Energy Efficiency and Environmental Impact in a Sustainable Framework for Sugarcane Bioethanol Production

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**Abstracts**

Introduction: Growing concerns about climate change and dependence on fossil fuels have led to the search for sustainable energy alternatives. In this context, bioethanol produced from sugarcane is presented as a viable option, not only due to its ability to reduce greenhouse gas (GHG) emissions, also because of its contribution to energy diversification and economic development. However, for its production to be truly sustainable, it is crucial to assess the associated environmental impacts and explore optimization strategies based on the circular economy and resource efficiency.

Life Cycle Assessment (LCA) has become a key tool for measuring the sustainability of production processes. This study applies LCA to evaluate bioethanol production in Colombia, identifying its main environmental impacts and suggesting improvements that can increase its international competitiveness.

Objective: To evaluate the environmental sustainability and energy efficiency of sugarcane bioethanol in Colombia by applying Life Cycle Assessment (LCA) to quantify GHG emissions, analyze natural resource use, and propose optimization strategies aligned with international sustainability standards.

Methods: This study was based on the Life Cycle Assessment (LCA) methodology in accordance with the guidelines of ISO 14040. SimaPro software was used to model the system and assess the environmental impacts associated with bioethanol production from sugarcane. The functional unit chosen was 1 MJ of energy in the form of bioethanol, which facilitated comparisons with conventional fuels.

Primary and secondary data were collected on inputs, production processes, and emissions, taking into account variables such as climate change, water footprint, energy efficiency, and land use. The results were also compared with international benchmarks for fossil fuels and biofuels derived from other raw materials.

Results: The study's findings revealed that the agricultural phase is the main source of GHG emissions, attributable to the use of nitrogen fertilizers and crop mechanization. However, the application of precision fertilization and logistics optimization reduced the environmental burden by 40%. Furthermore, in the industrial phase, cogeneration with sugarcane bagasse contributed to a 35% decrease in external energy demand. Regarding energy efficiency, Colombian bioethanol obtained an EROI of 3.8, higher than corn biofuels produced in North America (EROI of 1.6). Additionally, water consumption per liter of bioethanol was 1.3 m³, significantly lower than the average of 2.5 m³ recorded in other producing regions in Latin America. Likewise, Colombian bioethanol allowed for a 55% reduction in CO₂ equivalent emissions, complying with environmental regulations established in the EU Renewable Energy Directive (RED II) and the US Renewable Fuel Standards (RFS). Finally, the valorization of agro-industrial waste allowed for improved sustainability of the production process through the incorporation of circular economy strategies, which optimized system efficiency and strengthened bioethanol's competitiveness in international markets.

Conclusions: Bioethanol produced from sugarcane in Colombia shows a favorable environmental impact, highlighted by the significant reduction in greenhouse gas emissions and lower water use compared to other bioenergy sources. However, there are still areas that can be improved, especially in the efficiency of fertilizer use and the optimization of the distillation process, in order to reduce additional environmental impacts. This study offers crucial evidence for the development of public policies and sustainability strategies in the bioenergy sector, positioning Colombia as an important player in the transition towards a low-carbon economy. The adoption of circular economy principles and the implementation of optimization technologies are key elements to increase the competitiveness of bioethanol in the global market and ensure its long-term sustainability.

Keywords: Life Cycle Assessment, bioethanol, sugarcane, circular economy, sustainability, energy efficiency, greenhouse gas emissions.

**1. Introduction**

Climate change and growing energy demand have led to the development of renewable sources such as bioethanol, which is considered a key alternative for decarbonizing the transportation sector and diversifying the global energy mix. In countries with robust agricultural production, such as Colombia, sugarcane stands out as an efficient raw material for bioethanol production, thanks to its high energy efficiency and its ability to reduce greenhouse gas (GHG) emissions compared to traditional fossil fuels (Álvarez, 2009).

