

LIFE CYCLE ANALYSIS OF BIOMASS POWER PLANTS

ANÁLISE DE CICLO DE VIDA DE USINAS DE BIOMASSA

ANÁLISIS DE CICLO DE VIDA DE CENTRALES DE BIOMASA

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ABSTRACT

Energy generation is essential for the population, not only in terms of production but also in ensuring access for everyone. To explore more sustainable energy forms, we conducted a review of existing literature on life cycle analysis in renewable energy generation, focusing specifically on biomass plants using sugarcane. The search terms employed were “renewable energy,” “life cycle analysis,” and “biomass.” The study limited searches to articles in English and Portuguese published within the past 20 years. Not all results pertained directly to energy generation; some addressed life cycle analysis from a laboratory perspective, while others analyzed life cycle analysis in renewable energy generation more broadly, without a specific focus on sugarcane. The articles most relevant to our research objectives were summarized and will form the foundation for continuing this study, with an emphasis on life cycle analysis in the energy generation process using sugarcane biomass. There is a gap in the literature regarding standardized methods, system boundaries, and impact categories for the assessment of sugarcane-based bioenergy systems, revealing that researchers have not prioritized harmonizing life cycle analysis approaches by integrating social and economic indicators alongside environmental metrics, nor have they considered regional variations in agricultural practices and energy conversion technologies.

Keywords: Sugarcane Bagasse. Bioenergy. Renewable Electricity. Cradle-To-Grave Assessment.

RESUMO

A geração de energia é essencial para a população, não apenas em termos de produção, mas também em garantir o acesso para todos. Para explorar formas de energia mais sustentáveis, foi realizada uma revisão da literatura existente sobre análise do ciclo de vida na geração de energia renovável, com foco específico em usinas de biomassa utilizando cana-de-açúcar. Os termos de busca empregados foram “energia renovável”, “análise do ciclo de vida” e “biomassa”. O estudo limitou-se a artigos em inglês e português publicados nos últimos 20 anos. Nem todos os resultados se referiam diretamente à geração de energia; alguns abordaram a análise do ciclo de

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vida a partir de uma perspectiva laboratorial, enquanto outros analisaram a análise do ciclo de vida na geração de energia renovável de forma mais ampla, sem um foco específico na cana-de-açúcar. Os artigos mais relevantes para nossos objetivos de pesquisa foram resumidos e formarão a base para a continuação deste estudo, com ênfase na análise do ciclo de vida no processo de geração de energia usando biomassa de cana-de-açúcar. Existe uma lacuna na literatura em relação a métodos padronizados, limites do sistema e categorias de impacto para a avaliação de sistemas de bioenergia baseados na cana-de-açúcar. Essa lacuna revela que os pesquisadores não priorizaram a harmonização das abordagens de análise do ciclo de vida, integrando indicadores socioeconômicos às métricas ambientais, nem consideraram as variações regionais nas práticas agrícolas e nas tecnologias de conversão de energia

Palavras-chave: Bagaço de Cana-de-Açúcar. Bioenergia. Eletricidade Renovável. Avaliação do Berço ao Túmulo.

RESUMEN

La generación de energía es esencial para la población, no solo en términos de producción, sino también para garantizar el acceso universal. Con el fin de explorar formas de energía más sostenibles, se realizó una revisión de la literatura existente sobre el análisis de ciclo de vida (ACV) en la generación de energía renovable, centrándose específicamente en las plantas de energía de biomasa a partir de caña de azúcar. Los términos de búsqueda utilizados fueron "energía renovable", "análisis de ciclo de vida" y "biomasa". El estudio se limitó a artículos en inglés y portugués publicados en los últimos 20 años. No todos los resultados abordaban directamente la generación de energía; algunos trataban el ACV desde una perspectiva de laboratorio, mientras que otros analizaban el ACV en la generación de energía renovable de manera más amplia, sin un enfoque específico en la caña de azúcar. Se resumieron los artículos más relevantes para los objetivos de nuestra investigación, los cuales servirán de base para la continuación de este estudio, haciendo hincapié en el ACV dentro del proceso de generación de energía mediante biomasa de caña de azúcar. Existe una brecha en la literatura respecto a los métodos estandarizados, los límites del sistema y las categorías de impacto para la evaluación de sistemas de bioenergía basados en la caña de azúcar. Esta brecha revela que los investigadores no han priorizado la armonización de los enfoques de ACV —integrando indicadores socioeconómicos con métricas ambientales— ni han considerado las variaciones regionales en las prácticas agrícolas y las tecnologías de conversión energética.

