SUSTAINABLE DEVELOPMENT ANALYSIS IN THE SUGAR INDUSTRY: ASSESSING ENVIRONMENTAL ENERGY IMPACT IN SUGAR PRODUCTION THROUGH LIFECYCLE ASSESSMENT

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ABSTRACT

This paper conducts a comprehensive analysis of sustainable development in the sugar industry of the Dominican Republic, focusing on the assessment of environmental and energy impact during sugar production in local mills. The implementation of lifecycle assessment (LCA) emerges as an essential tool to comprehend the complexity and implications of these crucial industrial operations in the Dominican context. The study addresses the implementation of sustainable practices in Dominican sugar mills, proposing innovative approaches based on LCA results. These strategies aim to mitigate negative impacts and maximize social and economic benefits associated with sugar production in the Dominican Republic. Results obtained through the LCA provide an integrated view of challenges and opportunities in the Dominican sugar industry in terms of sustainable development. The necessity for specific strategies tailored to the unique conditions of this industry in the Dominican Republic is emphasized, encouraging the adoption of environmentally friendly and socially responsible practices. This paper represents a valuable contribution to current knowledge on sustainable development in the Dominican sugar industry and offers significant insights for researchers, professionals and decision-makers striving for a more sustainable future in this crucial sector at the national level.
Keywords: sugar industry, lifecycle assessment (LCA), sustainable.

1 INTRODUCTION

In the world we live in, sustainable development has become an undeniable global priority, especially for the Dominican Republic, which faces significant challenges in terms of environmental sustainability and economic development [1]. Industries, including sugar mills, are under pressure to reduce their environmental impact and optimize resource use. The Dominican sugar industry, besides being a key economic pillar, is particularly relevant due to its intensive consumption of natural resources and waste generation. Sugar mills not only confront direct environmental challenges such as effluent management and carbon footprint but also must adapt to increasingly stringent environmental regulations and the expectations of consumers and international markets demanding sustainable practices.

In this context, lifecycle assessment (LCA) emerges as an essential tool to evaluate how production processes affect the environment throughout their lifecycle [2]. From raw material extraction to final product distribution and waste management, LCA identifies significant environmental impacts and critical areas for improvement. In the specific case of sugar production, LCA can reveal not only greenhouse gas emissions and water consumption but also impacts on local biodiversity and soil quality [3]. This provides a solid foundation for implementing continuous improvement strategies and adopting more sustainable practices. The application of LCA in Dominican sugar mills aims not only to mitigate negative environmental impacts but also to promote operational efficiency and long-term profitability across all processes.

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By optimizing resource use and reducing waste, sugar mills can enhance their competitiveness in global markets that value sustainability and environmental responsibility [4]. Moreover, these practices can catalyse more balanced and resilient economic development in the sugar industry, creating environmentally conscious jobs and promoting technological innovation.

In summary, this article not only addresses the growing demand for sustainable practices in the Dominican sugar industry but also provides valuable insights for effectively implementing these practices in key industrial sectors of the Dominican Republic. By adopting the LCA approach, we are not only improving the environmental sustainability of industrial processes but also ensuring a more promising, sustainable, and mindful future for generations to come.

2 SUGAR MILLS IN THE DOMINICAN REPUBLIC

Sugar mills, as integral parts of the sugar industry, play a crucial role in the production of sugar and biofuels. However, this industrial process is not without significant environmental impacts, ranging from natural resource consumption to waste generation and atmospheric emissions. LCA emerges as an essential tool to understand and mitigate these impacts by providing a holistic view of the environmental aspects associated with each stage of the production process [5]. The LCA methodology is based on a systematic approach that spans from raw material extraction to the final product disposal, enabling the assessment of environmental impacts throughout the entire life cycle [6]. This includes identifying and quantifying material and energy flows, as well as emissions of greenhouse gases and other atmospheric pollutants [7].

Moreover, LCA can consider impacts across different environmental categories such as climate change, acidification, eutrophication, and natural resource depletion [8]. In the specific case of sugar mills in the Dominican Republic, LCA presents itself as a valuable tool to address environmental challenges and promote sustainable practices in the sugar industry [9]. This assessment helps identify key hotspots contributing to the carbon footprint, including sugarcane harvesting, processing at the mill, sugar and biofuel production, as well as product distribution and final disposal.

