

Review

Analysis of the Sugarcane Biomass Use to Produce Green Hydrogen: Brazilian Case Study

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Abstract: Conventional hydrogen production processes, which often involve fossil raw materials, emit significant amounts of carbon dioxide into the atmosphere. This study critically evaluates the feasibility of using sugarcane biomass as an energy source to produce green hydrogen. In the 2023/2024 harvest, Brazil, the world's largest sugarcane producer, processed approximately 713.2 million metric tons of sugarcane. This yielded 45.68 million metric tons of sugar and 29.69 billion liters of first-generation ethanol, equivalent to approximately 0.0416 liters of ethanol per kilogram of sugarcane. A systematic literature review was conducted using Scopus and Clarivate Analytics Web of Science, resulting in the assessment of 335 articles. The study has identified seven potential biohydrogen production methods, including two direct approaches from second-generation ethanol and five from integrated bioenergy systems. Experimental data indicate that second-generation ethanol can yield 594 MJ per metric ton of biomass, with additional energy recovery from lignin combustion (1705 MJ per metric ton). Moreover, advances in electrocatalytic reforming and plasma-driven hydrogen production have demonstrated high conversion efficiencies, addressing key technical barriers. The results highlight Brazil's strategic potential to integrate biohydrogen production within its existing bioenergy infrastructure. By leveraging sugarcane biomass for green hydrogen, the country can contribute significantly to the global transition to sustainable energy while enhancing its energy security.

Keywords: biohydrogen production; lignocellulosic feedstock; sustainable biofuels; renewable energies; Brazilian energy transition



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1. Introduction

One of the biggest challenges today is developing clean fuels and alternative energy sources, given the rising global energy demand and pressure to control pollutant emissions, particularly those contributing to global warming [1–4]. Hydrogen has gained significant attention as a versatile and clean energy carrier, offering potential solutions for reducing carbon emissions in various sectors. In this context, recent studies have shown that the adoption of modern technologies—such as monitoring, optimization, and automation—not only enhances energy efficiency but also plays a crucial role in promoting sustainable development [5,6].

Hydrogen production through conventional methods, which typically rely on fossil raw materials, is among the largest sources of carbon dioxide (CO₂) emissions. Hydrogen production can occur from gaseous or liquid fuels. Such methods differ according to the nature of the primary fuel used (water, ammonia, ethanol, gaseous or liquid hydrocarbons or methanol) and the chemical reaction involved (e.g., decomposition, electrolysis, gasification, steam reform or partial oxidation). Therefore, it is crucial to explore alternative and sustainable hydrogen production methods, such as utilizing sugarcane biomass, to reduce carbon emissions and foster environmental sustainability.

In recent years, biorefinery has become a viable alternative to petrorefinery, as biofuels hold significant potential to replace fossil fuels and contribute to the sustainable development of society [7]. Lignocellulosic biomasses, which include sugarcane, are among the most abundant and ubiquitous raw materials on Earth and represent a promising source to produce biofuels like bioethanol, biohydrogen, and biogas [7]. However, the recalcitrance of biomass to enzymatic hydrolysis remains a significant challenge, as the cellulose, hemicellulose, and lignin components are intricately bound together, making their separation a complex and energy-intensive process [7]. Lignocellulosic biomasses typically contain 40–50% cellulose, 20–30% hemicellulose, and 20–30% lignin, in addition to other minor components such as ash and extractives, which further complicates the conversion process [8].

Hydrogen, the most abundant element in nature, has long been recognized as a promising biofuel due to its clean and high-energy properties, offering a sustainable alternative to fossil fuels [3,4,9]. Renewable energy sources, such as bioethanol, biodiesel, and bio-oil, are being increasingly explored as environmentally friendly replacements for fossil fuels [10]. Among these, biohydrogen stands out for its potential to contribute to a low-carbon economy, with its production being vital for the global transition to sustainable energy systems [10].