Palabras clave: Bagazo de Caña de Azúcar. Bioenergía. Electricidad Renovable. Evaluación de la Cuna a la Tumba.



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INTRODUCTION

Since ancient times, energy has been a cornerstone of human progress throughout history.

From the earliest reliance on manual and animal labor to the discovery of fire and, later, the industrial revolution powered by coal, humanity's approach to energy production has constantly evolved. Today, this evolution continues as nations transition toward more sustainable and renewable energy systems.

A notable feature of the Brazilian energy matrix is its historically high percentage of renewable energy. In 1970, renewable sources accounted for over 58% of the matrix, predominantly due to the use of firewood. However, with the introduction of more efficient energy sources, this share decreased to 44.5% by 2005. From 2005 to 2030, there is a clear trend reversal, with the share of renewable energy rising to 46.5% by 2030. This increase is largely attributed to the integration of biomass, biodiesel, and the H-bio process into Brazil's array of energy options, with the latter two being introduced in 2010. With the incorporation of these alternative sources, the Brazilian energy matrix is expected to maintain a strong renewable presence, reaching 46.6% by 2030, in contrast to 44.5% in 2005. This positions Brazil favorably in terms of particulate emissions from fuel burning, especially compared to the energy matrices of wealthier nations, which average only 6% renewables, and the global average of 16% (EPE, 2007).

In seeking to provide energy to the population more sustainably, research into renewable sources with lower environmental impacts has been prioritized. As previously discussed, Brazil's energy matrix includes a substantial proportion of renewable sources, positioning the country advantageously. Renewable energy is increasingly important, as evidenced by the growing use of biomass.

An examination of biomass' role in the Brazilian energy matrix reveals that sugarcane comprises 18% of it, as noted by an EPE publication. This raises several questions for the life cycle analysis (LCA) of a biomass plant: How should the cycle be evaluated? What gases are emitted? This article aims to analyze existing studies on energy generation using sugarcane derivatives to foster a deeper understanding of the subject.

THEORETICAL FRAMEWORK

Energy Matrix

Worldwide, fossil fuels such as coal, petroleum, and natural gas continue to dominate the energy landscape. Brazil, however, presents a contrasting model, with renewables accounting for nearly half of its energy production. According to data from the Energy Research Company (EPE, 2021), renewable sources, including hydropower, biomass from sugarcane, firewood, and other renewables, constitute approximately 46.2% of total national consumption.

While hydropower remains the main renewable contributor, biomass plays a crucial and expanding role, supplying over 8% of the national total (Biomassa BR, 2016). By 2013, Brazil had an installed biomass capacity of roughly 11,250 MW, equivalent to the projected generation capacity of the Belo Monte Dam. This capacity is distributed among nearly 500 plants, primarily utilizing sugarcane bagasse and straw (Biomassa BR, 2016).

Biomass Plants

Biomass encompasses all organic matter within the biosphere, originating from both plant and animal sources, as well as materials obtained through natural or artificial transformations. Biofuels derived from biomass include firewood, wood chips, pellets, certain fruit stones such as olives and avocados, and nut shells. Among these, chopped firewood is the least processed and is typically burned directly in domestic appliances like stoves and boilers. Chips are produced by grinding agricultural and forestry biomass, with their size varying based on the manufacturing or transformation processes they undergo. Lastly, pellets are the most refined biofuel, consisting of small cylinders measuring 6–12 mm in diameter and 10–30 mm in length, created by pressing biofuels with binders.

Biomass refers to all organic matter derived from biological sources, including agricultural residues, forestry by-products, and industrial waste. Firewood, wood chips, pellets, and agricultural residues such as fruit pits and shells are among the most common solid biofuels. Although often underutilized, these residues have shown high energy potential and can significantly contribute to heat and power generation while reducing CO₂ emissions (Perea-Moreno *et al.*, 2019).

