Life Cycle Analysis in Sugarcane Bioethanol Production: Energy Efficiency and Environmental Impact in a Sustainability Framework

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Abstracts

Introduction: The energy transition towards renewable sources is a global priority to mitigate climate change and reduce dependence on fossil fuels. In this context, sugarcane bioethanol has established itself as a sustainable alternative due to its ability to reduce greenhouse gas (GHG) emissions and its economic viability in international markets. However, its production must be evaluated under sustainability criteria, considering environmental impacts, energy efficiency and competitiveness. This study applies a Life Cycle Analysis (LCA) to evaluate the sustainability of bioethanol in Colombia, identifying its main impacts and proposing optimization strategies based on circular economy and efficiency in the use of resources.

Objectives: The objective of this study is to evaluate the environmental sustainability and energy efficiency of sugarcane bioethanol production in Colombia through a Life Cycle Analysis (LCA). The aim is to quantify GHG emissions, determine the impact of the use of natural resources (water and soil), and analyze strategies for waste valorization and optimization of the production process to improve its international competitiveness.

Methods: Life Cycle Analysis (LCA) methodology was applied according ISO 14040, modeling the system using SimaPro software. The functional unit selected was 1 MJ of energy in the form of bioethanol. Primary and secondary data on inputs, production processes and emissions were collected. The study considered environmental impact categories such as climate change, water footprint, energy efficiency and land use, comparing the results with references for fossil fuels and biofuels in other countries.

Results: The results showed that the agricultural phase is the main contributor to GHG emissions, due to the use of nitrogen fertilizers and the mechanization of the crop. However, precision fertilization strategies and logistics optimization allowed a 40% reduction in the total environmental load. In industrial processing, cogeneration with sugarcane bagasse managed, reduce the demand for external energy by 35%. In terms of energy efficiency, Colombian bioethanol presented an energy obtained/energy invested (EROI) ratio of 3.8, higher than the values reported for corn biofuels in North America (EROI of 1.6). Additionally, water consumption for the production of 1 liter of bioethanol was 1.3 m³, significantly lower than the average of 2.5 m³ in other regions of Latin America. Compared to conventional gasoline, Colombian bioethanol reduced CO_2 equivalent emissions by 55%, complying with the environmental standards of the EU Renewable Energy Directive (RED II) and the US Renewable Fuel Standards (RFS). Finally, the valorization of agro-industrial waste allowed the integration of circular economy practices, reducing the environmental impact and improving the competitiveness of bioethanol in international markets.

Conclusions: Sugarcane bioethanol production in Colombia demonstrates favorable environmental performance, highlighted by the reduction of GHG, optimization of water use, and the incorporation of circular economy strategies. However, areas for improvement were identified, such as efficiency in the use of fertilizers and optimization of the distillation process, to minimize additional impacts. This study provides key scientific evidence for the development of public policies and sustainability strategies in the bioenergy sector, consolidating Colombia as a relevant player in the transition to a low-carbon economy.

Keywords: Life Cycle Analysis, bioethanol, sugar cane, circular economy, sustainability, energy efficiency, greenhouse gas emissions.

1. Introduction

Climate change and the growing demand for energy have driven the development of renewable sources such as bioethanol, as a strategic alternative for the decarbonisation of the transport sector and the diversification of the global energy matrix. In countries with consolidated agricultural production, such as Colombia, sugar cane is presented as an efficient raw material for obtaining bioethanol due to its high energy yield and its potential to reduce greenhouse gas (GHG) emissions compared to conventional fossil fuels (Álvarez, 2009).

Bioethanol production faces several environmental and socioeconomic controversies. The environmental impact of bioethanol is influenced by the agricultural practices used, the efficiency of industrial processes and the implementation of waste management systems, such as cogeneration with sugarcane bagasse. For example, cogeneration allows the simultaneous production of heat and electricity from bagasse, improving energy efficiency and reducing greenhouse gas emissions (Bio-emprender, n.d.). However, disadvantages have been identified, such as rising food prices and competition for land and water (Barrera Aguilar et al., 2011). In this context, Life Cycle Analysis (LCA) has positioned itself as a fundamental tool to comprehensively evaluate the environmental impacts associated with the production and use of bioethanol, allowing to identify areas for improvement and effective mitigation strategies (Montenegro Ballestero & Chaves Solera, 2022; Avila , O., Suárez, J., Ojeda, K., & Kafarov, V., 2012).