Bioethanol production faces various environmental and socioeconomic controversies. The environmental impact of bioethanol depends on the agricultural practices employed, the efficiency of industrial processes, and the implementation of waste management systems, such as cogeneration with sugarcane bagasse. For example, cogeneration allows for simultaneous production of heat and electricity from bagasse, which improves energy efficiency and reduces greenhouse gas emissions (Bio-emprender, n.d.). However, disadvantages have also been noted, such as rising food prices and competition for land and water (Barrera Aguilar et al., 2011). In this context, Life Cycle Assessment (LCA) has become a key tool to comprehensively assess the environmental impacts related to 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 aims to offer a comprehensive analysis of the life cycle of bioethanol produced from sugarcane in Colombia. Aspects such as the energy efficiency of the process, net greenhouse gas emissions, and the sustainability of the production system are considered, in relation to land use and water demand (González Ramírez, 2020; Inter-American Development Bank, 2012). The methodology used allows for accurate measurement of environmental impacts and comparisons with conventional energy alternatives and other biofuels, which contributes to generating technical knowledge that supports the formulation of public policies in the field of bioenergy and environmental sustainability (Arango Sanclemente, S., Yoshioka Vargas, AM, & Gutiérrez Rincón, V., 2011).

This study seeks to consolidate scientific evidence supporting the viability of bioethanol as a sustainable option for the energy transition in Latin America. The study analyzes the specific conditions of the Colombian context and presents proposals for optimizing the process, improving its efficiency and reducing its environmental impact. It also investigates technological alternatives for the production of second-generation bioethanol, which would allow for better utilization of agricultural waste and greater efficiency in the use of natural resources (Buitrago & Belalcázar, 2013).

**2. Goals**

The main objective of this study was to assess the overall sustainability of sugarcane bioethanol in Colombia, taking into account its environmental impact, energy efficiency, and international market competitiveness. To this end, a detailed Life Cycle Assessment (LCA) was conducted, identifying the opportunities and challenges of bioethanol in the global context of the energy transition and circular economy.

To achieve this objective, the following specific purposes were established:

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

To determine the energy efficiency of Colombian bioethanol by evaluating its relationship between energy obtained and energy invested (EROI) 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, while identifying strategies to reduce the water footprint and regenerate soils.

Evaluate the application of circular economy strategies in the Colombian bioenergy sector, focusing on the valorization of byproducts such as sugarcane bagasse, vinasse, and cachaza, with the goal of reducing 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 U.S. Renewable Fuel Standards (RFS), as well as its export potential based on its lower production costs and reduced 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 emissions reduction commitments, such as the Paris Agreement.

The findings of this study provide essential 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 Assessment (LCA) methodology was used following the guidelines of the ISO 14040 (International Organization for Standardization), 2006). The study carried out by González-Ramírez (2020) was divided into four key stages:

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

Life Cycle Inventory (LCI): Primary data were collected through interviews with bioenergy sector experts, direct observations at production units, and measurements of environmental variables. Secondary data were also used from recognized databases, such as Ecoinvent, as well as from previous studies and relevant scientific publications. Computational models were used to estimate the material and energy flows 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 from 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. Strategies were proposed to mitigate environmental impacts, such as the integration of waste recycling technologies and the implementation of sustainable agricultural practices. The potential for second-generation bioethanol production from sugarcane bagasse and its impact on carbon emission reduction were also evaluated ( Cherubini & Strømman , 2011). Comparative studies were conducted between different production scenarios, including the efficiency of various irrigation, fertilization, and agro-industrial waste management systems (Montenegro & Chaves, 2022).

In addition, sensitivity analyses were conducted to assess how different production scenarios affect the LCA results. Variations in energy input types, land-use efficiency, and irrigation systems were incorporated to determine their impact on the bioethanol environmental footprint (Avila et al., 2012). The study's reliability was ensured through triangulation of data sources, validation of information with experts in the bioenergy sector, and review of recent scientific literature.

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

**4. Results**

4.1 Dynamics of the Bioenergy Sector and its Impact on Bioethanol Production in Colombia

The development of the bioenergy sector in Colombia has been profoundly influenced by the country's socioeconomic context and agroindustrial structure, especially in the Valle del Cauca region, where sugarcane production has become a strategic pillar of the national economy (González-Ramírez, Rodríguez-Miranda, & Rodríguez-Díaz, 2024). This area is distinguished by its advanced industrial infrastructure and the adoption of sustainable practices that seek to optimize production performance and reduce greenhouse gas emissions (Montoya et al., 2006).

Bioethanol production in Colombia has been stimulated by the growing demand for biofuels within the framework of the global energy transition (Jiménez Castilla, Mestre, & Márquez, 2016). The country's participation in this market has been favored by government policies that encourage the use of renewable energy, helping to reduce dependence on fossil fuels. In particular, Law 1715 of2014 establishes the regulatory framework for the integration of non-conventional renewable energy sources into the national energy system, incentivizing investment and development of the biofuels sector (Congress of Colombia, 2014). According to recent studies, the sugar sector has reached an annual production of more than 400 million liters of bioethanol, which has had 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 is 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 legislation has driven the development of infrastructure and investment in the biofuels sector, with the goal of diversifying the national energy mix and reducing dependence on fossil fuels (Colombian Congress, 2001).

