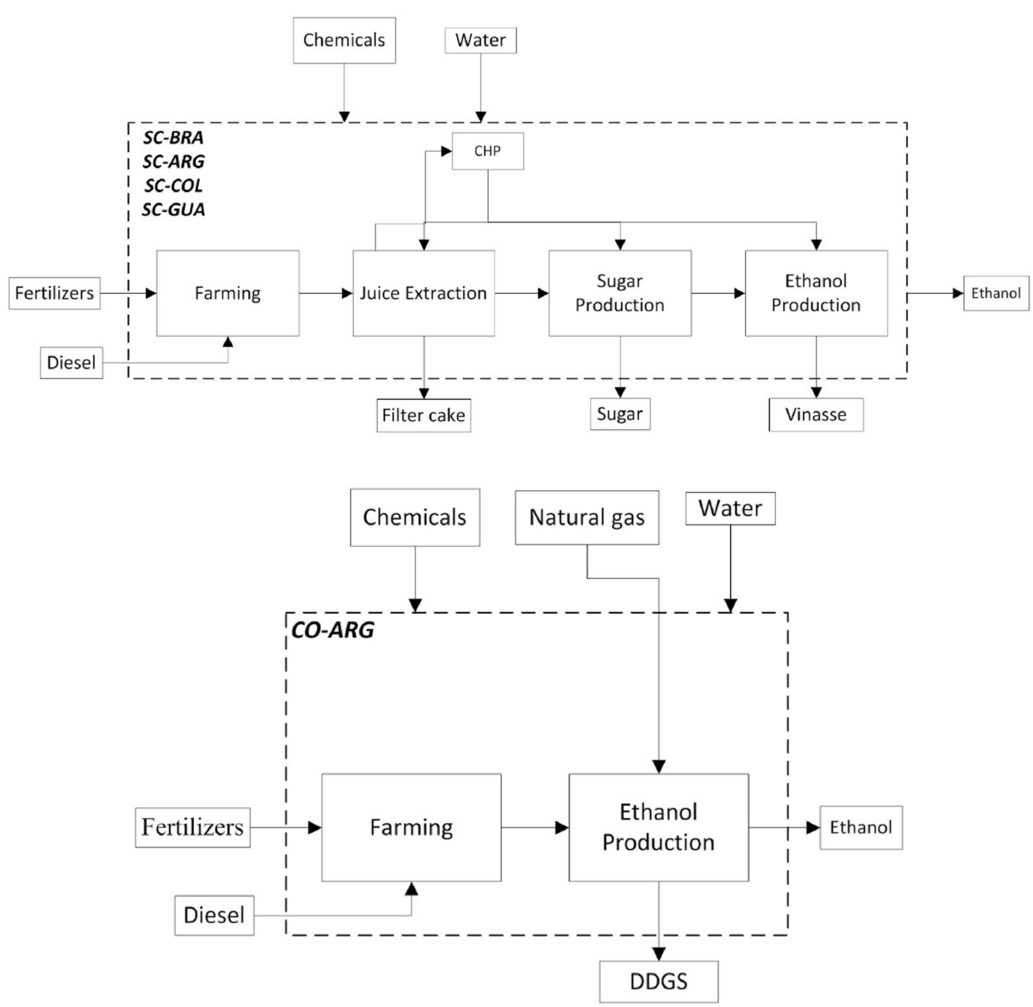

Fig. 3. Systems diagrams for ethanol production from sugarcane and corn.

Guatemala are imported from the United States [19]. Several studies have previously investigated the Guatemalan ethanol paradox and have demonstrated the main barriers to implementing biofuel blending mandates in the country [17,20], which include the high costs of ethanol–gasoline blends relative to gasoline and the lack of political support.

Although biofuels have considerable potential to aid the transition to low-carbon energy systems, large-scale biofuel production has garnered attention because of the many aspects and complexities involved in land use for feedstock cultivation, land-use changes, and agriculture in general [21]. According to the International Renewable Energy Agency (IRENA) [22], biofuel production is expected to account for 25% of total global transportation energy consumption by 2050. Agriculture, forestry, and other land use (AFOLU) is second only to electricity production in terms of GHG emissions. In recent years, these activities have generated ~12 Gt CO_{2eq} net GHG emissions. Moreover, bioenergy is considered a key pillar of decarbonization [23]. Concerns have been raised regarding biofuel sustainability, which has incited debates on food security, water resources, carbon soil, biodiversity, among others.

Notably, regarding food security, transformative agricultural systems that use a circular bioeconomy already exist and produce food and bioenergy, sustainably increasing incomes and improving the access to food [24]. Sugarcane and cattle integration, for instance, has been proposed as a new model that shows techno-economical feasibility with improved climate benefits and avoidance of ILUC [10]. The impact of bioenergy production on food security has been thoroughly investigated, indicating that it is less of a concern in regions where adequate climate, fertile land, and sufficient water are available to expand agricultural activities [25]. These favorable natural conditions are observed in many humid tropical developing countries, where sustainable biofuels can be produced without harming the food supply. This aspect is discussed further for the countries studied [26]. Sustainable biofuels are crucial for the transition to low-carbon energy systems, providing diversification of energy sources and reducing dependence on fossil sources to guarantee the nation's energy security [27] while providing sustainable use of land and food production. Many efforts have been made to address the sustainability of biofuel production processes [1,13–16,28–33] because it is a critical concern for policymakers designing bioenergy-based policies. Life cycle assessment (LCA) methods are important tools for environmental sustainability assessments. These methods focus on assessing environmental impacts based on the entire product life cycle. Impact categories such as global warming, acidification, eutrophication, ozone and water depletion, and particulate matter formation were analyzed [7,28]. Previous studies have demonstrated the advantages of biofuel utilization over fossil fuels [12,28,34–36] and the impact of public policies on the biofuel production chain [29,37]. However, there is a lack of comprehensive outlook on biofuel production in emerging economies.

In the present study, biofuel production in Latin American countries (Argentina, Brazil, Colombia, and Guatemala) was assessed. Basic information on biofuel production in these countries and their effects on land-use change and agricultural indicators has been compiled to counterbalance the advantages and disadvantages of increasing biofuel production. LCA was performed for ethanol and biodiesel production to assess the environmental impacts using the open-source OpenLCA® software. In addition, the environmental impacts of biofuel production were compared to those of gasoline and diesel oil. Lastly, the consequences of enacting a biofuel policy like RenovaBio on revenues and GHG emissions were also analyzed. Conducting this analysis in the early stages of implementing biofuel mandates is essential for defining the strategies with the greatest potential.

2. Outlook of biofuel production in selected Latin American countries

The status analysis is organized into three sections to address the potential for biofuel production in Argentina, Brazil, Colombia, and Guatemala. The first section presents the biofuel production *status quo* in these countries and the necessary raw materials for ethanol and biodiesel production. Existing regulations for biofuel blending were also examined. The second section addresses the impacts of current biofuel production on land demand and the effects of the eventual large-scale expansion of biofuels. Data were obtained from government reports and the Food and Agricultural Organization (FAO) of United Nations [38] (Argentina [39,40], Brazil [41], Colombia [42,43], and Guatemala [44]).

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 process sustainability and strategies to increase the production of liquid biofuels. A detailed description of the methodology adopted to obtain agricultural indicators is provided in *Appendix A*, Section 2. Owing to the pandemic, 2020 was an atypical year. For this reason, data from 2019 were used in this analysis.