Previous studies have highlighted the significant environmental impact of sugar mills, focusing on water and energy consumption, natural resource use, and greenhouse gas emissions associated with biomass burning and biofuel production [10]. These impacts can be evaluated and quantified using LCA methodologies, enabling the identification of improvement and optimization opportunities in the production process. In summary, the application of LCA in Dominican sugar mills is crucial for understanding and improving their environmental performance. By providing a comprehensive assessment of the environmental impacts associated with sugar and biofuel production processes, LCA offers a solid foundation for informed decision-making and the implementation of mitigation and improvement measures in the sugar industry.

Fig. 1 sequentially represents the fundamental processes involved in sugar production at a Dominican sugar mill. It begins with the reception of sugar cane, where the raw material is unloaded and weighed before processing begins. Next, the cane undergoes a milling process to extract the juice, which is then clarified to remove impurities. The clarified juice is concentrated through evaporation and then crystallized to form sugar crystals. These crystals are separated from the residual molasses and dried to obtain raw sugar, which undergoes a refining process to produce high-purity white sugar. Finally, the refined product is packaged and stored for distribution. The diagram provides a clear and detailed visualization of how

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sugar cane is transformed into processed sugar, highlighting each essential step in the industrial process of a Dominican sugar mill.

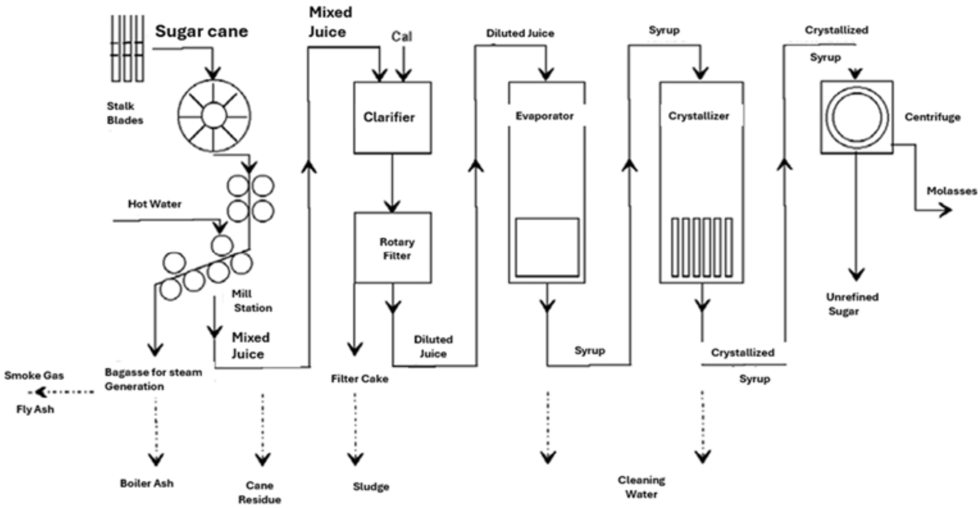

Figure 1: Production processes of Dominican sugar mills.

2.1 Detailed description of processes and fuels

In the assessment of the baseline study, the following industrial processes were considered:

1. Reception and preparation of the cane: The sugar cane is received, unloaded, and weighed before being processed.
2. Juice extraction: The cane undergoes a milling process to extract the juice.
3. Clarification: The extracted juice is clarified to remove impurities.
4. Evaporation: The clarified juice is concentrated through evaporation.
5. Crystallization: The concentrated juice is crystallized to form sugar crystals.
6. Molasses separation: The sugar crystals are separated from the residual molasses.
7. Drying: The crystals are dried to obtain raw sugar.
8. Refining: The raw sugar is refined to produce high-purity white sugar.
9. Packaging and storage: The refined sugar is packaged and stored for distribution.

Fuels used

- Bagasse:

1. Specific consumption: In the Dominican Republic, the average consumption of bagasse is approximately 1.2 tons per ton of cane processed [11].
2. Emission factor: The emission factor for bagasse is approximately 0.06 kg of CO_2 per kg of bagasse burned [12].

- Natural gas:

1. Specific consumption: The specific consumption of natural gas in Dominican sugar mills is approximately 27 m^3 per ton of sugar produced [13].
2. Emission factor: The emission factor for natural gas is 2.75 kg of CO_2 per m^3, according to international standards and local studies [12].