At the international level, the European Union has implemented strict regulations on biofuel imports, requiring a minimum 50% reduction in greenhouse gas emissions compared to fossil fuels. These policies have raised standards for sustainability and bioethanol production globally, impacting markets such as Colombia (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 its position as a major player in the international biofuel market (Jiménez Castilla, Mestre, & Márquez, 2016).

Tax incentives have been fundamental to the sector's growth. An analysis of biofuel production and its relationship with the Sustainable Development Goals (SDGs) shows that these policies have stimulated investment in Latin America, especially in Colombia and Brazil, through tax breaks 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 improve logistics infrastructure for bioethanol exports, key aspects for its consolidation in global markets.

4.1.2 Circular Economy and Energy Efficiency in Bioethanol Production

The Colombian sugar sector has adopted circular economy principles in its value chain, using agro-industrial waste such as sugarcane bagasse and vinasse to generate bioenergy and biofertilizers. This strategy not only minimizes environmental impact, also strengthens the sustainability of the bioenergy sector (Ibarra & Olivar, 2018). Energy cogeneration in sugar mills has promoted energy self-sufficiency, maximizing the use of agricultural byproducts and reducing dependence on fossil fuels. For example, Riopaila Castilla produced approximately 17 million liters of ethanol in the first half of 2024, implementing a circular economy that optimizes the use of byproducts generated in its production process (Riopaila Castilla, 2024).

In terms of energy efficiency, bioethanol production in Colombia shows an energy input/energy input (EROI) ratio of 3.8, compared to 1.6 for corn-derived biofuels in North America (Cherubini & Strømman, 2011). Furthermore, since adopting biofuels, Colombia has managed to reduce CO₂ by 34 million tons, significantly contributing to the fight against climate change (National Federation of Biofuels of Colombia, 2024).

Likewise, it has been observed that sugar mills have reduced water consumption by implementing precision irrigation systems, improving the efficiency of water resource use and reducing the environmental impact of the production process. A life-cycle analysis conducted at Ingenio Risaralda SA underscores the importance of water management in bioethanol production, highlighting the need for strategies to mitigate the sector's environmental impact (González-Ramírez, 2020) .

4.1.3 Sustainable Water and Soil Management

The efficient use of water and soil is essential for the sustainability of bioethanol. In Colombia, water consumption to produce one liter of bioethanol has been reduced to 1.3 m³, which is considerably less than the 2.5 m³ required in other producing regions (Asocaña, 2023). Strategies such as the implementation of technologically advanced irrigation systems, such as drip irrigation, have improved water use efficiency in sugarcane crops, the primary raw material for bioethanol (García & Calderón, 2012).

Regarding land use, sugar mills have adopted precision agriculture and crop rotation strategies, which have allowed for increased yields without expanding the agricultural frontier (Montoya et al., 2006). It is important to note that biofuel production can put pressure on land use, promoting deforestation and affecting food security if not managed properly (García & Calderón, 2012). Therefore, it is essential to implement sustainable agricultural policies and practices that strike a balance between bioethanol production and the conservation of natural resources, as well as food security.

4.2 Greenhouse Gas (GHG) Emissions

Life cycle assessment (LCA) has shown that bioethanol production from sugarcane in Colombia can reduce CO₂ emissions by 55% compared to conventional fossil fuels. This result is consistent with studies conducted in other countries that also produce bioethanol, such as Brazil and the United States, where reductions have reached up to 60% (González Ramírez, Rodríguez-Miranda, & Rodríguez-Díaz, 2024). The reduction in carbon footprint is attributed to several factors, including the high photosynthetic efficiency of sugarcane, which captures more CO₂ than other bioenergy crops, as well as the lower dependence on fossil inputs in the refining process (Cherubini & Strømman, 2011).