Biomass can be transformed into fuels and chemicals of high added value using thermochemical and biochemical conversion techniques [11]. It is economically and geographically abundant and can serve as an important resource for generating alternative transport fuels, electricity, heat, and valuable chemicals [12]. Carbon neutrality and low levels of SO_x and NO_x emissions are some of the other merits of using biomass as an alternative energy source [13]. In summary, biomass stands out as a versatile and sustainable energy source with significant environmental and economic benefits, making it a promising alternative for reducing dependence on fossil fuels.

Given the urgent need for carbon-neutral hydrogen production, this study aims to explore how Brazil's sugarcane industry can contribute to large-scale biohydrogen generation. By leveraging its vast sugarcane biomass resources, the country has the potential to integrate sustainable hydrogen production into its existing bioenergy infrastructure.

Although bioethanol, biomethane, and other biofuels are considered renewable—since the carbon they release during combustion was previously absorbed by the biomass during its growth, their use is not entirely environmentally neutral. The CO₂ emitted still contributes to atmospheric concentrations, even if it is part of a short-term carbon cycle rather than releasing long-stored fossil carbon. This underscores the need to convert ethanol (C₂H₆O) into a fuel whose complete combustion is truly green, meaning it results in no pollutant emissions.

In this study, data were collected through a comprehensive analysis and synthesis of technical-scientific articles and reports from relevant funding agencies to ensure a thorough understanding of the challenges and opportunities in green hydrogen production. The data used in this analysis were obtained from the Scopus and Clarivate Analytics Web of Science, focusing on publications from 2019 to 2023 written in English. The choice of this time frame

was based on the significant growth in research and development related to green hydrogen during this period, driven by increasing global interest in sustainable energy solutions and advancements in hydrogen production technologies. The search included articles related to the following keywords: green hydrogen, biohydrogen, renewable hydrogen, sustainable hydrogen, sugarcane biomass, and lignocellulosic biomass.

A total of 131 articles were retrieved from Scopus and 307 from Clarivate Analytics WoS. After removing duplicates, 335 unique articles remained for analysis. The exclusion criteria included articles published outside the 2019–2023 period, documents not written in English, publications not directly related to the specified keywords, and non-peer-reviewed articles or non-scientific documents such as conference abstracts and book chapters. The R programming language was used to analyze and integrate data from both databases, facilitating the bibliometric analysis of relevant articles.

To ground the research in a practical context, sugarcane production was chosen as a case study, focusing specifically on Brazil's 2023/2024 harvest, with data sourced from the 4th survey by the National Supply Company (Conab) conducted in April 2024. Additionally, projections for ethanol production were assessed through the national agricultural sector's statistical database, managed jointly by the Organization for Economic Cooperation and Development (OECD) and the United Nations Food and Agriculture Organization (FAO). This methodological approach provides a foundation for exploring the potential of sugarcane biomass within a sustainable framework and identifies viable pathways for reducing carbon emissions associated with hydrogen production.

Figure 1 illustrates a comparison of total and per capita sugarcane biomass production among the world's leading producers in 2023, using data from the World Bank and FAO. This visual comparison highlights Brazil's dominance in the field, supporting the selection of the country as the focal point of this study.