- Diesel:

1. Specific consumption: The consumption of diesel in machinery and equipment in sugar mills is approximately 5 litres per ton of cane processed [14].
2. Emission factor: The emission factor for diesel is 2.68 kg of CO_2 per litre, based on EPA regulations and emission studies in the Dominican Republic [15].

These data provide a solid basis for understanding the environmental impact of the baseline scenario and for identifying opportunities to improve energy efficiency and reduce emissions.

2.2 Analysis of the representativeness of the selected industries

The industries selected for this study, Central Romana, Cristóbal Colón and Barahona, represent a significant sample of the Dominican sugar sector. These three mills encompass a wide range of production and environmental management practices, facilitating a comprehensive assessment of emissions and consumption in the industry. By including both large and medium-sized mills and considering different regions of the country, the study provides a balanced and detailed perspective that reflects the realities of the sugar sector in the Dominican Republic. Additionally, these three mills represent 75% of the total sugar mills in the country, ensuring a significant sample for analysis.

3 LIFECYCLE ASSESSMENT

LCA is a fundamental analytical tool used to systematically evaluate the environmental impacts associated with a product, process, or service throughout its entire life cycle. This cycle encompasses raw material extraction, production, use, and disposal. The primary objective of LCA is to identify and quantify significant environmental burdens. This includes natural resource consumption such as energy and water, emissions to the atmosphere like greenhouse gases, releases to water and soil, as well as impacts on human health and the environment overall.

The LCA methodology is typically divided into four interconnected stages:

- Goal and scope definition: In this stage, study objectives are established, and the system to be evaluated is clearly defined. This involves setting system boundaries (e.g., from raw material extraction to product disposal) and criteria for selecting relevant environmental impacts.
- Inventory analysis: This involves compiling and quantifying material, energy, and waste flows associated with each life cycle stage of the product. Obtaining accurate and representative data on consumptions and emissions is crucial to ensure the analysis' robustness.
- Impact assessment: During this stage, the potential effects of identified input and output flows from the inventory analysis on various environmental impacts are evaluated. This

may include natural resource depletion, climate change, acidification, eutrophication, among other impacts.

- Interpretation of results: Finally, results from the LCA are interpreted and communicated. This includes assessing the environmental implications of analysed products or processes and comparing different options to identify opportunities for environmental improvement.

LCA adheres to international standards such as ISO 14040 and ISO 14044, which provide detailed guidelines for conducting LCA studies, ensuring methodological consistency and facilitating comparability of results across different studies and industrial sectors [16]. This methodology has been widely applied in industry to support environmentally informed decision-making, enabling the optimization of products and processes towards sustainability (Fig. 2).

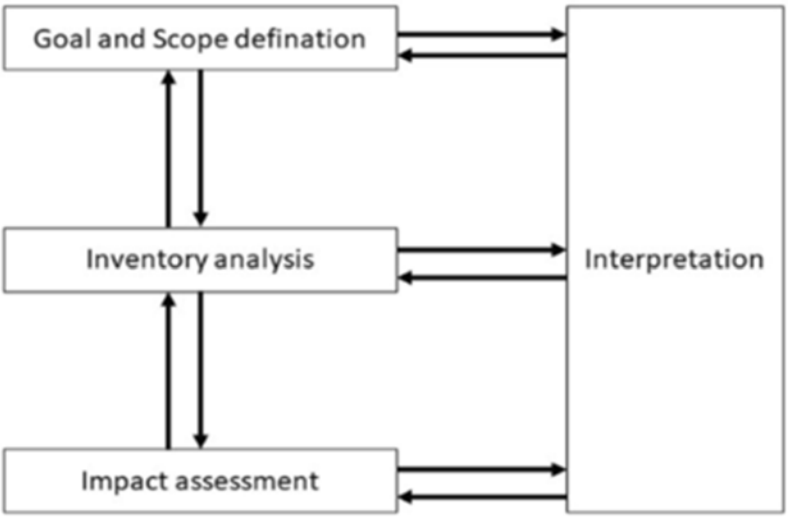

Figure 2: The general phases of an LCA, as described by ISO 14040.