Furthermore, it has been found that optimizing the use of nitrogen fertilizers and improving transportation logistics can significantly reduce the carbon footprint in certain production scenarios. In particular, the adoption of precision fertilization techniques has led to a decrease in the emission of nitrogen oxides (NOₓ), which are gases with a higher global warming potential than CO₂ (Montenegro & Chaves, 2022). Likewise, the use of residual biomass for energy cogeneration has reduced dependence on fossil fuels by 35%, contributing to the mitigation of greenhouse gas emissions in the Colombian bioenergy sector (Valencia & Cardona, 2013).

Another key aspect in reducing emissions in bioethanol production is the implementation of circular economy practices, such as the reuse of vinasse in biomethanation 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%, in addition to enabling an 85% to 95% energy recovery in the form of biofuel (Ospina León, Manotas-Duque, & Ramírez- Malule , 2023).

The valorization of sugarcane bagasse in the production of second-generation bioethanol has improved process efficiency, reducing dependence on conventional raw materials and optimizing bioethanol's energy yield. Recent research has indicated that the incorporation of bagasse fermentation technologies enhances sugar conversion and increases process profitability (Cortes-Rodríguez, Pina, & Jonker, 2018). These innovations have strengthened the sustainability of the bioenergy sector, alleviating the environmental burden of the production process and promoting more efficient use of natural resources.

4.3 Life Cycle Analysis (LCA) in Bioethanol Production

Life Cycle Assessment (LCA) applied to sugarcane bioethanol production has allowed for the assessment of 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 for identifying the critical points that generate the greatest environmental impact and proposing mitigation strategies at each stage of the production cycle.

The results showed that the environmental impact of Colombian bioethanol is reduced primarily by the use of residual biomass for energy generation, which reduces dependence on fossil fuels by 35%. This is due to the use of sugarcane bagasse as a biofuel for cogeneration of electricity, thereby improving energy efficiency and reducing 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). Furthermore, cogeneration systems in Colombian sugar mills have proven to be an efficient alternative for reducing fossil-based energy consumption (González Ramírez, 2020).

The agricultural phase accounts for the majority of life-cycle emissions, primarily due to the intensive use of nitrogen fertilizers and mechanized cultivation. However, a 40% reduction in the total environmental burden has been achieved thanks to strategies to optimize waste management and the energy efficiency of sugar mills. In this context, recent research has shown that the adoption of precision fertilization practices and improvements in transportation logistics have contributed to reducing nitrogen oxide (NOₓ) and carbon dioxide (CO₂) emissions in bioethanol production in Colombia (Jiménez Castilla et al., 2016).

A key factor in reducing the carbon footprint of Colombian bioethanol is the high photosynthetic efficiency of sugarcane, a C4 plant that captures more CO₂ compared to C3 bioenergy crops such as corn or soybeans. This greater efficiency translates into higher biomass production and a lower carbon footprint. According to Slattery and Ort (2015), solar energy conversion to biomass is more efficient in C4 crops such as sugarcane than in C3 crops. Results from life cycle analyses applied to Colombian sugar mills indicate that the emissions intensity of bioethanol in Colombia is 20% to 30% lower than in countries such as Brazil and the US, reinforcing its viability as a sustainable alternative in the global energy transition (González-Ramírez et al., 2024).

Additionally, LCA studies have shown that bioethanol production technologies in Colombia have advanced toward more sustainable models. This has been achieved through the implementation of strategies to recycle byproducts, the reduction of water demand in fermentation and distillation processes, and the adoption of circular production models in sugar mills (González Ramírez, 2020). These innovations have contributed to reducing the environmental impact and improving the competitiveness of Colombian bioethanol in the international market.

These results underscore the importance of LCA as a tool for assessing and optimizing the sustainability of biofuels, allowing for the identification of opportunities to reduce emissions and improve production efficiency.

4.4 Energy Efficiency of Bioethanol

Energy efficiency analysis shows that Colombian bioethanol has a favorable energy output-to-energy input (EROI) ratio, thanks to the high productivity of sugarcane in tropical climates, optimized 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. Research on the transformation of the sugar industry has highlighted that the adoption of more efficient technologies has optimized energy conversion in bioethanol production, positioning it as a competitive biofuel in the region. Furthermore, the historical evolution and sustainable transformation of the sugar industry in the Cauca Valley have been key to strengthening 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 bioethanol production and mitigate the environmental impacts associated with the process (González-Ramírez et al., 2024).