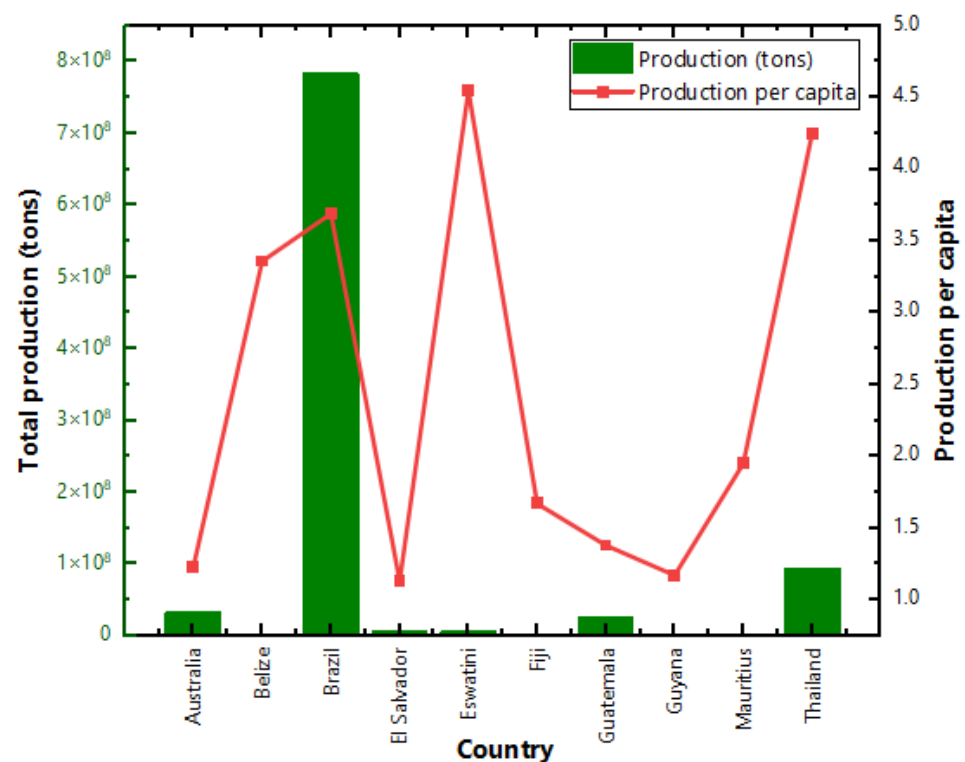


Figure 1. Comparison of total and per capita sugarcane biomass production among leading producers (2023). Data were sourced from the World Bank and FAO.

Brazil was selected as the case study due to its unparalleled leadership in sugarcane production and ethanol output, as well as its significant role in the global renewable energy landscape. With its extensive sugarcane industry and advanced bioenergy infrastructure, Brazil provides an ideal context for exploring the potential of sugarcane biomass in green hydrogen production.

Recent studies explored various innovative strategies to enhance the flexibility of green hydrogen production. One proposal involves the development of electrolysis ships capable of traveling to regions with the lowest renewable energy costs worldwide. This mobility would enable the use of affordable electricity for on-site green hydrogen production [14]. Another concept, known as the Hydrogen Deep Ocean Link, was proposed to address challenges such as hydrogen compression, long-term storage, intercontinental transportation, and transit between islands, aiming to reduce associated costs [15]. These innovative approaches highlight the potential for overcoming key logistical and economic challenges in green hydrogen production, paving the way for more cost-effective and globally accessible solutions.

This study seeks to address the following research questions: (i) What are the main opportunities and challenges associated with the production of green hydrogen from sugarcane biomass in Brazil? (ii) How can emerging technologies be adapted and optimized to facilitate a sustainable energy transition using lignocellulosic resources? (iii) What are the potential environmental and economic benefits of this approach in the Brazilian context? The key contributions of this review include: (1) a detailed bibliometric analysis of the recent literature on green hydrogen production, focusing on global and regional trends; (2) an evaluation of Brazil's energy matrix in 2023, emphasizing the role of sugarcane biomass as a strategic resource; (3) the identification of innovative strategies to address technological and logistical barriers in biohydrogen production; and (4) an exploration of pathways to integrate green hydrogen technologies within a sustainable biorefinery framework. These contributions provide a strong foundation for advancing research and policy initiatives, supporting the global transition to renewable energy systems.

The structure of the remainder of this article is organized into distinct sections. Section 2 provides a bibliometric analysis of relevant publications, focusing on the role of sugarcane biomass in green hydrogen production. Section 3 offers an overview of Brazil's energy supply and electricity mix in 2023. Section 4 provides an overview of sugarcane production in Brazil. Section 5 discusses environmental impacts and sustainable solutions. Section 6 presents the discussion, analyzing implications for energy policy, technological challenges, infrastructure needs, and economic considerations. Section 7 suggests new avenues for future research. Finally, Section 8 concludes by summarizing key insights, addressing study limitations, and suggesting future research directions for Brazil's energy sector.