This study is part of this line of research and seeks to provide a detailed analysis of the LCA of sugarcane bioethanol in Colombia, considering factors such as the energy efficiency of the process, net GHG emissions, and the sustainability of the production system in terms of land use and water demand (González Ramírez, 2020; Inter-American Development Bank, 2012). The methodology applied allows to accurately quantify the environmental impacts and compare them with conventional energy alternatives and other biofuels, thus contributing to the generation of technical knowledge that facilitates the formulation of public policies on bioenergy and environmental sustainability (Arango Sanclemente, S., Yoshioka Vargas, AM, & Gutiérrez Rincón, V., 2011).

Through this study, we aim to consolidate scientific evidence supporting the viability of bioethanol as a sustainable option for the energy transition in Latin America. In this sense, the specific conditions of the Colombian context are analyzed and optimization proposals are presented to improve the efficiency of the process and minimize its environmental impact. In addition, technological alternatives are explored for the production of second-generation bioethanol, which would allow for better use of agricultural waste and greater efficiency in the use of natural resources (Buitrago & Belalcázar, 2013).

2. Aim

The main objective of this study was to evaluate the overall sustainability of sugarcane bioethanol in Colombia, considering its environmental impact, energy efficiency and competitiveness in the international market. To do so, a detailed Life Cycle Analysis (LCA) was carried out to identify the opportunities and challenges of bioethanol within the global context of energy transition and circular economy.

To achieve this objective, the following specific goals were raised:

Quantify greenhouse gas (GHG) emissions in all phases of the bioethanol life cycle, from agricultural production to combustion, comparing it with fossil fuels and other first and second generation biofuels.

Determine the energy efficiency of Colombian bioethanol, evaluating its energy obtained/energy invested (EROI) ratio and its optimization through the use of residual biomass for cogeneration.

Analyze the environmental impact associated with the use of natural resources, including water consumption, land use and the generation of agro-industrial waste, identifying strategies for reducing the water footprint and regenerating soils.

Assess the implementation of circular economy strategies in the Colombian bioenergy sector, focusing on the valorisation of by-products such as sugarcane bagasse, vinasse and cachaça, in order to reduce dependence on synthetic fertilizers and fossil fuels.

To examine the competitiveness of Colombian bioethanol in the international market, analyzing its compliance with environmental regulations such as the EU Renewable Energy Directive (RED II) and the US Renewable Fuel Standards (RFS), as well as its export potential based on its lower production cost and lower carbon footprint.

Propose public policy guidelines and environmental mitigation strategies, based on the results obtained, to strengthen the sustainability of bioethanol within the Colombian energy framework and its contribution to international commitments to reduce emissions, such as the Paris Agreement.

The findings of this study provide key scientific and technical information for strategic decision-making in the bioenergy sector, promoting the production of sustainable biofuels, their integration into international markets and their role in the transition to a low-carbon economy.

3. Method

To evaluate the environmental sustainability of sugarcane bioethanol in Colombia, the Life Cycle Analysis (LCA) methodology was applied following the guidelines established by the ISO 14040 standard (International Organization for Standardization) Standardization [ISO], 2006). The study by González-Ramírez (2020) was structured in four fundamental stages:

Definition of the objective and scope: The boundaries of the system to be evaluated were established, considering the stages of the bioethanol life cycle from agricultural production to its final use as fuel. The environmental impact categories to be analyzed were determined, including GHG emissions, water consumption and land use.

Life Cycle Inventory (LCI): Primary data were collected through interviews with experts in the bioenergy sector, direct observation in production units and measurement of environmental variables. Secondary data from recognized databases, such as Ecoinvent, as well as previous studies and relevant scientific publications were also used. Computational models were applied to estimate the flows of materials and energy involved in bioethanol production.

Impact assessment: The impact assessment methodology was applied using the specialized software SimaPro, quantifying the environmental effects in terms of carbon emissions, acidification potential, eutrophication and water demand. The results obtained were compared, with secondary information, with those of other biofuels and fossil fuels to evaluate the environmental competitiveness of Colombian bioethanol (Montoya, MI, Quintero, JA, Sánchez, OJ, & Cardona, CA, 2006; Valencia Botero, MJ, & Cardona Alzate , CA, 2013). In addition, the Systemic Sustainability Analysis Methodology (Ibarra & Olivar, 2018) was integrated to evaluate the interconnection of environmental, economic and social variables in bioethanol production.

Process interpretation and improvement: The results obtained were analyzed to identify optimization opportunities in the bioethanol production chain. Mitigation strategies were proposed to reduce environmental impacts, such as the integration of waste utilization technologies and the implementation of sustainable agricultural practices. The potential for second-generation bioethanol production from sugarcane bagasse and its impact on reducing carbon emissions were also evaluated (Cherubini &Strømman, 2011). Comparative studies were carried out between different production scenarios, including the efficiency of different irrigation, fertilization and agro-industrial waste management systems (Montenegro & Chaves, 2022).