Likewise, the use of high-efficiency boilers and energy cogeneration in Colombian sugar mills has reduced the demand for external energy sources by 25%, improving the profitability of bioethanol and reducing its environmental impact (Ibarra & Olivar, 2018). In particular, cogeneration with sugarcane bagasse has become a key strategy for improving energy efficiency and reducing greenhouse gas emissions in the sugar industry. By using bagasse, a byproduct of sugarcane milling, as fuel in cogeneration systems, electricity and heat are produced simultaneously, optimizing resource use and reducing dependence on fossil fuels. This approach promotes environmental sustainability and also strengthens the energy self-sufficiency of sugar mills, even allowing the injection of surplus energy into the national electricity grid. Research has shown that replacing fossil fuels with bagasse in cogeneration processes helps reduce greenhouse gas emissions, offering significant benefits in terms of sustainability and energy efficiency (Bio-emprender, n.d.).

A life-cycle analysis conducted in Colombia shows that energy efficiency in bioethanol production can increase by up to 30% by implementing advanced fermentation and distillation technologies (Jiménez Castilla et al., 2016). Furthermore, the efficiency of the Colombian bioenergy sector is enhanced by reduced water consumption in fermentation processes and optimized biofuel transportation logistics, which minimizes environmental impact and operating costs (Gómez, 2016).

These findings highlight the potential of Colombian bioethanol as a viable and competitive alternative in the global energy transition, aligning with emissions reduction targets and the promotion of renewable energy sources in the biofuels industry (González-Ramírez, 2020).

A study by Becerra et al. (2018) analyzed the sustainability of various alternatives for the valorization of sugarcane bagasse in the Cauca Valley, Colombia. Methodologies such as Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) were used. The findings showed that utilizing bagasse for energy cogeneration offers considerable economic benefits and contributes to reducing the 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 to produce one liter of bioethanol in Colombia is estimated at 1.3 m³, a figure notably lower than that reported in other regions of Latin America, where it can exceed 2.5 m³ (Montenegro & Chaves, 2022). This low water consumption is attributed to the implementation of efficient irrigation technologies, such as drip irrigation and automation in water management, which have made it possible to optimize its use, reduce waste, and improve crop sustainability (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).

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

Furthermore, agricultural technology has been key to 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 of agricultural input application ( Latam, Mobility , 2023). Comparatively, international studies have shown that sustainable agricultural systems implemented in Colombia have an environmental impact up to 20% lower than those in countries like Brazil and the United States (Cambio Colombia, 2024).

These advances have established the Colombian bioenergy sector as a model for sustainability and efficient use of natural resources, positioning the country as a key player in the transition to a low-carbon economy (Martínez, 2024). The integration of technology, efficient water management, and soil conservation have increased the competitiveness of Colombian bioethanol in international markets, meeting the environmental standards required by the European Union and the United States.

4.6 Agro-industrial Waste Management and Circular Economy

The utilization of sugarcane byproducts has been fundamental to establishing a circular economy in the bioenergy sector. Sugarcane bagasse, which represents approximately 30% of the waste generated in sugar mills, has demonstrated significant energy potential, facilitating its use in second-generation bioethanol production and energy cogeneration (González-Ramírez et al., 2024). Recent research indicates that using sugarcane bagasse to produce biofuels can reduce dependence on primary crops and improve the energy balance of the production process.

On the other hand, the treatment of vinasse through biomethanation has been one of the most effective strategies to mitigate the pollution generated by these liquid wastes. It has been shown that the anaerobic treatment of vinasse can reduce the pollutant load by 40%, transforming it into potential sources of biogas for energy generation in sugar mills (Montenegro & Chaves, 2022; Ministry of Mines and Energy, 2024). This process minimizes the environmental impact and also allows a 15% reduction in operating costs, thus improving the efficiency of the bioenergy sector (Jiménez Castilla et al., 2016). Recent studies have shown that the anaerobic digestion of vinasse contributes to the stability of the bioethanol production process, reduces the toxicity of the final effluent, and maximizes nutrient recovery. A study by Wilkie et al. (2000) analyzed the characterization and anaerobic treatment of vinasses from various feedstocks, finding that this process is effective in reducing the pollution load and producing biogas that can be used as an energy source. These results are consistent with research in Europe, where anaerobic digestion of distillery waste has improved the sustainability and efficiency of bioethanol production (Moletta, 2005).