4 METHODOLOGIES USED

To conduct this study, a comprehensive review of available literature on sustainable development in the global sugar industry was performed, with a particular focus on the Dominican Republic. This review included consulting previous studies that have applied LCA in sugar production, providing a framework to understand specific challenges and opportunities in Ministry of Environment and Natural Resources [17]. Subsequently, detailed data collection was carried out from major Dominican sugar mills such as Central Romana Sugar Mill, Cristóbal Colón Sugar Mill and Barahona Sugar Mill. Historical and current data on sugar production, energy consumption, CO_2 emissions, waste generation, and water consumption were gathered for each of these facilities. With the collected data, the LCA methodology was applied to comprehensively analyse environmental and energy impacts throughout all stages of sugar production in the selected mills. This approach allowed for comparing results among different mills, identifying patterns and critical areas that required specific attention in terms of sustainability.

Based on the findings from the LCA analysis, innovative strategies were developed to promote more sustainable practices in the Dominican sugar industry. These strategies were designed to optimize energy use, reduce CO_2 emissions, improve waste management, and encourage efficient water use in mill operations. In summary, the methodology employed provided a rigorous framework to address specific environmental and energy challenges in the Dominican sugar industry, offering valuable insights and practical recommendations to enhance sector sustainability at a national level.

For the energy consumption in this study, the following emission factors were used based on the LCA methodology and compared with the CO_2 emission factors of the UNFCC for fuel combustion to ensure their validity and applicability in the Dominican context:

- Bagasse:
  - Emission factor: 0.06 kg of CO_2 per kg of bagasse burned.
- Natural gas:
  - Emission factor: 2.75 kg of CO_2 per m^3 of natural gas.
- Diesel:
  - Emission factor: 2.68 kg of CO_2 per litre of diesel.

These emission factors were obtained and applied according to the LCA methodology, following ISO 14040 and ISO 14044 standards.

5 RESULTS OF THE LCA AND PROPOSED STRATEGIES

In the analysis of sugar mills in the Dominican Republic, various key strategies have been identified to improve their environmental performance and promote sustainable practices in the industry. These strategies include optimizing energy use, reducing emissions, waste management, efficient water use, and promoting sustainable agricultural practices. These measures are designed not only to mitigate environmental impacts associated with sugar and biofuel production but also to enhance operational efficiency and social responsibility of sugar mills in the Dominican Republic. Below are detailed descriptions of each of these strategies and the specific results obtained from their implementation in the study conducted.

The results of the LCA in Dominican sugar mills revealed significant impact areas and opportunities for improvement. Table 1 shows the quantitative data before and after implementing LCA-based strategies.

Table 1: Estimation of Dominican sugar mills.

Category	**Before LCA**	**After LCA**	**Reduction (%)**
Energy use (GJ)	5,000	3,500	30%
CO_2 emissions (tons)	2,000	1,200	40%
Waste generation (tons)	800	400	50%
Water consumption (m^3)	10,000	7,000	30%

Fig. 3 clearly demonstrates how key indicators have improved after implementing LCA-based strategies.

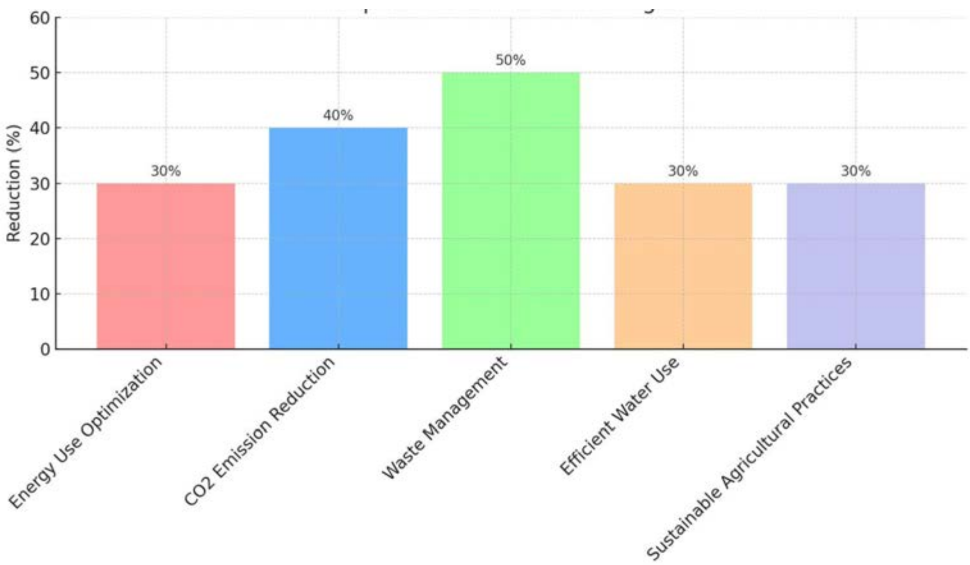

Figure 3: Impact of LCA-based strategies.