2.1. *Status quo of biofuel production*

Fig. 2 shows the total amount of biofuel (ethanol and biodiesel) produced in 2019 and the respective raw materials for each country.

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), whereas 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 [41]. 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 biofuel policies and implemented a compulsory blend of at least 5% of anhydrous ethanol in the gasoline composition since 1931 [46]. Later, in response to the impacts caused by oil shocks during the 1970s, the Brazilian government launched the National Alcohol Program (Proálcool), which aimed to increase the ethanol blending level to 25% in gasoline (E25) and introduce hydrated ethanol (~95% ethanol and 5% water, E100) for use in light vehicles. For over 80 years, Brazilian cars have used blends of ethanol and gasoline; 27% ethanol (E27) is currently being utilized [46,47]. Brazil has at least 363 plants producing anhydrous and hydrated ethanol, corresponding to 129,000 and 243,000 m^3/day, respectively [48].

Brazil is the third-largest biodiesel producer in the world, behind the United States and Indonesia [49]; in 2019, its production was ~6 billion liters distributed in 50 biodiesel plants. Notably, ~45% of the biodiesel production capacity is idle. In 2019, the raw materials used in its manufacture were approximately 68% soybeans, 11% tallow, 2% palm oil, and 19% others (*ie.,* chicken and pork fat, cotton oil, used cooking oil, corn oil, and canola oil). Based on the biodiesel blending mandate (Law 11097/2005), the biodiesel blend with diesel varied from 2% in 2008 to 5% in 2010, and gradually increased to 12% (B12) by 2020.

Ethanol production in Argentina exceeded one billion liters in 2019. Argentinian ethanol is made from sugarcane and corn, approximately 50% of each feedstock, according to the Ministry of Agriculture (MAGyP [39]). Argentina has at least 22 ethanol plants, corresponding to a production capacity of 1.65 billion liters. The sugarcane sector has 12 dehydrators and 16 distilleries, whereas the corn sector has five medium-to large-scale plants and 5–10 small plants that are used intermittently. Argentina produced approximately 2.5 billion liters of biodiesel from soybean oil in 2019. Approximately 48% of the biodiesel was exported exclusively to Europe. Exports to the United States and Peru are hindered by high import taxes. At least 33 biodiesel plants were expected to operate in Argentina in 2021, with a total capacity of 4.43 billion liters. The Argentinian government launched a new public policy for biofuel blending mandates (new Biofuels Law 27,640, July 2021), which replaced Law 26,093 of 2006 and established 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 a minimum of 12% (E12), whereas a minimum of 5% (B5) is allowed for biodiesel [50].

In 2019, the ethanol and biodiesel production in Colombia reached 450 and 610 million liters, respectively [51]. There are seven distilleries and twelve biodiesel plants with production capacities 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, the Colombian government has been implementing policies for biofuels since 2002. Aimed at reducing pollution, contributing to climate change commitments, and incentivizing local production, the government established the highest ever blending mandates for ethanol and biodiesel: 10% (E10) and 12% (B12), respectively. However, owing to the adverse effects caused by the La Niña weather phenomena, the Colombian Ministry of Mines and Energy issued a resolution to decrease the ethanol blending mandate from 10% (E10) to 4% (E4) from April to July of 2021. As reported by the Colombian government, this phenomenon has significantly impacted the national sugarcane production, with consequences in mill operations [51].

In Guatemala, the current sugar industry comprises 12 sugar mills located on the Pacific Ocean coastal plain. In 2017, sugar was Guatemala's second most valuable export, ranking first among agricultural products. In the 2016–2017 season, Guatemala harvested almost 25.8 million tonnes of sugarcane and produced 2719 million tonnes of sugar, reaching a yield of 10.63 tonnes/ha. Guatemala has an installed capacity of 253.6 million liters of ethanol per year (fuel and other uses). All distilleries use molasses as feedstock and export approximately 80% of the total ethanol produced to Europe and the United States [19,52]. Guatemala is identified as a leader in Central America for the production and trade of ethanol; the remaining 20% of ethanol is consumed as alcoholic beverages and hygiene products for internal use. Although Guatemala has favorable conditions for adopting ethanol as a transportation fuel in its energy matrix, the country does not yet have a domestic biofuel market. The Guatemalan case highlighted that the adoption of biofuel mandates is not just a simple relationship between price and demand. It also highlights the importance of political and social factors in supporting the development of the biofuel market. Biofuel public policies and decisions have been influenced by more powerful actors to whom the creation of a biofuel mandate represents an economic threat [17,53].

2.2. Crop yields and feedstock production efficiencies

Table 1 provides agricultural indicators for the primary raw materials used in biofuel production in Argentina, Brazil, Colombia, and Guatemala. There were significant differences in yield, even for the same raw material. Sugarcane productivity in Argentina and Colombia was 55.6 and 120 tonnes/ha, respectively, whereas Brazil and Guatemala exhibited sugarcane yields of 75.4 and 115.7 tonnes/ha, respectively. The main factors affecting yield are the climate and soil [54,55]. Seth quality, soil fertility, precipitation indices, sugarcane variety, solar radiation, and other factors may have caused these discrepancies. As expected, sugary feedstocks are more productive than starchy feedstocks [56], as can 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, reaching a productivity of 7.5 tonnes/ha. Palm is more effective than soy as a raw material for biodiesel production. However, the specific conditions necessary for the development of palm (temperature and humidity) have limited its expansion and exhibit strong issues regarding deforestation associated with its cultivation, particularly in Asia [57]. For example, in Brazil, soy cultivation has spread across several regions. At the same time, palm is produced in the country's north, where the climatic conditions are similar to those in Colombia and are ideal for its cultivation [57].

Several efforts have been made to expand palm cultivation to other Brazilian regions, such as the southeast and midwest regions. These climatic and soil features facilitate the cultivation of this crop as long as the water needs are satisfied by full irrigation [58]. Notably, improving the productivity of the raw material will increase the energy contained in the biomass per hectare, thus yielding higher values of agricultural ratio and, consequently, improving biofuel production. Therefore, efforts to discover higher yielding feedstock genotypes should be intensified, that adapt to climate change and soil limiting conditions such as low fertility.

3. Materials and methods

This section presents all the relevant information on the production of ethanol and biodiesel and the guidelines used for ALCA to understand the impacts associated with biofuel production. The system boundaries for each biofuel production process and the steps to conduct the life cycle impact assessment (LCIA) were described. The concerns related to water use and biodiversity in biofuel production were not assessed in the ALCA, but specialized literature was reviewed and discussed.

3.1. System boundaries

The scenarios assessed were (i) anhydrous ethanol production in Argentina, Colombia, Brazil, and Guatemala and (ii) biodiesel production in Argentina, Brazil, and Colombia. The selected Latin American countries employed a variety of feedstocks for biofuel production, suggesting various biofuel production pathways (Section 2.1). Considering ethanol production from sugarcane, the supply chain production comprises four main stages in the system boundary: *(i) farming, (ii) juice extraction, (iii) sugar production,* and *(iv) ethanol production*. Corn-based ethanol produced in Argentina is divided into two main stages: *(i) farming* and *(ii) ethanol production*. The production of both soybean oil

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

		Argentina			Brazil[e]		Colombia[f]		Guatemala[g]
Indicators	*Units*	*Corn*[c]	*Sugarcane*[d]	*Soybean*[d]	*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[a]	–	27.2	27.0	16.3	28.5	17.4	50.1	24.1	4.3
Biofuel yield[b]	(GJ/ha)	50.7	35.4	20.2	135.7	22.6	46.6	28.9	21.2

[a] The ratio between Biomass Energy and Crop production energy consumption. Based on.
[b] [59].
[c] [40].
[d] [39].
[e] [60].
[f] [42,43].
[g] [44].