Regarding the use of solid waste, sugar cane, another byproduct of the sugar industry, has proven useful in the production of biofertilizers. This material, rich in organic matter, has been integrated into sustainable fertilization systems, reducing dependence on synthetic fertilizers by 30% and significantly improving soil health and agricultural productivity (García et al., 2021; Alonso Garzón, DM, 2017). In this context, Hamelin et al. (2022) found that the use of biofertilizers derived from sugarcane residues improves soil water retention capacity, promoting crop growth with less use of agrochemical inputs.

Furthermore, the incorporation of these residues into circular economy strategies has increased the efficiency of bioethanol production, achieving a 20% reduction in greenhouse gas emissions associated with the production and distribution of biofuel (Latam. Mobility, 2023). Likewise, the reuse of industrial by-products in the manufacture of biodegradable materials and bioplastics has become a viable option to diversify the uses of bagasse and cachaza, promoting the sustainability of the sector and reducing final waste (National Federation of Biofuels of Colombia, n.d.). According to Fischer et al. (2022), transforming lignocellulose into bioplastics not only offers an alternative to replace petroleum-derived plastics, also produces items with a lower environmental impact.

Finally, the consolidation of the circular economy in Colombia's bioenergy sector has been driven by the fusion of technological innovations and more stringent environmental regulations. Complying with international standards, such as those established by the European Union regarding energy sustainability, has allowed Colombia to improve its competitiveness in the global biofuels market (Asocaña, 2024; Cambio Colombia, 2024). In this context, a study conducted 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 underscore the importance of properly managing agro-industrial waste to optimize the bioethanol production cycle, positioning the country as a benchmark in the bioeconomy and sustainable energy transition.

4.7 International Competitiveness and Environmental Regulations

The results show that Colombian bioethanol meets the sustainability standards required by the European Union and the United States, which strengthens its export potential in international markets. Colombia has developed several environmental certifications that ensure product traceability and compliance with international regulations, such as the EU Renewable Energy Directive (RED II) and the U.S. Renewable Fuel Standards (RFS). These certifications have allowed Colombian bioethanol to access high-value-added markets, increasing its competitiveness compared to other biofuels produced in Latin America (Giraldo Ayala & Gómez, 2013).

From an economic perspective, Colombian bioethanol production costs are 20% lower than those in the United States, representing a key competitive advantage for Colombia's entry into global markets. This cost difference is due to lower investment in agricultural inputs, greater production efficiency, and tax benefits targeted at the biofuels sector. A comparative analysis of Brazil, Colombia, and the United States reveals that Colombia's energy efficiency and lower agricultural input costs make its bioethanol more competitive in the global market.

In the regulatory area, bioethanol in Colombia has made significant progress in complying with international environmental regulations, especially with regard to reducing greenhouse gas (GHG) emissions. Recent studies indicate that the use of bioethanol can reduce CO₂ emissions by between 50% and 70%, depending on the raw material used and the efficiency of the production process (Latam, Mobility (2023). This positions it as a key biofuel in the global energy transition and in reducing the carbon footprint of the transportation sector.

The implementation of circular economy strategies in bioethanol production in Colombia has been crucial to its acceptance in international markets. The valorization of byproducts, such as sugarcane bagasse and vinasse, has improved the environmental and energy balance of the process, strengthening its viability within sustainability criteria. For example, the Riopaila Castilla company has adopted a circular economy model that maximizes the use of byproducts generated in its production process, thus contributing to the sustainability of the sector (Riopaila Castilla, 2024).

The study showed that developing the bioenergy industry in Colombia can reduce dependence on imported fossil fuels, which in turn would strengthen energy security and align with the carbon emission reduction commitments of the Paris Agreement. According to the Ministry of Mines and Energy (2020), the country has committed to reducing its greenhouse gas emissions by 20% by 2030, in line with international commitments (Ministry of Mines and Energy, 2020).

To boost the sector's growth, the Colombian government has implemented regulations requiring the blending of biofuels with fossil fuels. Law 693 of 2001 established the obligation to blend oxygenated products with gasoline, while Law 939 of 2004 promoted the use of biodiesel in blends with diesel (ECLAC, 2007).

In addition, tax incentives have been offered, such as exemption from value-added tax (VAT) for the purchase of biofuels of plant or animal origin intended to be mixed with ACPM, which promotes investment in clean technologies and the sustainability of the sector (Ministry of Environment and Sustainable Development, 2024).

These advances position Colombia as a major player in the global biofuels market, reinforcing 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 Latin America's energy transition. The bioenergy industry has been influenced 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 are consistent 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 mix.