2. The Role of Sugarcane Biomass in Green Hydrogen Production: A Bibliometric Analysis of Relevant Publications

The distribution of publications across the top 10 countries provides valuable insights into regional research trends and contributions to biohydrogen production, as illustrated in Figure 2. This analysis highlights the growing global emphasis on biohydrogen research and underscores the efforts of leading nations in advancing technologies in this field. The articles analyzed, sourced from the Scopus and Clarivate Analytics WoS, were published between 2019 and 2023 and written in English, focusing on key terms such as green hydrogen, biohydrogen, renewable hydrogen, sustainable hydrogen, sugarcane biomass, and lignocellulosic biomass.

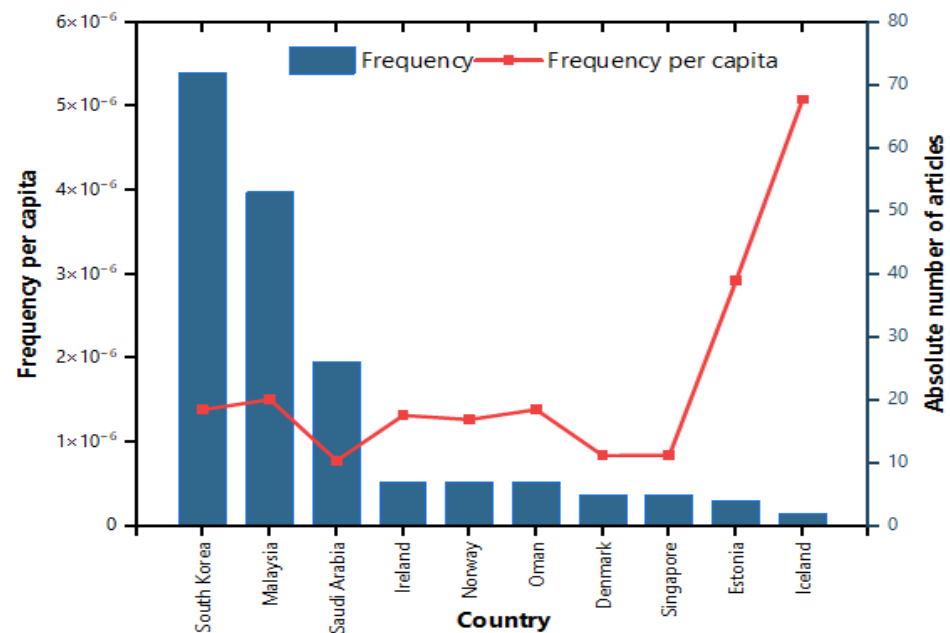


Figure 2. Top 10 countries: Article frequency and per capita proportion analysis. Data were sourced from the World Bank.

The figure shows the distribution of research publications on biohydrogen production among the top 10 countries ranked by publication frequency per capita between 2019 and 2023. South Korea, Malaysia, and Saudi Arabia are the leading contributors in terms of total publication numbers, with South Korea showing the highest frequency. This reflects a strong emphasis by these countries on advancing biohydrogen technologies, likely driven by their strategic energy policies and investment in renewable energy research.

When considering publications per capita, Iceland stands out as the top contributor, indicating a significant focus on biohydrogen research relative to its population size. Similarly, Denmark and Norway exhibit high per capita contributions, consistent with their established leadership in renewable energy and sustainability initiatives.

The data highlight a dual dynamic: countries such as South Korea and Malaysia lead in total research output, reflecting their capacity for large-scale initiatives, while smaller nations like Iceland and Denmark demonstrate strong proportional contributions, emphasizing targeted research efforts. This global distribution underscores the collaborative nature of biohydrogen research, with diverse nations contributing according to their unique resources and priorities. Together, these efforts support the ongoing global transition to clean and sustainable energy sources.