Biomass can be converted into thermal energy, liquid, solid, or gaseous fuels, and other chemical products through a range of conversion processes. Biopower technologies are proven options for electricity generation in the United States, with 10 GW of installed capacity. All current capacity is based on mature direct combustion technology. Future efficiency improvements will include the firing of biomass in existing coal-fired boilers and the introduction of high-efficiency gasification, combined cycle systems, fuel cell systems, and modular systems. Predominant bioenergy technologies generally comprise direct combustion, co-firing, gasification, pyrolysis, anaerobic digestion, and fermentation (Khan *et al.*, 2015).

Numerous technologies exist for converting biomass into electricity, all of which transform the raw material into an intermediate product used in a driving machine to generate mechanical energy, subsequently powering the electricity generator. The two main technologies are combustion and gasification. Combustion involves the direct burning of biomass in boilers at high temperatures with ample oxygen, producing high-pressure steam used to drive electric generator turbines. This is one of the most prevalent forms of biomass energy utilization, with an energy efficiency varying by 20–25%. Gasification, meanwhile, is the process of heating biomass in the absence of oxygen, resulting in a flammable gas as the end product. This gas can be filtered to remove some residual chemical components.

Gasification does not require high temperatures, resulting in biogas, which can either be used as mechanical energy to activate a generator or be utilized in boilers for direct burning and cogeneration of thermal energy. In Brazil, biomass is the third-largest source of energy generation, according to data from the Brazilian Ministry of Mines and Energy, following hydropower and the burning of natural gas in the electricity matrix, underscoring the importance of this energy source (CBIE, 2019).

Life Cycle Analysis of Biomass Power Plants

The reduction of fossil fuel dependence in the energy sector is central to achieving sustainability goals. Life cycle assessment (LCA) provides a framework for evaluating the environmental consequences of different energy scenarios. Tonini & Astrup (2012) investigated future Danish energy systems dominated by wind and biomass and found that greenhouse gas (GHG) emissions per unit of energy could be cut by more than half. Nevertheless, they also highlighted that biofuel cultivation can introduce. Overall, the results indicated that GHG

emissions per PJ of energy supplied could be more than halved by increasing the use of wind and residual biomass resources, as well as by electrifying the transportation sector. Energy crops for biofuel production and the use of these biofuels for heavy land transport were responsible for most of the environmental impacts in the 2050 scenarios.

Notably, the upstream impacts of changes in land use, fertilizer use, and nitrogen oxide emissions from the transport sector were critical. Land take, including land use change effects, caused by energy crop production, increased to a range of 600–2100 x 106m²/PJ depending on the quantities and types of energy crops introduced. The use of fossil diesel in the transport sector appeared to be environmentally preferable to biodiesel in terms of acidification, aquatic eutrophication, and land occupation. However, for global warming, biodiesel production via Fischer-Tropsch was comparable to fossil diesel (Tonini & Astrup, 2012).

Zulkipli *et al.* (2022) broadened this perspective by integrating LCA into the context of the circular economy. Their study assessed various biomass conversion pathways—including pyrolysis, gasification, hydrothermal processing, and anaerobic digestion—and emphasized that sustainability outcomes vary depending on feedstock characteristics and conversion technologies.

Silva *et al.* (2005) reported that Brazil's experience with biomass-based power generation is well established in the sugar–ethanol industry, where the process has proven technically, operationally, and economically viable. The authors recommend expanding operational initiatives involving forest biomass in the Northern region, particularly within isolated electrical systems and hydroelectric reservoir areas, to enable the use of the substantial forest resources expected to become available in the coming years. For sugarcane bagasse, where operational maturity is already higher, they emphasize the need for institutional, technical, and financial support from the federal government to facilitate the implementation of a cogeneration program within the sugar-ethanol sector.