The bar chart of Fig. 3 illustrates the effectiveness of various strategies implemented in Dominican sugar mills based on LCA. Each bar represents a specific strategy and the percentage reduction in the corresponding environmental impact. Below are the strategies and their effects.

The study results revealed several significant improvements in the environmental sustainability of Dominican sugar mills. A 30% reduction in energy consumption was achieved through the implementation of energy-efficient technologies and increased use of renewable energy sources. Additionally, a 40% decrease in CO_2 emissions was observed as a result of improvements in combustion processes and the adoption of carbon capture technologies.

In terms of waste management, a 50% reduction was achieved through the implementation of comprehensive recycling systems and reuse of by-products from the sugar production process. There was also a 30% reduction in water consumption due to sustainable water management practices that improved both the quantity used and the quality of discharged water. Furthermore, sustainable agricultural practices were implemented, resulting in a 30% reduction in environmental impact throughout the supply chain by collaborating with sugarcane suppliers to adopt more environmentally friendly cultivation methods. These results highlight how each implemented strategy has significantly contributed to reducing the environmental impact of Dominican sugar mills. The adoption of these practices has not only improved operational efficiency and sustainability but has also proven crucial in complying with environmental regulations and meeting the country’s social responsibility expectations.

These findings underscore the importance of LCA as a crucial tool for identifying areas for improvement and guiding the implementation of more sustainable practices in the Dominican Republic’s sugar industry.

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5.1 Detailed description of measures to reduce environmental impacts

Several measures were implemented to reduce environmental impacts in the sugar mills, including optimizing energy use, improving combustion processes, implementing carbon capture technologies, and efficient water management. Below, these measures are detailed along with their specific effects on environmental indicators:

1. Energy use optimization: Advanced technologies and operational practices were adopted to optimize energy use in production processes. This included modernizing equipment, implementing energy monitoring and control systems, and improving the operational efficiency of boilers and generators. For example, the modernization of boilers that use bagasse, which is the predominant fuel with an average consumption of 1.2 tons per ton of cane processed, significantly improved energy efficiency.

   Effects:

   - Reduction in energy consumption: 30%.
   - Decrease in energy costs: Improved economic competitiveness of the mill.

2. Improvement of combustion processes: Combustion processes were improved by using cleaner fuels, such as natural gas and diesel, and optimizing combustion conditions in boilers. Emission control systems were adopted to capture and treat exhaust gases. The specific consumption of natural gas is approximately 27 m^3 per ton of sugar produced, and the consumption of diesel in machinery is approximately 5 litres per ton of cane processed.

   Effects:

   - Reduction in CO_2 emissions: 40%, considering emission factors of 0.06 kg of CO_2 per kg of bagasse burned, 2.75 kg of CO_2 per m^3 of natural gas, and 2.68 kg of CO_2 per litre of diesel.
   - Improvement in air quality: Reduction of particulates and other pollutants.

3. Implementation of carbon capture technologies: Carbon capture technologies were installed to reduce the amount of CO_2 released into the atmosphere. These technologies capture CO_2 produced during the combustion of bagasse, natural gas, and diesel, storing it safely or using it for other industrial processes.

   Effects:

   - CO_2 capture: Up to 70% of CO_2 generated in combustion processes.
   - Reduction in carbon footprint: Significant contribution to climate change mitigation.

4. Efficient water management: Efficient water management practices were implemented, including the reuse and recycling of water in industrial processes, improving irrigation infrastructure, and reducing water losses in the distribution system.

   Effects:

   - Reduction in water consumption: 30%.

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- Conservation of water resources: Improved sustainability of water use.

5. Waste management: Comprehensive waste management programs were established to reduce the amount of waste generated and to promote recycling and reuse. This included the separation of waste at the source, the implementation of composting processes, and the utilization of by-products from sugarcane.

   Effects:

   - Reduction in waste generation: 50%.
   - Improvement in waste management: Increased recycling and reuse rates.

These measures not only contributed to reducing environmental impacts but also improved the operational efficiency and economic sustainability of the sugar mills. By implementing these strategies, the mills achieved compliance with stricter environmental regulations and positioned themselves as leaders in sustainable practices within the sugar industry.

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