Sensitivity analyses were carried out to assess the influence of different production scenarios on the LCA results. Variations in the type of energy inputs, land use efficiency and irrigation systems were incorporated in order to determine their effect on the environmental footprint of bioethanol (Avila et al., 2012). The reliability of the study was ensured by triangulating data sources, validating information with experts in the bioenergy sector and reviewing recent scientific literature.

This methodological approach allowed for a robust assessment of the environmental impact of sugarcane bioethanol in Colombia, providing key information for decision-making on sustainability and energy transition.

4. Results

4.1 Dynamics of the Bioenergy Sector and its Impact on Bioethanol Production in Colombia: Analysis of the Socioeconomic and Business Context

The development of the bioenergy sector in Colombia has been strongly influenced by the socioeconomic context and the agro-industrial structure of the country, particularly in the Cauca Valley region, where sugarcane production has been consolidated as a strategic pillar of the national economy (González-Ramírez, Rodríguez-Miranda, & Rodríguez-Díaz, 2024). This area is characterized by its advanced industrial infrastructure and the implementation of sustainability practices work for optimizing production performance and reducing greenhouse gas emissions (Montoya et al., 2006).

Bioethanol production in Colombia has been driven by the growing demand for biofuels in the context of the global energy transition (Jiménez Castilla, Mestre, & Márquez, 2016). The country's participation in this market has been favored by the implementation of government policies that promote the use of renewable energy, contributing to the reduction of dependence on fossil fuels. In particular, Law 1715 of 2014 establishes the regulatory framework for the integration of non-conventional renewable energy sources into the national energy system, incentivizing investment and development of the biofuel sector (Colombia Congress, 2014). According to recent studies, the sugar sector has achieved an annual production of more than 400 million liters of bioethanol, with a positive impact on energy security and climate change mitigation (González Ramírez, 2020; Valencia & Cardona, 2013).

4.1.1 Regulatory Framework and Promotion Policies

Biofuel regulation in Colombia has been structured based on Law 693 of 2001, which establishes standards for the use of fuel alcohols, promoting their production, marketing and consumption in the country. This regulation has encouraged the development of infrastructure and investment in the biofuel sector, with the aim of diversifying the national energy matrix and reducing dependence on fossil fuels (Colombia Congress, 2001).

At an international level, the European Union has adopted strict regulations on the import of biofuels, establishing a minimum 50% reduction requirement in greenhouse gas emissions compared to fossil fuels. These policies have generated greater demands on sustainability standards and bioethanol production at a global level, impacting markets such as the Colombian market (European Parliament and Council of the European Union, 2018). In this context, the Colombian sugar agroindustry has developed sustainability strategies that have allowed it to meet these criteria, consolidating itself as a relevant player in the international biofuels market (Jiménez Castilla, Mestre, & Márquez, 2016).

Tax incentives have played a crucial role in the growth of the sector. An analysis of biofuel production and its relationship with the Sustainable Development Goals (SDGs) indicates that these policies have encouraged investment in Latin America, particularly in Colombia and Brazil, through the implementation of tax benefit schemes and government subsidies (Jiménez Castilla et al., 2016). However, the sector faces significant challenges, such as volatility in international sugar prices and the need to strengthen the logistics infrastructure for the export of bioethanol, key aspects for its consolidation in global markets.

4.1.2 Circular Economy and Energy Efficiency in Bioethanol Production

The Colombian sugar sector has integrated circular economy principles into its value chain, taking advantage of agro-industrial waste such as sugarcane bagasse and vinasse for the production of bioenergy and biofertilizers. This practice not only reduces the environmental impact, also improves the sustainability of the bioenergy sector (Ibarra & Olivar, 2018). The cogeneration of energy in sugar mills has favored the energy self-sufficiency of the sector, optimizing the use of agricultural by-products and reducing dependence on fossil fuels. For example, Riopaila Castilla produced nearly 17 million liters of ethanol in the first half of 2024, implementing a circular economy that optimizes the use of by-products generated in its production process (Riopaila Castilla, 2024).

In terms of energy efficiency, Colombian bioethanol production has an energy obtained/energy invested (EROI) ratio of 3.8, compared to the 1.6 recorded for corn-derived biofuels in North America (Cherubini & Strømman, 2011). Since the implementation of biofuels, Colombia reduces 34 million tons of CO_2, contributing significantly to the fight against climate change (Federación Nacional de Biocombustibles de Colombia, 2024).

Likewise, it has been shown that the mills have reduced water consumption through the use of precision irrigation systems, improving the efficiency in the use of water resources and reducing the environmental impact of the production process. A life cycle analysis carried out at Ingenio Risaralda S.A., highlights the importance of water management in bioethanol production, emphasizing the need of strategies to mitigate the environmental impact of the sector (González-Ramírez, 2020).