This study offers a global and cross-sectoral analysis of LCA applications in major biomass conversion routes (pyrolysis, gasification, anaerobic digestion, hydrothermal processes, and direct combustion), highlighting methodological challenges and research gaps. The findings contribute to advancing sustainable biomass energy systems within a circular and low-carbon economy (Zulkipli *et al.*, 2022)

Bioenergy systems have significant potential worldwide to replace fossil fuels, mainly because they can help reduce GHG emissions. In Portugal, several biomass combustion-based

energy plants have been built in the past decade. Biomass gasification is a potential alternative to combustion, but its environmental impact must be assessed.

Given the above, this study aimed to evaluate and compare the environmental and energy performance of direct gasification and combustion (both conducted in a fluidized bed) using residual eucalyptus forest biomass in Portugal. To achieve this goal, LCA was applied, complemented with the Energy-Returned-On-Energy-Invested indicator. The environmental performance of gasification and combustion was assessed using LCA according to ISO standards 14040 and 14044 (ISO, 2006a, 2006b) and the SimaPro software (Briones-Hidrovo *et al.*, 2021).

In Burmester (2023), the life cycle analysis of the analyzed biomass plant presents the major impacts related to the occupation of agricultural land and climate change, which, in the case of biomass plants, depending on the use, such as biodiesel production, for example, uses large plantations like sugarcane.

METHODOLOGY

A systematic review was adopted as the methodology, providing a structured approach to conducting literature reviews, allowing evaluation and interpretation of all relevant works available on a given subject. Systematic reviews aim to present a fair assessment of a research topic, offering greater theoretical foundation and scientific reliability (Kitchenham, 2004). To establish a search parameter, the following databases were consulted: ResearchGate, ScienceDirect and ABEC Brasil, with publications from the last twenty years. The search terms used were: “renewable energy,” “biomass,” “life cycle analysis,” and “sugarcane,” in both English and Portuguese. In an initial screening, fifty-nine articles were selected, including four dissertations, two theses, and one undergraduate thesis. Thirty-eight articles addressed other energy sources in life cycle analysis, leaving fourteen for further review.

RESULT AND DISCUSSION

Table 1 shows the relevant papers found according to the search criteria.

Table 1*The relevant papers found in the database search*

Reference	Article title	Journal name	Use of sugarcane	Database
Contreras <i>et al.</i> (2009)	Comparative life cycle assessment of four alternatives for using by-products of cane sugar production	Journal of Cleaner Production	Yes	ScienceDirect
Nguyen & Hermansen (2012)	System expansion for handling co-products in LCA of sugarcane bio-energy systems: GHG consequences of using molasses for ethanol production	Applied energy	Yes	ScienceDirect
Moya <i>et al.</i> (2013)	Exergetic analysis in cane sugar production in combination with life cycle assessment	Journal of Cleaner Production	Yes	ScienceDirect
Caldeira-Pires <i>et al.</i> (2018)	Implications of removing straw from soil for bioenergy: An LCA of ethanol production using total sugarcane biomass	Journal of Cleaner Production	Yes	ScienceDirect
Chary <i>et al.</i> (2018)	Growing biomass locally or importing it? LCA of biomass provision scenarios for cleaner electricity production in a small tropical island	Biomass and Bioenergy	Yes	ScienceDirect
Siregar <i>et al.</i> (2020)	Life cycle impact assessment on electricity production from biomass power plant system through life cycle assessment (LCA) method using biomass from palm oil mill in Indonesia	E3S Web of Conferences	No	ResearchGate
Mohammadi <i>et al.</i> (2020)	Life cycle assessment (LCA) of the energetic use of bagasse in Iranian sugar industry	Renewable Energy	Yes	ScienceDirect
Barjoveanu <i>et al.</i> (2020)	Life cycle assessment of polyphenols extraction processes from waste biomass	Scientific Reports	No	ResearchGate
Yu <i>et al.</i> (2022)	Review in life cycle assessment of biomass conversion through pyrolysis-issues and recommendations	Green Chemical Engineering	No	ScienceDirect
Arfelli <i>et al.</i> (2024)	Life Cycle Assessment of a Wood Biomass Gasification Plant and Implications for Syngas and Biochar Utilization	Energies	No	ScienceDirect
Ahmed <i>et al.</i> (2024)	Life cycle assessment and techno-economic analysis of sustainable bioenergy production: a review	Environmental Chemistry Letters	Yes	ScienceDirect
Patel & Singh (2024)	Environmental sustainability analysis of biofuels: a critical review of LCA studies	Clean Technologies and Environmental Policy	Yes	ScienceDirect
Yasmin <i>et al.</i> (2024)	A review on waste biomass-to-energy: integrated thermochemical and biochemical conversion for resource recovery	Environmental Science Advances	No	ScienceDirect
Deitos <i>et al.</i> (2024)	Sustentabilidade e Inovação em energias verdes: Biomassa como alternative energética renovável	Revista de Gestão Social e Ambiental	Yes	ABEC Brasil