(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*. Detailed schemes of these systems for ethanol and biodiesel production are shown in Figs. 3 and 4, respectively. The general characteristics of each system are described below, and more detailed information about each system can be found elsewhere (*sugarcane ethanol* [13,15,61], *corn ethanol* [14,32], *soybean biodiesel* [33,62], and *palm oil biodiesel* [15,61,63]). As indicated in Section 3.1.2, data for each country were obtained through a review of specialized literature.

3.1.1. *Ethanol production*

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, termed dedicated ethanol plants. When both products (sugar and ethanol) are produced, the mill is referred to as an annexed mill; approximately 70% of Brazilian mills are related to this configuration. Conversely, 100% of the ethanol plants in Argentina, Colombia, and Guatemala produce sugar and ethanol. Therefore, this configuration was adopted in the present study. Brazil has 361 sugarcane ethanol plants and eight corn ethanol plants, corresponding to processing capacities of 745 million tonnes of sugarcane and 14 million tonnes of corn grain, respectively [41]. However, the share of corn in the production of Brazilian ethanol is still small, ~6% of the total ethanol produced.

Therefore, corn ethanol production in Brazil was not considered in this study. A different scenario was observed in Argentina: there are six corn ethanol plants and 16 sugarcane ethanol plants operating, corresponding to a production capacity of approximately 950,000 tonnes of ethanol per year [39]. In this case, the share of corn in the production of Argentinian ethanol is ~50%, reinforcing the importance of assessing the process.

The cultivation of sugarcane and corn (*cultivation system*) includes fertilizer application, harvesting, and transport of the raw material to the mill. In this stage, the use of fertilizers, herbicides, fuels, and lime was considered. The transportation distance to the industry was assumed to be 30 km. The differences in fuel consumption are detailed in *Appendix A* (Tables A.4–A.29) for each country. During ethanol production from sugarcane, the cane was first transported on a conveyor belt to the mill. Sugarcane was chopped and cleaned at this stage. The lignocellulosic fraction (bagasse) was separated from the liquid fraction (juice). Sugarcane juice was then transferred to a sugar and alcohol mill and processed into sugar and ethanol. Sugar was obtained by the evaporation, clarification, and crystallization of the sugar contained in the juic. The leftover juice formed a by-product with high concentrations of fermentable sugars (molasses), which were converted to ethanol by fermentation with yeast. These processes are typical for annexed sugar/ethanol mills. Ethanol can be produced from sugarcane juice, molasses, or both. The use of chemicals was also considered in the fermentation step. The information for each country is detailed in *Appendix A*. Sugarcane ethanol plants were considered energetically self-sufficient. This means that the plant was supplied with sufficient energy generated by burning bagasse (electricity and steam) to feed all the systems; in some cases, an electricity surplus was sold to the grid.

There are two main systems of corn-based ethanol production in Argentina. The farming steps are similar to those described for sugarcane, where fertilizers, herbicides, fuels, and other chemicals are employed. Dry milling was used to assess corn-based ethanol production in Argentina. This system comprises four subsystems: grinding, liquefaction and saccharification, fermentation, and distillation. First, the corn grains were washed and finely ground. The mashed corn grain was then converted into fermentable sugars through enzymatic hydrolysis,

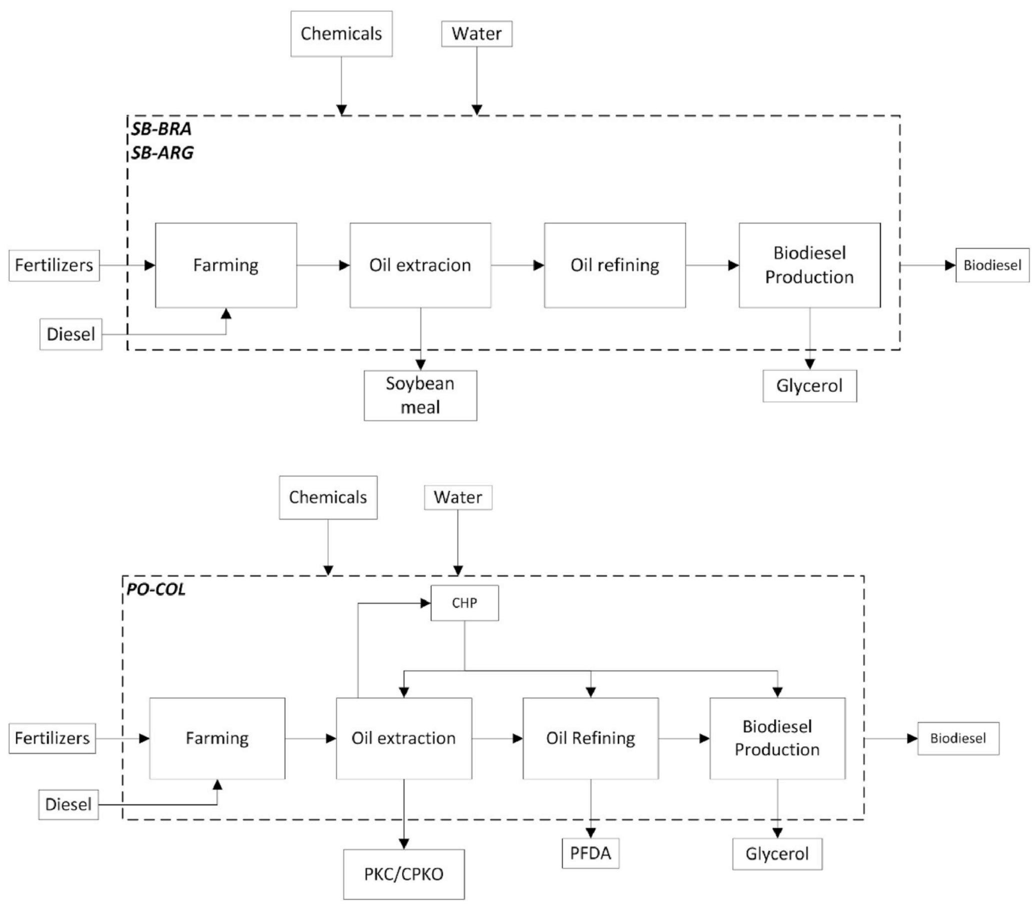

Fig. 4. Systems diagrams for biodiesel production from soybean oil and palm oil.

which breaks the glycosidic bonds from starch macromolecules. Next, output stream from the liquefaction process was combined with a recycled stream referred to as backset (liquid portion of stillage separated by centrifugation later in the process). The backset stream is important in the fermentation step because it provides essential nutrients for yeast. In addition, glucose syrup was fermented into ethanol (9% v/v) and carbon dioxide by yeast action in this step. Finally, the ethanol obtained in the fermentation step was separated by distillation from hydrated ethanol (95 wt%). It was then separated using molecular sieves to obtain anhydrous ethanol (99.8 wt%). A more detailed description of this process can be found elsewhere [14,32]. Unlike plants in Brazil, corn ethanol plants in Argentina and the United States are not energetically self-sufficient. They use fossil fuels such as natural gas during their operations.

3.1.2. 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 comprise four central systems. The farming system involves soybean and palm planting, growing and harvesting activities, and feedstock transportation to the mill. This stage considered the use of fertilizers, herbicides, fuels, chemicals, etc. The transportation distance to the industry was assumed to be 50 km. The differences in fuel consumption are detailed in *Appendix A* (Tables A.4–A.29) for each country.