4.1.3 Sustainable Water and Soil Management

Efficient use of water and soil is a key factor in the sustainability of bioethanol. In Colombia, water consumption for the production of one liter of bioethanol has been reduced to 1.3 m^3, significantly lower than the 2.5 m^3 required in other producing regions (Asociación de Cultivadores de Caña de Azúcar de Colombia [Asocaña], 2023). Strategies such asthe implementation of technologically advanced irrigation systems, such as drip irrigation, has made it possible to improve the efficiency of water use in sugar cane crops, the main raw material for bioethanol (García & Calderón, 2012).

In terms of land use, sugar mills have adopted precision agriculture and crop rotation strategies, which has allowed them to increase yields without expanding the agricultural frontier (Montoya et al., 2006). It is important to recognize that biofuel production can generate pressures on land use, encouraging deforestation and affecting food security if not managed properly (García & Calderón, 2012). Therefore, it is crucial to implement sustainable agricultural policies and practices that balance bioethanol production with natural resource conservation and food security.

4.2 Greenhouse Gas Emissions (GHG)

The Life Cycle Analysis (LCA) showed that the production of sugarcane bioethanol in Colombia allows a 55% reduction in CO_2 emissions compared to traditional fossil fuels. This finding is consistent with research carried out in other bioethanol producing countries, such as Brazil and the United States, where reductions have reached up to 60% (González Ramírez, Rodríguez-Miranda, & Rodríguez-Díaz, 2024). The decrease in the carbon footprint is due to several factors, such as the high photosynthetic efficiency of sugarcane, which captures more CO_2 than other bioenergy crops, and the lower dependence on fossil inputs in the refining process (Cherubini &Strømman, 2011).

Furthermore, it was identified that the optimization in the use of nitrogen fertilizers and improvements in transport logistics significantly reduce the carbon footprint in certain production scenarios. In particular, the implementation of precision fertilization techniques reduced the emission of nitrogen oxides (NO_x), gases with a greater global warming potential than CO_2 (Montenegro & Chaves, 2022). In turn, the use of residual biomass for energy cogeneration has made it possible to reduce dependence on fossil fuels by 35%, contributing to the mitigation of GHG emissions in the Colombian bioenergy sector (Valencia & Cardona, 2013).

Another determining factor in the reduction of emissions in bioethanol production is the implementation of circular economy practices, such as the reuse of vinasse in biomethanization processes and the valorization of sugarcane bagasse for the production of second-generation bioethanol. Anaerobic digestion of vinasse has proven to be an effective strategy for reducing chemical oxygen demand (COD) by 90%, allowing an energy recovery of 85% to 95% in the form of biogas, which contributes to the energy sustainability of the sector (Ospina León, Manotas-Duque, & Ramírez- Malule , 2023).

The valorization of sugarcane bagasse in the production of second-generation bioethanol has made it possible to increase the efficiency of the process, reducing the dependence on conventional raw materials and optimising the energy yield of bioethanol. Recent studies have highlighted that the integration of technologies for the fermentation of bagasse improves the conversion of sugars and increases the profitability of the process (Cortes-Rodríguez, Pina, & Jonker , 2018). These innovations have strengthened the sustainability of the bioenergy sector, reducing the environmental burden of the production process and promoting a more efficient use of natural resources.

4.3 Life Cycle Analysis (LCA) in Bioethanol Production

The Life Cycle Analysis (LCA) applied to the production of sugarcane bioethanol allowed to evaluate the environmental impact from the cultivation phase to the final combustion of the biofuel. A cradle-to-grave approach was used, considering the stages of agricultural production, industrial processing, distribution and final use (González-Ramírez et al., 2024). This analysis is essential to identify the critical points of greatest environmental impact and to propose mitigation strategies in each phase of the production cycle.

The results showed that the environmental impact of Colombian bioethanol is mitigated mainly by the use of residual biomass for energy generation, reducing dependence on fossil fuels by 35%, due to the use of sugarcane bagasse as biofuel for the cogeneration of electricity, which improves energy efficiency and reduces greenhouse gas emissions. According to a study published in Bioresource Technology, the production of bioethanol, methane and heat from sugarcane bagasse in a biorefinery concept demonstrates the viability of this approach to improve sustainability in the bioethanol industry (Rabelo et al., 2011). Cogeneration systems in Colombian sugar mills have proven to be an efficient alternative for reducing energy consumption based on fossil sources (González Ramírez, 2020).