Contreras *et al.* (2009) conducted an LCA of four alternative strategies for managing sugarcane by-products and waste at a Cuban mill, seeking to identify key environmental impacts and propose system improvements. The scenarios included conventional sugar production, substituting synthetic fertilizers with effluent and residues, generating biogas from filter cake and wastewater, and integrating alcohol and biogas production. The analysis showed that land use, fuel consumption, and agrochemical inputs during the agricultural phase were the most significant contributors to impacts, while bagasse-based cogeneration in the industrial phase was linked to respiratory effects due to particulate emissions. Comparative assessment indicated that valorizing by-products via alcohol, biogas, animal feed, and fertilizer production offers clear advantages, particularly in terms of resource savings, highlighting the potential for integrated approaches to enhance the sustainability of sugarcane systems. The LCA was performed according to ISO 14040 standards using SimaPro 6.0 software, the Ecoinvent database, and the Eco-indicator 99 method.

Nguyen and Hermansen (2012) developed a methodological framework for addressing by-products in the LCA of sugarcane systems, focusing on ethanol derived from molasses. The study compared system expansion and allocation procedures for estimating GHG emissions, finding that system expansion produced the highest emissions values but was also the most appropriate approach for decision-making contexts. In all methods, ethanol exhibited lower life cycle GHG emissions than gasoline, primarily due to reductions during the fuel phase in bioenergy substitution scenarios. However, sensitivity analyses showed that incorporating indirect land use change, especially deforestation resulting from diverting molasses from feed to fuel, could significantly worsen ethanol's GHG balance, potentially converting it from a carbon-saving to a carbon-emitting fuel.

Caldeira-Pires *et al.* (2018) demonstrated that changes in biotic parameters associated with land use are critical for evaluating the GHG balance of bioenergy systems. This LCA examined the use of sugarcane straw and bagasse for bioethanol production at a Petrobras facility, focusing on global warming potential (GWP). Two scenarios were assessed: (1) straw left in the field (RS) and (2) straw used for energy (SS). The results showed that straw use for energy increased GWP by 161%, shifting biotic emissions from soil to boilers, but reduced fossil GWP by 39% and improved overall system efficiency. Sensitivity analyses revealed that both sugar content variation ($\pm 10\%$) and second-generation (2G) ethanol production significantly influenced

GWP. Overall, integrating straw use enhances environmental performance when optimized for combined ethanol and electricity production.

Chary *et al.* (2018) investigated biomass as a renewable energy option for small islands reliant on imported fossil fuels, focusing on Guadeloupe. Using LCA, they compared electricity generation from locally grown energy cane and imported wood pellets. Energy cane reduced several environmental burdens by nearly 30% compared to pellets, though cultivation impacts varied across regions. Substituting a small share of fossil energy with biomass lowered global warming potential but required significantly more land, leading the authors to recommend a hybrid strategy combining local crops with imported biomass.

Moya *et al.* (2018) highlighted the importance of comprehensive life cycle assessment in evaluating the environmental sustainability of sugarcane production. By integrating exergetic analysis with conventional LCA, the study quantified cumulative exergy consumption across different by-product valorization alternatives. This combined approach provided a clearer assessment of resource use and efficiency, confirming the environmental benefits of converting sugarcane by-products into alcohol, biogas, feed, and fertilizer. In this study, exergetic life cycle assessment was integrated with a conventional LCA process of sugarcane production developed by Contreras *et al.* (2009) applied LCA to four alternatives for valorizing sugarcane by-products, incorporating exergetic analysis to quantify cumulative exergy consumption across process stages. This integrative approach clarified aspects of resource use, renewability, and sustainability, highlighting the agricultural phase as the dominant contributor to overall impacts. The findings confirmed that valorizing by-products via alcohol, biogas, feed, and fertilizer offers significant environmental advantages, underscoring the value of integrated strategies to enhance resource efficiency in sugarcane production.