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

Palm-based biodiesel is energetically self-sufficient, as the solid by-products, fibers and shells, combine heat and power units to produce electricity and heat at the oil extraction stage. Approximately 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) were obtained from 1 tonne of palm. The subsequent stages are similar to those presented for soybean-based biodiesel, and the details can be accessed elsewhere [12,15,61,62]. Differences in the life cycle inventory for each biodiesel pathway can be found in *Appendix A*.

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 [15,32,33,61–63].

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 of 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 modelled using the OpenLCA®v.1.10.3 software (Green Delta, 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 of 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:

$$ER = \frac{\text{Bioenergy}_{\text{output}}}{\text{Fossil energy input}_{\text{input}}} \tag{1}$$

$$NER = \frac{\left(\text{Biofuel energy}_{\text{output}} - \text{Fossil energy input}_{\text{input}}\right)}{\text{Biofuel energy}_{\text{output}}} \tag{2}$$

$\text{Bioenergy}_{\text{output}}$ 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 [28,64]. 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 evaluated. Thus, a Monte Carlo analysis was performed with 10,000 interactions and normal distribution with a 95% confidence interval ($p = 0.05$). The parameters analyzed were based on LCIA results and ranged between 25 and 100% of the LCI values.

3.3. Incentives and policies for biofuels: the RenovaBio case

The impact of public policies on biofuels production in Latin American countries was assessed, if 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. RenovaBio provides a market-based incentive by issuing GHG emissions reduction certificates, named "CBIO" which is sold in the stock market (1 CBIO averaging US$ 10) This new law has been 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) [48].

4. Results and discussion

4.1. Life cycle assessment

4.1.1. Life cycle impact assessment (LCIA) – ReCiPe midpoint

The LCIA for the four countries in which for biofuel production was analyzed was evaluated in all 18 midpoint categories using the ReCiPe

Midpoint H method, as shown in Figure A4 (*Appendix A*, Section 3). The results revealed discrepancies among the midpoint categories evaluated per megajoule of biofuels produced by different countries. The discussion focuses on global warming, terrestrial acidification (TAP), and ozone depletion. For simplicity, all the impact categories are presented as farming and industrial phases.

4.1.2. Global warming potential (GWP)

Global warming potential (GWP) is the most well-known LCIA midpoint. It is generally used as a parameter to measure the impact of human activity on natural resources. Therefore, special attention has been given to this category. The values of the GWP for liquid biofuels (ethanol and biodiesel) were compared with those for fossil fuels (gasoline and diesel) (Figs. 3 and 4). In the case of sugarcane ethanol production (Fig. 5), a comparative analysis of different scenarios demonstrated a considerable reduction in the GWP. Contrasting with the GWP for gasoline, the GWPs of sugarcane ethanol production were 66%, 70%, 74%, and 81% lower in Guatemala, Argentina, Brazil, and Colombia, respectively. Conversely, the production of corn ethanol in Argentina has less impact on climate change, thereby reducing the value of the GWP by only 37% compared to gasoline. This is attributed to of the large amount of natural gas used in the production of corn ethanol because this process does not have a combined heat and energy plant attached for the self-production of steam and bioelectricity. In all cases studied, farming activities contributed to global warming, ranging from 39.1% to 80.9% of GHG emissions. Our study corroborates the results of Gabisa et al. (2019) [28]. These authors conducted an LCA for ethanol production from sugarcane molasses and demonstrated that sugarcane farming significantly contributes to GHG emissions from the ethanol production in Ethiopia. Similarly, the study performed by Carvalho et al. (2021) [37] 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 (Fig. 6) are similar to those observed for ethanol production. Although the LCA was performed for different raw materials, compared to diesel, all the pathways analyzed in this study exhibited reduced emissions. GHG emissions reductions of 84%, 79%, and 68% of biodiesel compared to diesel were observed for Colombia, Argentina, and Brazil, respectively. The considerable reduction in GHG emissions in Colombia is worth noting. Different systems influence GHG emissions differently for each country. Except for Argentina, which demonstrated a significant contribution from the industrial phase (70%), the considerable contribution to Colombian and Brazilian emissions from biofuels originated 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, approximately 5% of the natural gas produced globally is consumed [65]. The replacement of this fuel with biogas could be an alternative to reduce GHG emissions during biofuel production. The GWPs for ethanol and biodiesel production were lower than those for gasoline and diesel, respectively. Our study indicates that there is room for improvement and there are opportunities for development to increase the benefits associated with liquid biofuel production in Argentina, Brazil, Colombia, and Guatemala. For example, a strategy that could potentially improve sustainability metrics and reduce GHG emissions is to adopt an integrated ethanol and biodiesel production system. Battle et al. (2021) [61] confirmed that the integrated production processes of palm oil biodiesel and sugarcane ethanol were energetically and economically efficient. However, the authors also highlighted the need to improve conversion technologies and tax incentives by reducing the use of fossil fuels and achieving higher conversion yields.

4.1.3. Terrestrial acidification (TAP)

For the ethanol production process, TAP was significantly impacted by the Argentinian and Guatemalan cultivation systems and the ethanol production systems in Brazil and Colombia (Table 2). The impact of TAP in Argentina and Guatemala was strongly influenced by the application of fertilizers (70.8% for Argentina) and use of diesel (64.9% for Guatemala) during the cultivation phase. The results of this study correlated with those of 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 TAP. The increased use of nitrogen fertilizers contributed to increasing soil acidity through the release of H^+ ions owing to the oxidative reaction of ammonium compounds, which consequently decreased soil pH [66].

In Brazil and Colombia, TAP was strongly affected by NO_X and SO_X emissions associated with burning biomass in the cogeneration system. According to Eugster and Haeni (2013) [67], emissions generated from biomass burning can increase the impact of TAP in two ways: dry or wet deposition. The first handles fog formation, and consequently, the deposition of SO_X and NO_X. In contrast, wet deposition occurs through the oxidative reaction between sulfur and nitrogen oxides and ozone, resulting in sulfuric acid and nitric acid, respectively. In general, the dissociation of these acids into H^+ ions results in acid precipitation, and consequently, an increase in TAP.

In terms of biodiesel production (Table 3), the farming system was responsible for a significant contribution to the impact category of TAP for the Argentinian and Brazilian scenarios, based on the same fact observed and discussed for the ethanol cases. The palm oil extraction system significantly influenced TAP in the Colombian scenario because of the high NO_X emissions during the burning of palm by-products in the cogeneration system. Compared with fossil fuels, such as gasoline and diesel, a cradle-to-gate LCA demonstrated a lower impact of fossil fuels on the TAP category than ethanol and biodiesel, respectively. However,

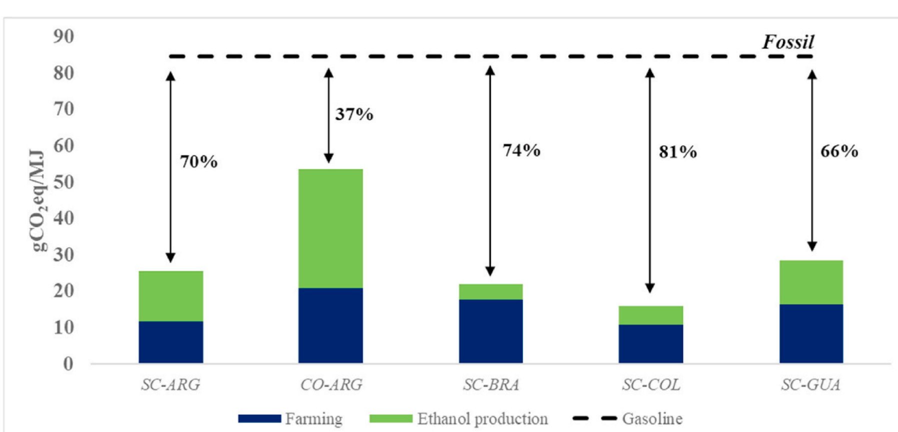

Fig. 5. Climate change impact (GWP 100) on ethanol production compared to gasoline use for the countries investigated in this study (Recipe Midpoint, H).