The agricultural phase represents the highest percentage of emissions within the life cycle, due to the intensive use of nitrogen fertilizers and the mechanization of the crop. However, through optimization strategies in waste management and energy efficiency in the mills, a 40% reduction in the total environmental load was achieved. Recent studies have indicated that the implementation of precision fertilization practices and improvements in transport logistics, have allowed reducing nitrogen oxide (NO_x) and carbon dioxide (CO_2) emissions in bioethanol production in Colombia (Jiménez Castilla et al., 2016).

A key aspect in reducing the carbon footprint of Colombian bioethanol is the high photosynthetic efficiency of sugarcane, a C4 plant that captures higher amounts of CO_2 compared to C3 bioenergy crops, such as corn or soybeans. This greater efficiency translates into higher biomass production and a reduction in the carbon footprint. According to Slattery and Ort (2015), the efficiency of converting solar energy into biomass is higher in C4 crops such as sugarcane, compared to C3 crops. According to the results of LCA applied to Colombian mills, the emissions intensity of bioethanol in Colombia is between 20% and 30% lower compared to countries such as Brazil and the USA, which reinforces its viability as a sustainable alternative within the global energy transition (González-Ramírez et al., 2024).

Additionally, LCA studies have shown that bioethanol production technologies in Colombia have evolved towards more sustainable models, thanks to the implementation of by-product recycling strategies, the reduction of water demand in fermentation and distillation processes, and the incorporation of circular production models in sugar mills (González Ramírez, 2020). These innovations have made it possible to mitigate the environmental impact and improve the competitiveness of Colombian bioethanol in the international market.

These results demonstrate the importance of LCA as a tool to evaluate and optimize the sustainability of biofuels, allowing the identification of opportunities for reducing emissions and improving the efficiency of the production process.

4.4 Energy Efficiency of Bioethanol

The energy efficiency analysis reveals that Colombian bioethanol has a favorable energy obtained/energy invested (EROI) ratio, attributed to the high productivity of sugarcane in tropical climates, the optimization of industrial processing and the valorization of energy byproducts such as bagasse. These characteristics have allowed the Colombian bioenergy sector to improve its efficiency and reduce its dependence on fossil fuels. Studies on the transformation of the sugar industry have highlighted that the implementation of more efficient technologies has optimized energy conversion in bioethanol production, consolidating it as a competitive biofuel in the region. The historical evolution and sustainable transformation of the sugar industry in the Cauca Valley have been fundamental to consolidating the competitiveness of Colombian bioethanol in the energy market. The implementation of advanced technologies and the adoption of circular economy strategies have allowed the sector to achieve greater efficiency in the production of bioethanol and mitigate the environmental impacts associated with the process (González-Ramírez et al., 2024).

Furthermore, the use of high-efficiency boilers and energy cogeneration in Colombian sugar mills has reduced the demand for external energy sources by 25%, which has improved the profitability of bioethanol and reduced its environmental impact (Ibarra & Olivar, 2018). In particular, cogeneration using sugarcane bagasse has been consolidated as an essential strategy to improve energy efficiency and reduce greenhouse gas emissions in the sugar industry. By using bagasse, a byproduct of sugarcane milling, as fuel in cogeneration systems, simultaneous production of electricity and heat is achieved, optimizing the use of resources and reducing dependence on fossil fuels. This approach not only contributes to environmental sustainability, also enhances the energy self-sufficiency of sugar mills, even allowing the injection of surplus energy into the national electricity grid. Studies have shown that replacing fossil fuels with bagasse in cogeneration processes allows for a reduction in greenhouse gas emissions, providing significant benefits in terms of sustainability and energy efficiency (Bio-emprender, n.d.).

A life cycle analysis carried out in Colombia indicates that the energy efficiency of bioethanol production can be increased by up to 30% through the implementation of advanced fermentation and distillation technologies (Jiménez Castilla et al., 2016). The efficiency of the Colombian bioenergy sector also benefits the reduction of water consumption in fermentation processes and the optimization of biofuel transport logistics, which minimizes environmental impact and operating costs (Gómez, 2016).

These findings reinforce the potential of Colombian bioethanol as a viable and competitive alternative within the global energy transition, aligning with the objectives of reducing emissions and promoting renewable energy sources in the biofuels industry (González-Ramírez, 2020).

Furthermore, a study by Becerra et al. (2018) evaluated the sustainability of different alternatives for valorizing sugarcane bagasse in the Cauca Valley, Colombia, using methodologies such as Life Cycle Analysis (LCA) and Life Cycle Cost Analysis (LCC). The results indicated that the use of bagasse for energy cogeneration presents significant economic benefits and a reduction in environmental impact, highlighting the importance of cogeneration in the energy efficiency and sustainability of the bioethanol industry in Colombia.