The work published by Siregar *et al.* (2020) does not specifically address the use of sugarcane in biomass energy generation, but the study includes a comprehensive LCA from “cradle-to-grave,” encompassing the acquisition of materials and land preparation to electricity production through a biomass plant system, distribution to consumers, and end-of-life considerations. The impact analysis focuses on GHG emissions, employing the LCA method.

The data used in the life cycle inventory pertains to the province of Aceh in Indonesia, with the functional unit (FU) defined as 1 kWh. Life cycle inventory analysis was based on data from oil palm plantations in Aceh Province, including transportation from seedlings to plantation

areas and from plantations to palm oil mills. The assumed distribution distance from the biomass plant system to the end user is 2 km.

Barjoveanu *et al.* (2020) investigated the use of biomass residues from forestry and wood processing industries as feedstock for fine chemicals, situating their utilization within a circular economy framework and addressing associated secondary environmental impacts. The study assessed the environmental performance of laboratory-scale processes for extracting polyphenols from spruce bark using LCA, and explored scale-up scenarios for the most promising alternative. Three extraction methods were compared: Soxhlet extraction with ethanol, alkaline extraction in NaOH solution, and ultrasound-assisted extraction. The functional unit was defined as 1 mg of polyphenols extracted (mg GAE/g spruce bark). The results indicated that electricity consumption for heating was the primary contributor to environmental impacts, followed by ethanol production and use. Scale-up modeling for the ultrasound-assisted process suggested that increasing the vessel capacity to 30 L and substituting the heating source with a biomass boiler could substantially reduce impacts. Sensitivity analysis confirmed that variations in laboratory equipment energy efficiency introduced acceptable levels of uncertainty into the LCA outcomes.

The article presented by Mohammadi *et al.* (2020) provided an overview of sugar production from sugarcane and examined the life cycle impacts from cradle to gate of energy generation from bagasse and sugarcane straw, considering combustion, gasification, and anaerobic digestion. The analysis showed that combustion presented the most promising indicators.

Yu *et al.* (2022) reported that biomass, a widely available and carbon-neutral energy source, has strong potential for electricity generation and for replacing fossil fuels. Pyrolysis is the primary method for converting biomass into bioenergy products; however, it involves significant resource consumption and generates notable environmental impacts. To assess these impacts, LCA is applied. Nevertheless, the use of different LCA methods can lead to significant variations in results. The study showed the methodological approaches used in the LCA of biomass conversion systems, providing recommendations for each of the four stages of the process: goal and scope definition, inventory analysis, impact assessment, and interpretation. Furthermore, the results also emphasized the global warming potential, considering different types of biomass such as agricultural residues, forest biomass, and microalgae. Lastly, the authors presented the current challenges and future perspectives for applying LCA to biomass conversion.

Arfelli *et al.* (2024) applied LCA to evaluate a wood biomass gasification system that generates electricity and heat from syngas and manages biochar. The study compared waste-derived biomass with dedicated energy crops, finding environmental benefits for both but a distinct advantage for waste-based feedstock. For climate change impacts, dedicated crops were comparable only when transport distances were below 600 km, while biochar composition raised toxicity concerns. Overall, the research affirmed LCA's value for evaluating bioenergy systems and informing sustainable decision-making.

Ahmed *et al.* (2024) scrutinized the global expansion of bioenergy, highlighting the need for sustainable management and comprehensive evaluation beyond greenhouse gas emissions and energy balance. The authors examined the LCA, chemical processes, and policy frameworks related to bioenergy production, covering key LCA aspects, including methods, environmental impacts, GHG emissions, land and water use, and techno-economic analysis, alongside the chemistry of conversion processes and efficiency improvements. Policy tools promoting sustainable energy are also discussed. Reported carbon dioxide removal of 45–99% across different bioenergy systems. Overall, the study underscores the role of chemistry and standardized LCA in advancing sustainable and secure bioenergy development.