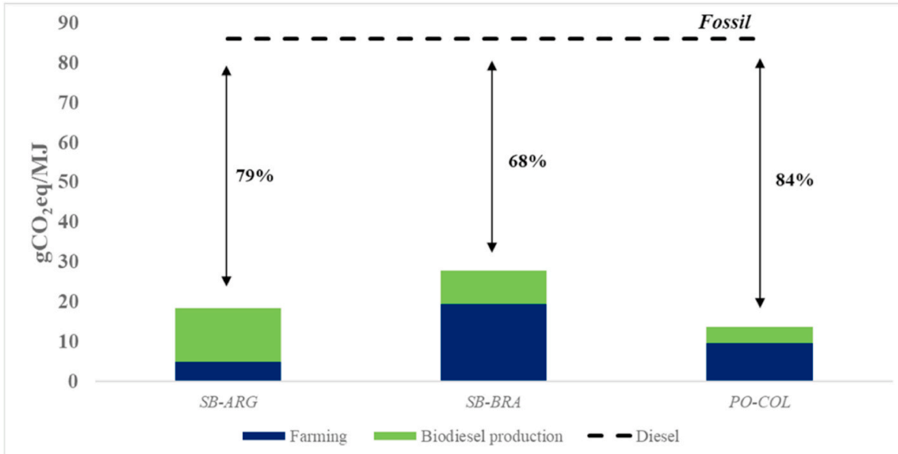

Fig. 6. Climate change impact (GWP 100) for biodiesel production compared with diesel use for the countries investigated in this work (Recipe Midpoint, H).

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[a]	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}

[a] 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[a]	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}

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

both diesel and gasoline contain sulfur in their composition. This inherent characteristic of fossil fuels will probably increase the number of impact categories of TAP 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, Eco-indicator 99, TRACI 2, ReCiPe midpoint (H), and Ecological Scarcity 2006). The results found in this work corroborate those obtained by Cavalett et al. (2013) [7], showing a higher impact of ethanol on the TAP category (5.34×10^{-4} kg SO_2eq) than gasoline (1.99×10^{-4} kg SO_2eq).

4.1.4. Ozone depletion

The results obtained for the impact category of ozone depletion (ODPinf) are listed in Tables 4 and 5. For ethanol production, the evaluated scenarios exhibited ODPinf values ranging from 1.9×10^{-9} to 7.9×10^{-9} kg CFC-11 eq. Except for corn ethanol in Argentina, all sugarcane ethanol production processes significantly contributed to the farming system. The shares of the sugarcane farming system in the ODPinf impact category were 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 these results. The considerable amounts of natural gas and diesel oil used to produce and apply fertilizers were responsible for almost all the impacts reported in the ozone layer depletion category. Gabisa et al. (2019) [28] also reported a significant contribution (~46%) of fertilizer production and use in the ODP impact category. As discussed in Section 4.1.2, the significant amount of natural gas utilized in the ethanol production system accounts for 33.8% of the ODP impact category for corn ethanol in Argentina.

Pieragostini et al. (2014) [14] performed LCA for corn ethanol production in Argentina and demonstrated a substantial contribution of natural gas in the ozone layer categories. According to the authors, the use of natural gas and heat supply accounted for 58% of the impact caused by the ozone layer depletion category. Compared with gasoline, all ethanol production scenarios analyzed in this study performed better in the ODP impact category. The results for the biodiesel production scenarios support the observations previously made for the ethanol scenarios. Table 5 shows that biodiesel production cases have lower ODP values than those of diesel oil.

Table 4
Process contribution of ozone depletion impact category for ethanol production in the different scenarios evaluated (Functional unit = 1 MJ).

Ozone depletion (kg CFC-11eq/MJ)				
Scenarios	Farming	Industrial phase[a]	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}

[a] Represents all the steps dedicated to extracting and converting vegetal oil into biodiesel (LCI on Appendix A, Section 5).

Table 5
Process contribution of ozone depletion impact category for biodiesel production (Functional unit = 1 MJ).

Ozone depletion (kg CFC-11eq/MJ)				
Scenarios	Farming	Industrial phase[a]	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}

[a] Represents all the steps dedicated to extracting and converting vegetal oil into biodiesel (LCI on Appendix A, Section 5).

4.1.5. Life cycle energy indicators

The life cycle energy indicator energy ratio (ER) and net energy balance (NEB) were estimated for all the investigated countries; the results are presented in Fig. 7 (A) and 7 (B) for ethanol and biodiesel production, respectively. The NEB values for the production of all biofuels ranged from 0.51 to 0.96 $MJ_{net\ energy}/MJ_{biofuel}$, whereas the ER values ranged from 2.5 to 9.3 $MJ_{bioenergy}/MJ_{fossil}$. NER values greater than zero indicate that all biofuel production pathways produced more energy than required to produce fuel. This is an essential criterion for the energy sustainability of biofuels in the transportation sector. Among the investigated ethanol production systems, the NER values for Colombia and Guatemala are worth highlighting. In the first case, the NER value was the lowest found in this study (NER = 0.51), whereas the second had a higher NER value (NER = 0.96). Although ethanol was produced from molasses in both cases (Colombia and Guatemala), the differences in product and co-product yields influenced the NER values. According to Chum et al. (2014) [8], the increased co-production of electricity (and other co-products) increased the NER values. Analysis of the LCI data (*Appendix A*, Tables A.4 to A.29) revealed a significant discrepancy between the amounts of bioelectricity, ethanol, and sugar produced in each country. These differences in LCI showed specificity for each country in the production of ethanol, even when a similar pathway was employed (Argentina, Colombia, and Guatemala produced ethanol from molasses). The results obtained for biodiesel production exhibited NER values of 0.24–0.69 $MJ_{net\ energy}/MJ_{biofuel}$; as for ethanol, all NER values were higher than zero. Comparison of the raw materials used for biodiesel in these countries enables understanding of the differences found in this study. When soybean was used for biodiesel production in Argentina and Brazil, there was no co-production of electricity, as soybean meal was used for human consumption or animal feed. As for biodiesel production from palm oil in Colombia, the co-products were intended for the co-production of electricity, contributing to an increase in bioenergy production [8,68].

Regarding the renewable energy per unit of fossil fuel used, the ER energy indicator exhibited significant variability for the countries evaluated in this study, as depicted in Fig. 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 utilizes the energy generated at the plant. The differences in sugarcane systems depend on the yield of ethanol and co-products, and the NEB values discussed above. The ER values obtained for the biodiesel production systems in Argentina and Brazil were higher than those obtained in Colombia. These values justify the co-production of electricity and electricity consumption from the grid or other alternative sources. In Colombia, during palm oil extraction, considerable amounts of electricity produced from the grid and diesel were used per tonne of fresh fruit bunches, contributing to the decrease in ER values. In Argentina and Brazil, a lower amount of electricity from the grid (per tonne of soybean) was used in the biofuel cradle-to-gate lifecycle than in Colombia. All biofuel production systems evaluated positively influenced energy sustainability.