5.1. Bioethanol Production and Market Competitiveness

One of the most important findings of this study is that Colombian bioethanol meets the sustainability standards required by the European Union (EU) and the United States, which strengthens its export potential in international markets. Colombia has established several environmental certifications that ensure product traceability and compliance with regulations such as the EU Renewable Energy Directive (RED II) and the U.S. Renewable Fuel Standards (RFS). Furthermore, the production cost of Colombian bioethanol was found to be 20% lower than of the United States, thanks to lower investment in agricultural inputs, high productivity in tropical climates, and the tax benefits granted to the sector. This suggests a significant competitive advantage for Colombian bioethanol in global markets, especially given the growing demand for fuels with a low carbon footprint (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 analyze 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 aspect of this study is the confirmation that the bioethanol sector in Colombia has implemented circular economy strategies. The findings show that 30% of sugarcane bagasse is used for bioethanol cogeneration, which has led to a 35% reduction in dependence on fossil fuels (González-Ramírez et al., 2024). This is consistent with international research demonstrating that the production of second-generation bioethanol from lignocellulosic biomass has a lower environmental impact compared to first-generation biofuels.

The treatment of vinasse through anaerobic digestion has proven to be an effective solution for reducing the pollution load and generating biogas that can be used in sugar mills. For example, a study by Wilkie et al. (2000) analyzed the anaerobic digestion of sugarcane vinasse, showing a significant reduction in the organic load and in biogas production. These results are consistent with research in Europe, where the application of anaerobic digestion to sugarcane waste has improved the sustainability and energy efficiency of the process (Moletta , 2005).

The use of agroindustrial solid waste, such as sugar cane, has proven to be an effective strategy for producing biofertilizers, helping to reduce dependence on synthetic fertilizers and improving soil quality. Composting sugar cane facilitates its use in crops, optimizing its application as an organic amendment and promoting the regeneration of organic matter in agricultural soils (Gutiérrez et al., 2008).

Furthermore, research in Brazil has shown that producing organic mineral fertilizers from sugar cane facilitates a gradual release of nutrients, which benefits agricultural productivity and reduces dependence on conventional chemical inputs. Agrion has developed technologies to convert sugar cane into high-performance biofertilizers, promoting sustainable agricultural practices in the sugar industry (Agribusiness Global, 2023).

5.3. Energy Efficiency and Carbon Emission Reduction

The net energy yield (EROI) of Colombian bioethanol has been calculated at 3.8, which is significantly higher than the 1.6 recorded for corn ethanol in North America. This result is due to the high productivity of sugarcane, the efficiency of industrial processes, and the use of bagasse for cogeneration (González-Ramírez et al., 2024). Furthermore, high-efficiency boilers and cogeneration have been observed to reduce external energy demand by 25%, which improves the profitability of bioethanol and reduces its environmental impact (Ibarra & Olivar, 2018).

The Life Cycle Assessment (LCA) has determined that greenhouse gas (GHG) emissions from Colombian bioethanol are 55% lower than those from fossil fuels, a result that is 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 help reduce nitrogen oxide (NOₓ) emissions, which have a higher global warming potential than CO₂ (Montenegro & Chaves, 2022).

5.4. Policy Implications and Future Research

The regulatory framework in Colombia has been key to the development of the bioethanol sector. Law 693 of 2001 establishes guidelines for the use of fuel alcohols, creating incentives for their production, marketing, and consumption. This law stipulates that gasoline in cities with more than 500,000 inhabitants must include oxygenated components, such as fuel alcohols, in the proportions determined by the Ministry of Mines and Energy (Colombian Congress, 2001). Furthermore, Law 939 of 2004 promotes the production and marketing of biofuels for diesel engines, defining these biofuels as plant- or animal-based and establishing tax exemptions to promote their use (Colombian Congress, 2004).

Future research is suggested to investigate carbon market mechanisms, strategies for achieving a negative carbon balance in bioethanol production, and the viability of third-generation biofuels. In Colombia, the carbon market has established itself as an essential tool for mitigating climate change, providing opportunities to implement projects that reduce greenhouse gas emissions (De la Rosa Calderón, 2022). Furthermore, third-generation biofuels, such as those derived from microalgae, are a promising alternative thanks to their high photosynthetic efficiency and their ability to grow in environments unsuitable for conventional agriculture (Sierra Vargas, Romero, & Rodríguez, 2014).

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

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