4.5 Use of Natural Resources: Water and Soil

Water consumption for the production of one liter of bioethanol in Colombia was estimated at 1.3 m³, a figure significantly lower than that reported in other Latin American regions, where it can exceed 2.5 m³ (Montenegro & Chaves, 2022). This low water consumption is due to the implementation of efficient irrigation technologies, such as drip irrigation and automation in water management, which have made it possible to optimize water use, reducing waste and improving the sustainability of the crop (Federación Nacional de Biocombustibles de Colombia, n.d.). Recent studies have indicated that the adoption of water recirculation and reuse strategies in sugar mills has reduced the environmental impact of the production process (Alonso Garzón, DM, 2017).

In terms of land use, the results show a 12% increase in productivity without the need to expand cultivated areas. This was possible thanks to integrated crop management strategies, the rotation of higher-yielding sugarcane varieties, and the optimization of fertilization based on soil analysis (Asocaña, 2024). The implementation of these practices has been key to maintaining soil quality and preventing soil degradation, ensuring the long-term sustainability of the crop.

Additionally, agricultural technology has played a fundamental role in optimizing land use in the Colombian bioenergy sector. The use of precision machinery and soil monitoring systems has reduced soil compaction and improved the efficiency in the application of agricultural inputs (Latam Mobility, 2023). On a comparative level, international studies have shown that sustainable agricultural systems implemented in Colombia have an environmental impact up to 20% lower than those in countries such as Brazil and the United States (Cambio Colombia, 2024).

These advances have consolidated the Colombian bioenergy sector as a benchmark in sustainability and efficiency in the use of natural resources, positioning the country as a key player in the transition towards a low-carbon economy (Martínez, 2024). Finally, the combination of technology, efficient water management and soil conservation has made it possible to improve the competitiveness of Colombian bioethanol in international markets, complying with the environmental standards required by the European Union and the United States.

4.6 Agro-industrial Waste Management and Circular Economy

The use of by-products derived from sugar cane has been a key strategy in the consolidation of a circular economy within the bioenergy sector. Sugar cane bagasse, which represents approximately 30% of the total waste generated in sugar mills, has demonstrated high energy potential, facilitating its use in the production of second-generation bioethanol and energy cogeneration (González-Ramírez et al., 2024). Recent studies have shown that the use of sugar cane bagasse in the production of biofuels can reduce the dependence on primary crops and optimize the energy balance of the production process.

The treatment of vinasses by biomethanization has been one of the most effective strategies to reduce the pollution generated by these liquid wastes. It has been shown that the anaerobic treatment of vinasses allows a 40% reduction in the pollutant load, turning them into potential sources of biogas for the generation of energy in the sugar mills themselves (Montenegro & Chaves, 2022; Mines and EnergyMinistry, 2024). This process not only reduces the environmental impact, also allows a 15% reduction in operating costs, improving the efficiency of the bioenergy sector (Jiménez Castilla et al., 2016). Recent research has shown that anaerobic digestion of vinasses improves the stability of the bioethanol production process, reduces the toxicity of the final effluent and maximizes nutrient recovery. For example, a study carried out by Wilkie et al. (2000) evaluated the characterization and anaerobic treatment of vinasses from different raw materials, finding that this process is effective in reducing the pollutant load and generating biogas that can be used as an energy source. These findings are consistent with research in Europe, where the application of anaerobic digestion in distillery waste has contributed to the sustainability and efficiency of bioethanol production (Moletta, 2005).

In terms of solid waste utilization, filter cake, another by-product of the sugar industry, has been successfully used in the production of biofertilizers. This material, rich in organic matter, has been incorporated into sustainable fertilization systems, reducing the dependence on synthetic fertilizers by 30% and significantly improving soil health and agricultural productivity (García et al., 2021; Alonso Garzón, DM , 2017). In this sense, Hamelin et al. (2022) found that the application of biofertilizers derived from sugarcane residues improves the water retention capacity of soils, favoring the growth of crops with less use of agrochemical inputs.

Likewise, the integration of these residues into circular economy strategies has allowed for greater efficiency in the production of bioethanol, reducing by 20% the greenhouse gas emissions associated with the production and distribution of biofuel (Latam Mobility, 2023). Furthermore, the reuse of industrial by-products in the manufacture of biodegradable materials and bioplastics has become a viable alternative to diversify the uses of bagasse and cachaza, favoring the sustainability of the sector and the reduction of final waste (Federación Nacional de Biocombustibles de Colombia,n.d.). According to Fischer et al. (2022), the conversion of lignocellulose into bioplastics not only represents an alternative for the replacement of fossil plastics, also generates products with a lower environmental impact.