4.1.6. Sensitivity analysis

Among the impact categories assessed, climate change (GWP100) has attracted considerable attention and is generally used to evaluate many environmental impacts. Fig. 8(A) and (B) depict the sensitivity analysis for the GWP category in Brazilian ethanol and biodiesel

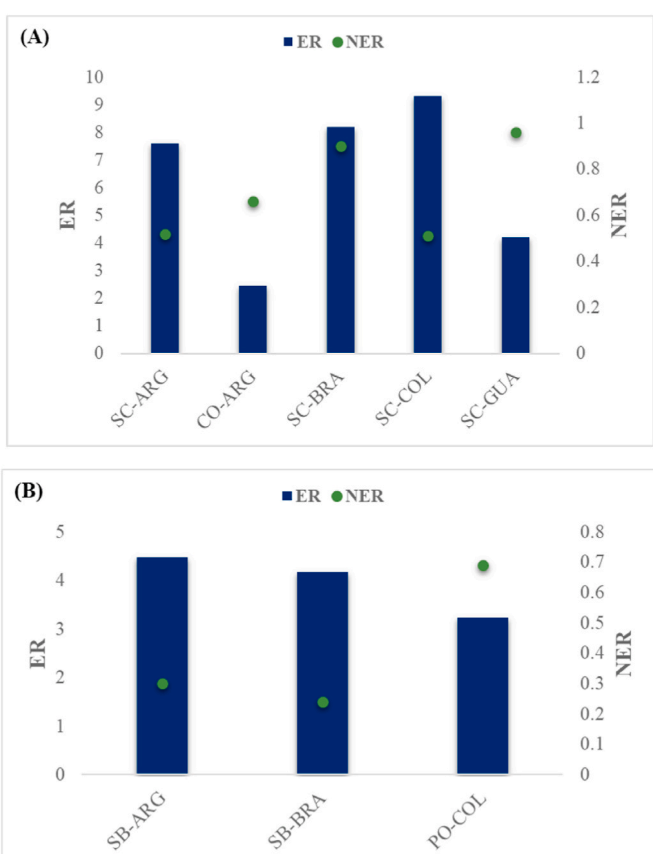

Fig. 7. Energy ratio (ER) and Net energy ratio (NER) for ethanol (A) and biodiesel (B) production in selected countries. CO-ARG* - Values provided by Ref. [32].

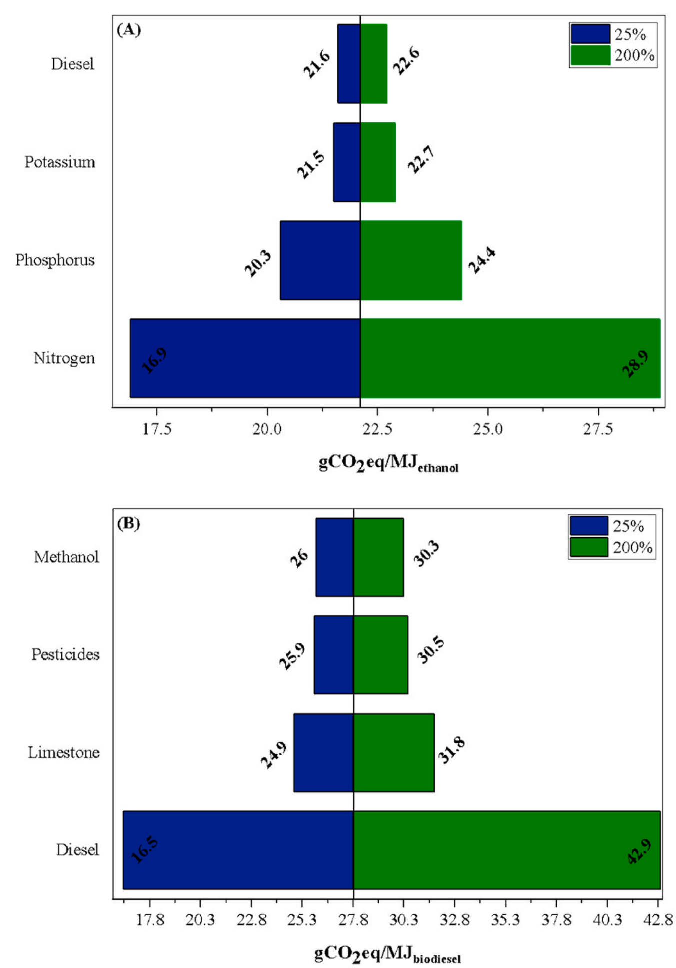

Fig. 8. Sensitivity analysis for global warming potential (GWP100) impact category in Brazilian ethanol (A) and biodiesel (B) productionwhere 25% and 200% are the minimum and maximum values obtained from LCI values.

production. The sensitivity analysis for all other scenarios evaluated in this study can be found in *Appendix A* (Figures A5 (A–C) and A.6 (A–B)).

In the case of Brazilian ethanol production (Fig. 8A), GHG emissions were extremely sensitive to fertilizer application and use. As mentioned in Section 4.1.2, the fertilizer production chain uses natural gas, and its application is also directly linked to diesel oil consumption. Therefore, activities involving fertilizer production and application were responsible for the changes observed in the GWP100 impact category. The biodiesel production scenario in Brazil (Fig. 8B) shows the considerable influence of diesel consumption in the climate change impact category. As shown in Section 2.3, soybean productivity was the lowest compared to the other raw materials used to produce biofuels analyzed in this study. This can explain the outstanding contribution of diesel consumption in the results because a large area is required to produce the raw material. In descending order, the production and use of fertilizers, pesticides, and methanol were the other elementary streams that exhibited sensitivity to the GWP100 impact category. The sensitivity analysis for Argentinian, Colombian, and Guatemalan scenarios followed the same pattern observed for Brazilian scenarios; the results can be found in *Appendix A*.

4.2. Incentives and policies

The GHG emissions obtained from the LCIA were used to demonstrate the impact of 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, such as the Brazilian Renovabio (described in *section3.4)*.

As shown in Table 6, the ethanol production in Argentina, Brazil, and Colombia is extremely environmentally sustainable, exhibiting reductions of 54.2%, 74.7%, and 82.3%, respectively, in total emissions compared with gasoline. Owing to political issues, Guatemala has not adopted blending mandates for biofuels, and policymakers have already discussed this possibility [69]. According to Cutz et al. (2020) [17], Guatemala has an adequate installed capacity to implement E10 (10% ethanol-gasoline blend), and has produced 270 million liters of ethanol in 2019. These authors reinforced the potential of Guatemala to replace gasoline with ethanol. If Guatemala implemented a public policy like RenovaBio, the country would reduce GHG emissions by 6% by blending gasoline and ethanol. Considering biodiesel production, the data presented in Table 7 revealed potential reductions in GHG emissions of 78.6%, 66.8%, and 83.4% when diesel was replaced by biodiesel in Argentina, Brazil, and Colombia, respectively. If 1 tonne of CO_2 was negotiated at US$ 10, the Brazilian biofuel producers would receive US$ 599.1 million per year, whereas the Argentinian, Colombian, and Guatemalan producers would receive annual profits of approximately US$ 58.1, US$ 21.1, and US$ 3.3 million, respectively, based on their respective productions in 2019. The issuing of decarbonization certificates could be an important mechanism for incentivizing practices to reduce GHG emissions.