Patel *et al.* (2023) the increasing use of fossil fuels in transportation has intensified greenhouse gas (GHG) emissions, driving interest in biofuels as a lower-carbon alternative. This review examines 53 peer-reviewed studies published between 2012 and 2022, covering over 25 biofuel feedstocks through Life Cycle Assessment (LCA). Results indicate that second-generation biofuels exhibit greater GHG reduction potential than first-generation ones, whereas third-generation biofuels can emit 10.2–1910 g CO₂ eq./MJ, surpassing fossil fuels in some cases. Net energy ratios range from 1.23–12.49, 0.003–15.04, and 3–18.5 for first-, second-, and third-generation biofuels, respectively. The water footprint of biofuels is 50–240 times higher than that of fossil fuels. Methodological uncertainties and variability across LCA studies are also discussed. Overall, the study emphasizes the need for comprehensive, methodologically consistent LCA approaches to ensure the sustainable development of biofuels.

Yasmin *et al.* (2024) in their review analyses that enhancing energy security and reducing greenhouse gas emissions require the use of renewable resources such as biomass. Their review examines recent advances and future perspectives on integrating thermochemical and biochemical conversion processes for producing biofuels and value-added chemicals. While biochemical methods face challenges of long processing times and low yields, thermochemical

routes demand high energy input and cost. Their integration promotes circular economy principles and more efficient resource utilization. The study provides a techno-economic assessment of major conversion pathways, identifying pyrolysis and hybrid systems as the most promising options. Life Cycle Assessment (LCA) is highlighted as a key tool for evaluating environmental and economic trade-offs among waste-to-energy technologies. Further research on feedstock pretreatment, catalyst design, and process optimization is essential to improve biofuel productivity and sustainability.

Deitos *et al.* (2024) in an integrative literature review, conducted between 2020 and 2023 in scientific databases such as SciELO, Web of Science, and Google Scholar, analyzed the role of this source in the Brazilian energy matrix. The results indicate that the energy use of MSW brings relevant environmental, sanitary, and social benefits. However, its potential is not sufficient to sustain the expansion of the country's electricity supply in the long term. In this scenario, public policies such as the National Solid Waste Policy (PNRS) and the Incentive Program for Alternative Sources of Electrical Energy (PROINFA) are fundamental. Even so, the lack of clarity in the integration of these initiatives and the absence of specific funding limit the replication of projects. Another challenge lies in the division of responsibilities: while waste management is municipal, energy planning is federal. This fragmentation makes it difficult to create unified guidelines and compromises the efficiency of actions. In short, biomass from municipal solid waste (MSW) represents a promising alternative for environmental and social gains. However, for it to become a more relevant component in the Brazilian energy matrix, it is essential to strengthen institutional and regulatory coordination, ensuring that the benefits of this source are fully utilized.

CONCLUSION

This review demonstrates that, despite the recognized potential of sugarcane biomass, comprehensive applications of life cycle analysis to its energy generation remain scarce. Of the more than fifty publications initially screened, only fourteen met the criteria for substantial relevance, and even among these, few addressed the environmental, economic, and social dimensions in an integrated manner.

The findings reveal a significant gap in the literature regarding standardized methodologies, system boundaries, and impact categories for sugarcane-based bioenergy

systems. This lack of harmonization limits comparability across studies and weakens the foundation for evidence-based policymaking. Furthermore, regional variations in agricultural practices and energy conversion technologies remain underexplored, underscoring the need for context-specific approaches.

While energy recovery from municipal solid waste in Brazil offers environmental and social benefits, it is insufficient to sustain long-term electricity expansion. In contrast, biomass from sugarcane presents a viable substitute for fossil fuels, with life cycle analysis serving as a critical tool to quantify CO₂ emissions and broader sustainability impacts.

Future research should prioritize the development of standardized frameworks that integrate environmental, economic, and social indicators, while also accounting for regional agricultural and technological contexts. Such efforts will not only advance academic knowledge but also provide actionable insights for policymakers, industry stakeholders, and urban planners seeking resilient and sustainable energy solutions.

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