Finally, the consolidation of the circular economy in the Colombian bioenergy sector has been driven by the combination of technological innovations and stricter environmental regulations. Compliance with international standards, such as those established by the European Union in terms of energy sustainability, has allowed Colombia to strengthen its competitiveness in the global biofuels market (Asocaña, 2024; Colombia Change, 2024). Along these lines, a study carried out in Italy by Rossi et al. (2023) highlights the importance of public policies and environmental certifications in promoting the circular bioeconomy in the energy sector.

These advances accentuate the fundamental role of agro-industrial waste management in optimising the bioethanol production cycle, consolidating the country as a benchmark in bioeconomy and sustainable energy transition.

4.7 International Competitiveness and Environmental Regulations

The results indicate that Colombian bioethanol meets the sustainability standards required by the European Union and the United States, which reinforces its export potential in international markets. Colombia has developed a matrix of environmental certifications that guarantees the traceability of the product and its alignment with international regulations, such as the EU Renewable Energy Directive (RED II) and the US Renewable Fuel Standards (RFS). These certifications have allowed Colombian bioethanol to access high value-added markets, strengthening its competitiveness against other biofuels produced in Latin America (Giraldo Ayala & Gómez, 2013).

From an economic perspective, the cost of producing Colombian bioethanol is 20% lower than in the United States, which represents a key competitive advantage for entering global markets. This differential cost is due to lower investment in agricultural inputs, greater production efficiency, and tax benefits directed at the biofuels sector. A comparative analysis in Brazil, Colombia, and the United States shows that energy efficiency and the lower cost of agricultural inputs in Colombia allow its bioethanol to be more competitive in the global market (Jiménez Castilla et al., 2016).

In regulatory terms, Colombian bioethanol has made progress in complying with international environmental regulations, especially in relation to the reduction of greenhouse gas (GHG) emissions. According to recent studies, the use of bioethanol can reduce CO_2 emissions between 50% and 70%, depending on the raw material used and the efficiency of the production process (Latam Mobility, 2023). This makes it a strategic biofuel within the global energy transition and the reduction of the carbon footprint in the transport sector.

The adoption of circular economy strategies in bioethanol production in Colombia has been fundamental for its acceptance in international markets. The valorisation of by-products, such as sugarcane bagasse and vinasse, has allowed the environmental and energy balance of the process to be optimised, strengthening its viability within sustainability criteria. For example, the Riopaila Castilla company has implemented a circular economy model that optimises the use of by-products generated in its production process, contributing to the sustainability of the sector (Riopaila Castilla, 2024).

Finally, the study showed that the consolidation of the bioenergy industry in Colombia can reduce dependence on fossil fuel imports, strengthening energy security and aligning with the carbon emission reduction commitments established in the Paris Agreement. According to the Mines and Energy Ministry (2020), the country has adopted measures to reduce its greenhouse gas emissions by 20% by 2030, in line with international commitments (Mines and EnergyMinistry, 2020).

To encourage the development of the sector, the Colombian government has implemented regulations for the mandatory mixing of biofuels with fossil fuels. Law 693 of 2001 established the obligation to mix oxygenated products with gasoline, while Law 939 of 2004 promoted the use of biodiesel in mixtures with diesel fuel (ECLAC, 2007).

In addition, tax incentives such as exemption from value-added tax (VAT) have been granted for the purchase of biofuels of plant or animal origin intended for mixing with diesel fuel, promoting investment in clean technologies and the sustainability of the sector (Environment and Sustainable DevelopmentMinistry, 2024).

These advances position Colombia as a relevant player in the global biofuels market, consolidating its leadership in Latin America in the production and export of sustainable bioethanol.

5. Discussion

The results of this study confirm that the bioethanol sector in Colombia has established itself as a key player in the energy transition in Latin America. It is evident that the bioenergy industry has been shaped by socioeconomic dynamics, regulatory policies and sustainability strategies, positioning the country as an internationally competitive bioethanol producer. The consolidation of sugarcane production in the Cauca Valley as a strategic pillar of the Colombian economy has facilitated technological innovation, improved energy efficiency and a significant reduction in greenhouse gas (GHG) emissions (González-Ramírez et al., 2024). These findings coincide with previous studies on bioethanol production in Brazil and the United States, reinforcing the viability of biofuels as a sustainable alternative in the global energy matrix.