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

The worldwide pressure for changes that may lead to lower GHG emissions has been reflected in recent years with the increase in biofuel production and use owing to the implementation of blending regulations (as stated in *Section2.1*) and a shift to low-carbon energy systems. Land use changes related to the production of biofuels are a central issue [21] that deserve systematic analysis because they depend on several factors. Data on land demand to produce ethanol and biodiesel in the Latin American countries selected in this study are presented in Tables 8 and 9.

Brazil has the largest biofuel area use compared to the other Latin American countries analyzed in this study, as shown in Table 8. Compared to the 2017/2018 sugarcane harvest season, the sugarcane harvested area in 2019 decreased by 1.1%, 3.2%, and 1.9% in Brazil [60], Colombia [38], and Guatemala [38], respectively. The reduced harvested area in Brazil was caused by the return of leased areas, sugarcane replacement with other crops, fewer new greenfield projects, and the shutdown of existing production units. Conversely, in Argentina [39], the harvested area increased by 6.8% and 4% for corn and sugarcane, respectively, between the 2017/2018 and 2018/2019 seasons. Notably, an increase in harvested area does not always imply an increase in biofuel production because the feedstock used for production may fluctuate depending on global sugar and corn grain prices and crop yields. Soy production in Brazil [60] and Argentina [39] decreased by 2.3% and 0.9%, respectively, compared to the previous 2018/2019 season. In Colombia [42], there was a reduction of 5.3% in palm crop yields between 2017/2018 and 2018/2019.

There have been extensive debates on biofuel production versus food supply in several countries, and several studies have argued that biofuel mandates have a negative impact [70–73]. The main impacts can be summarized as reduced exports of some crops, increased food prices, and conversion of non-agricultural land to agricultural land. However, improved energy access can potentially enhance food production in rural regions [25]. In addition, there is sufficient land worldwide for substantial bioenergy production and increased food demand, considering the impacts on crop production, predictions of yield, and preservation of urban areas, forestry, and protected land [74,75]. Recently, a call for reframing the discourse of food versus fuels towards food and biofuels has been raised by reviewing developments in which bioenergy has contributed to sustainable development with regenerative agricultural practices [24]. There are several examples of best practices that should be followed to increase the advantages of bioenergy in developing regions [76].

The land use data represent an estimate of the amount of land currently used to produce feedstocks for liquid biofuels based on official data and the pasture required to double biofuel production. Pastures generally have low productivity and are underutilized. However, proper fertilization, rotational grazing, and integrated livestock-forestry systems can improve land productivity [76,77]. The data presented in

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[a] (Gg CO_2eq)	Emissions avoided by replacing gasoline with ethanol[b]		Value of CBIOs issued (M US$)[c]
				(%)	Mtonnes (CO_2eq)	
***SC*-ARG CO-ARG**	1.07	910	1989	54.2	1.08	10.8
***SC*-BRA**	35.3	16,544	65,427	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

[a] GHG for gasoline 87.4 gCO_2eq/M.J.
[b] Assuming all countries have a public policy like Renovabio.
[c] 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[a] (Gg CO_2eq)	Emissions avoided by replacing diesel with biodiesel[b]		Value of CBIOs issued (M US$)[c]
				(%)	Mtonnes (CO_2eq)	
SB-ARG	2.4	1284	6013	78.6	4.73	47.3
SB-BRA	5.9	5483	16,508	66.8	11.02	110.2
PO-COL	0.6	283	1706	83.4	1.42	14.2

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

Table 8
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

Based on: (EPE, 2021 [78]; Argentina Biofuels Report (June 2021) [39]; FEPA Colombia 2021 [79]; Cengicaña statistical report [44], 2020; FAO, 2021 [38]).

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

	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)
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

Based on: (EPE, 2021 [78]; Argentine Biofuels Report (June 2021) [39]; Fedepalma Colombia 2021 [42]; FAO, 2021 [38]).

Tables 8 and 9 show that even for countries with a small territorial extension, the use of small portions of pastureland indicates significant potential for biofuel feedstock expansion. In Brazil, the results demonstrated that approximately 3.1% of pastureland is sufficient to duplicate ethanol production. In contrast, 0.15% and 0.2% of pastureland would be necessary to achieve the same goal for Argentina and Colombia, respectively (Fig. 9A). Guatemala is the smallest country that would demand the conversion of 10% of pastures 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 where ~4.5% of the pasture area would be sufficient to double biodiesel production. The use of 3.3% and 0.05% of pastureland would be sufficient to reach the same goal for Brazil and Colombia, respectively. Therefore, using a small portion of pasture can significantly increase the production of biofuels and, consequently, increase the participation of biofuels in blending regulations. These differences are even more remarkable when compared to the total land devoted to agriculture (including crops and livestock). This leads us to believe that if the lands were efficiently managed and best practices used [64], biofuel production would not be a challenge for these countries. Compared to total agricultural land, the share of land for biofuels (ethanol and biodiesel) was approximately 4.7%, 4.5%, 3.2%, and 0.2% for Brazil, Guatemala, Argentina, and Colombia, respectively (Fig. 9B). According to the roadmap performed by IEA (2021) [23], if land-use remains constant until 2050, the share of bioenergy would be 10% lower. The productivity of feedstocks and biofuels is strongly related to land use, and can vary significantly globally, even for similar biofuels.

4.4. Biodiversity and ecosystem services considerations

The effects of biofuel feedstock production on biodiversity and ecosystem services are context specific, and location-specific management of biofuel supply chains should be implemented to maintain biodiversity and ecosystem services [80–82]. Different crops have distinct effects on biodiversity [83]. Regarding the expansion of sugarcane into pastureland in Brazil, studies project the biodiversity impact of increased ethanol demand to be less than the impact of other drivers of land-use change [84]. The conversion of pasturelands to sugarcane fields has the potential to enhance many ecosystem parameters except biodiversity [85]. Therefore, clear and proper legislations and enforcement are required to protect pristine areas and native species.

Biofuels benefits (socio-economic and environmental) can be expected to bring in the future further gains to mitigation efforts by adopting processes that can contribute to the Sustainable Development Goals, that use sustainably sourced wastes, native perennial crops, microalgal production systems produced on low-biodiversity or degraded lands and that do not put additional pressure on ecosystems [86–88].

Water is essential for feedstock (biomass) production and processing.