5.1. Bioethanol Production and Market Competitiveness

One of the most relevant findings of this study is that Colombian bioethanol meets the sustainability standards required by the European Union (EU) and the United States, which reinforces its export potential in international markets. Colombia has implemented an environmental certification matrix that guarantees product traceability and its alignment with regulations such as the EU Renewable Energy Directive (RED II) and the US Renewable Fuel Standards (RFS). In addition, the production cost of Colombian bioethanol was found to be 20% lower compared to that of the United States, due to lower investment in agricultural inputs, high productivity in tropical climates, and tax benefits granted to the sector. This suggests a key competitive advantage for Colombian bioethanol in global markets, especially with the growing demand for low-carbon footprint fuels (Jiménez Castilla et al., 2016).

However, significant challenges remain, such as the volatility of international sugar prices and logistical barriers to bioethanol exports. Future research should assess the economic resilience of Colombian bioethanol in volatile markets, especially considering the evolution of energy policies in key importing regions such as the EU and North America.

5.2. Environmental Sustainability: Circular Economy and Resource Optimization

A key contribution of this study is the confirmation that the bioethanol sector in Colombia has adopted circular economy strategies. The results indicate that 30% of sugarcane bagasse is used in the cogeneration of bioethanol, which has allowed a 35% reduction in dependence on fossil fuels (González-Ramírez et al., 2024). This coincides with international studies that show that the production of second-generation bioethanol from lignocellulosic biomass has a lower environmental impact compared to first-generation biofuels.

Furthermore, the treatment of vinasses by anaerobic digestion has proven to be an effective solution to reduce the pollutant load and generate usable biogas in sugar mills. For example, a study by Wilkie et al. (2000) evaluated the anaerobic digestion of sugar cane vinasses, showing a significant reduction in the organic load and biogas production. These results are consistent with research in Europe, where the application of anaerobic digestion in waste from the sugar industry has improved the sustainability and energy efficiency of the process (Moletta , 2005).

The use of agro-industrial solid waste, such as filter cake, has proven to be an efficient strategy in the production of biofertilizers, contributing to the reduction of dependence on synthetic fertilizers and improving soil quality. Composting filter cake facilitates its application in crops, optimizing its use as an organic amendment and promoting the regeneration of organic matter content in agricultural soils (Gutiérrez et al., 2008).

In addition, studies in Brazil have shown that the production of mineral organic fertilizers from filter cake allows for a gradual release of nutrients, benefiting agricultural productivity and reducing the use of conventional chemical inputs. Agrion company has developed technologies to transform filter cake into high-performance biofertilizers, promoting sustainable agricultural practices in the sugar sector (Agribusiness Global, 2023).

5.3. Energy Efficiency and Carbon Emissions Reduction

The net energy return (EROI) of Colombian bioethanol was calculated at 3.8, significantly higher than the 1.6 recorded for corn ethanol in North America. This result is attributed to the high productivity of sugarcane, the efficiency of industrial processes, and the use of bagasse for cogeneration (González-Ramírez et al., 2024). In addition, high-efficiency boilers and cogeneration were found to have reduced external energy demand by 25%, improving the profitability of bioethanol and decreasing its environmental impact (Ibarra & Olivar, 2018).

The Life Cycle Analysis (LCA) determined that GHG emissions of Colombian bioethanol are 55% lower than those of fossil fuels, a result similar to the reductions observed in Brazil and the United States (González-Ramírez et al., 2024).

To further optimize the sustainability of the sector, it is recommended to improve precision fertilization and transport logistics, as these factors can reduce nitrogen oxide (NO_x) emissions, which have a higher global warming potential than CO_2 (Montenegro & Chaves, 2022).

5.4. Policy Implications and Future Research

The Colombian regulatory framework has been fundamental in the development of the bioethanol sector. Law 693 of 2001 establishes standards on the use of fuel alcohols, creating incentives for their production, marketing and consumption. This law stipulates that gasoline used in urban centers with more than 500,000 inhabitants must contain oxygenated components, such as fuel alcohols, in the proportions determined by the Mines and Energy Ministry (ColombiaCongress, 2001). For its part, Law 939 of 2004 promotes the production and marketing of biofuels for diesel engines, defining biofuels of plant or animal origin and establishing tax exemptions to encourage their use (ColombiaCongress, 2004).

Future research is recommended to explore carbon market mechanisms, strategies to achieve a negative carbon balance in bioethanol production, and the viability of third-generation biofuels. In Colombia, the carbon market has been consolidated as a key instrument for climate change mitigation, offering opportunities for the implementation of projects that reduce greenhouse gas emissions (De la Rosa Calderón, 2022). Furthermore, third-generation biofuels, such as those obtained from microalgae, represent a promising alternative due to their high photosynthetic efficiency and their ability to grow in environments unsuitable for traditional agriculture (Sierra Vargas, Romero, & Rodríguez, 2014).

Colombia could consolidate its position as a global leader in sustainable bioenergy, promoting low-carbon economies and ensuring its competitiveness in international markets, with these advances.

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