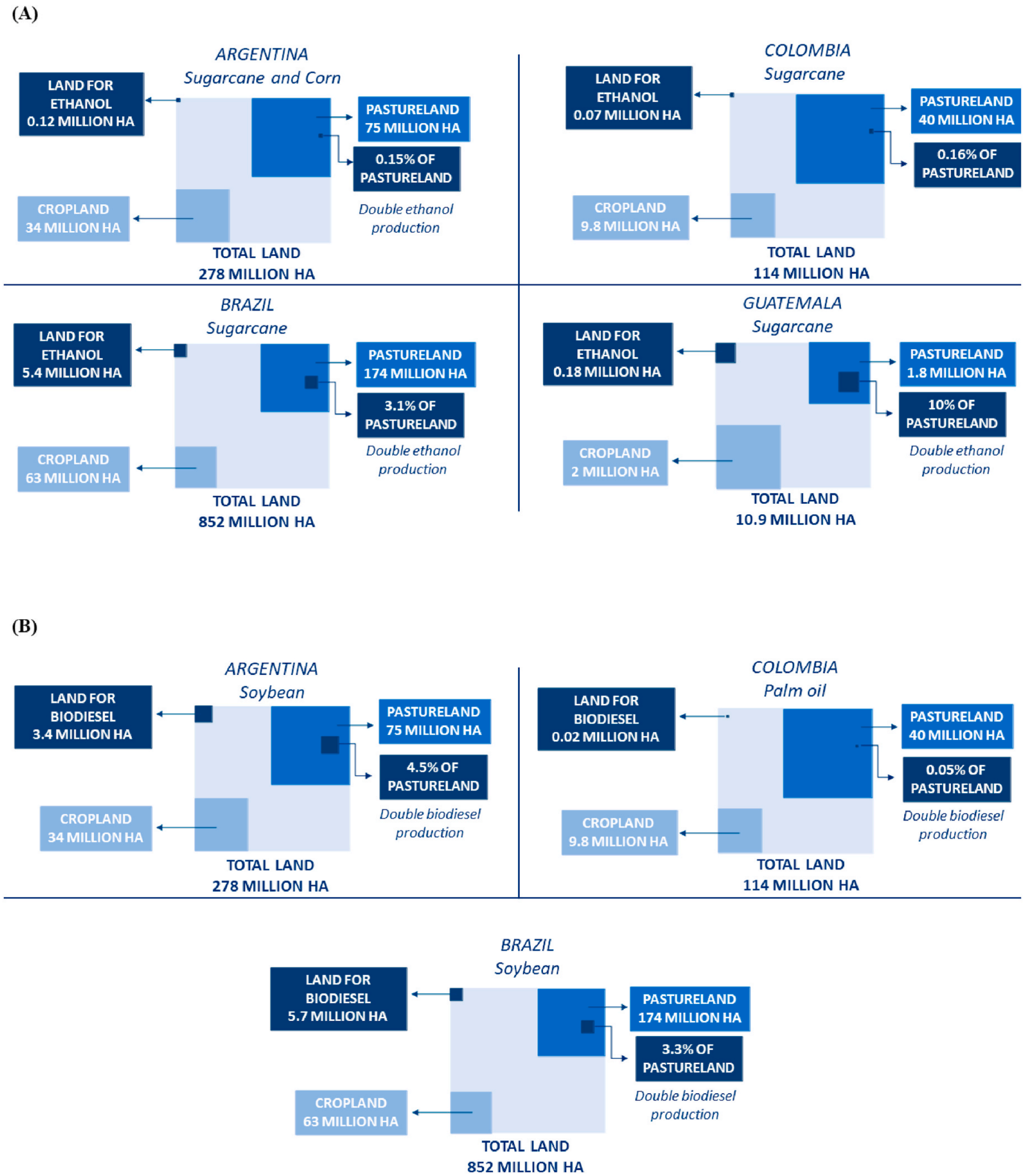

Fig. 9. Current land used for biofuels (ethanol (A) and biodiesel (B)).

Certainly feedstock production requires much more water than processing; however, rainfall can supply the water demand in proper climates, with some complementation in the growing stage. Even so, irrigation can be adopted when rainfall is deficient or aiming for higher yields. The amount of irrigation needed is the difference between the crop water requirement (evapotranspiration) and the effective precipitation, plus additional water to compensate for losses and non-uniformity of water application. The high-water demand, in this case, imposes careful water resources management. Although 500–900 million hectares have been estimated to exist for rainfed cultivation of energy crops [74], climate change is affecting agricultural systems (IPCC Special Report on Climate Change and Land; https://www.ipcc.ch/srccl/). Best management practices and breeding of crops for high water use efficiency are recommended [56]. Best Management Practices (BMPs) constitute a multifaceted system of recommended actions. In bioenergy production, these can relate to resource stewardship, biomass cultivation and harvest, and waste disposal in agreement with State and National environmental regulations and goals, land management objectives, certification for markets, commitment to sustainability goals, integration of ecosystem services into resource management, cultural and religious legacy, conservation heritage, and a basic desire to emulate successful examples of good natural resources management [89]. Lessons have been learned over the years in BMPs regarding water that radically decreased the water consumption and water captured from ecosystems and recycling of plant water. Legislation and monitoring must be in place to decrease negative impacts, such as in the control of the quality of superficial and underground water (contamination by pesticides), the controlling of the fauna (maintenance of preservation areas and buffer zones), atmospheric pollutant emissions, and agricultural soil preservation and quality [90]. Some solutions applied to reduce industrial water include replacing the washing system of sugarcane with a dry washing system, optimizing the evaporation stage, tapping the steam and taking advantage of condensation to produce water, technologies that use membranes in distillation and dehydration processes, the concentration of vinasse integrated into the distillation process. On the agricultural side, maintaining straw over the soil as in no-till systems or green cane can preserve soil moisture. Brazil's average water consumption (use and reuse) in biorefineries was around 22 m^3 of water/tonne of cane [91] in 2010. At the current technological stage of water reuse water capture is near 1 m^3 of water/tonne of cane, a fivefold decrease in three decades (5–0.91 m^3/tonne of cane) [91]. The industrial stage of ethanol production in Colombia has a demand of 8 m^3 of water/tonne of cane [92], while corn-based ethanol in Argentina consumes around 11.2 m^3 of water/-tonne of corn [32]. For biodiesel, its industrial stage production from palm oil in Colombia has consumed on average 4 m^3 of water/tonne of FFB [92] and a similar number is observed for soybean-based biodiesel (3 m^3 of water/tonne of soybean) [86]. Countries such as Argentina, Colombia, and Brazil generally present enough rainfall precipitation , avoiding the use of irrigation systems for bioenergy crop production [32, 93,94].

5. Conclusions and recommendations

The expansion of liquid biofuel production in Argentina, Brazil, Colombia, and Guatemala has proved feasible and could support the transition to a low-carbon energy system in the transportation sector. Biofuels produced in these countries significantly reduce emissions, are energetically favorable, and have the potential to benefit producers through low-carbon biofuel certification schemes and carbon credit negotiations. Constraints on land demand are of little significance, as demonstrated by comparisons of the pastureland available in these countries, which can partially be converted to biofuel feedstock with the potential to double biofuel production. Even when a similar process is adopted to obtain biofuels, significant differences in the productivity of biofuels and the yield of raw materials were observed for the selected countries. Therefore, the need to encourage investments in breeding, biotechnology, soil nutrition, and conversion technologies must be emphasized because such actions can help improve the general performance of biofuel production in the region. Although fossil fuels perform better in TAP, biofuels can drastically reduce the impacts related to GHG emissions and ozone layer depletion. Except for corn ethanol in Argentina, agricultural activities exhibited the largest share of GHG emissions and ozone layer depletion for ethanol production, primarily due to the production and use of fertilizers. The opposite was verified for biodiesel production in Argentina and Colombia, which appears to be drastically impacted by industrial activities, mainly due to the use of natural gas in some processes. Sensitivity analysis confirmed the significant relationship between GHG emissions and the use 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. Although the impacts related to water use and biodiversity categories were not considered in the LCA analysis, a brief description of the main features was presented that are relevant to public policies. The adoption of public policies for biofuels, that do not lead to deforestation, and which generate decarbonization certificates, is an excellent alternative to encourage the reduction of GHG emissions. The market of CBIOs can encourage farmers and biofuel producers to adopt best management practices to reduce GHG emissions throughout the biofuel production chain.

Credit author statement

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Declaration of competing interest

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.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

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