The keyword co-occurrence network in Figure 3 illustrates the relationships among the most significant keywords and their frequencies, based on articles analyzed from Scopus and Clarivate Analytics WoS. The data from these two databases were merged using the R programming language. The network, created with VOSviewer software, version 1.6.20, includes 50 selected keywords grouped into six clusters, with a minimum co-occurrence threshold of four. Keyword variability is represented by font size, where larger fonts indicate higher frequencies. This approach provides a clear representation of the connections and relevance of terms related to biohydrogen production, supporting the identification of optimal keyword combinations for literature reviews.

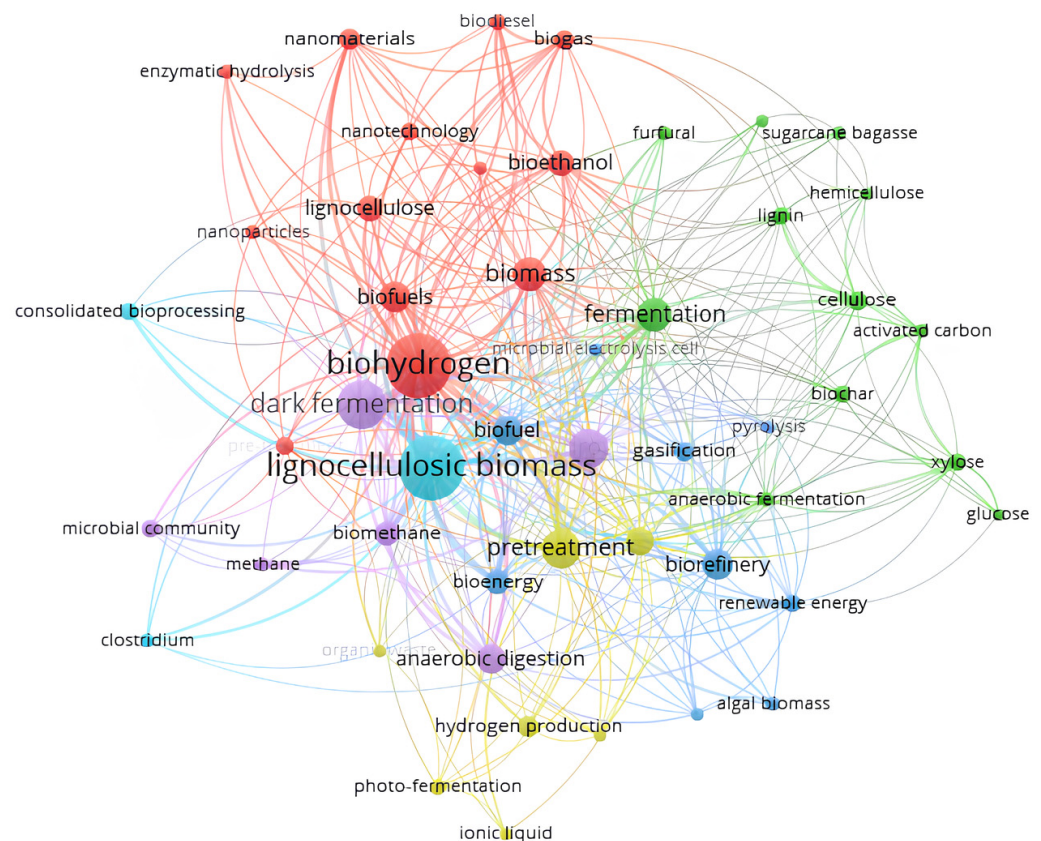


Figure 3. Keyword co-occurrence network, 2019–2023 (Scopus and Clarivate Analytics WoS).

Based on the visualization in Figure 3, the most prominent keyword is “biohydrogen”, reflecting its central importance in the field of biohydrogen production. Other significant terms include “lignocellulosic biomass”, “pretreatment”, “fermentation”, and “biomass”, which highlight the focus on feedstock preparation, biological processes, and the conversion of organic materials for hydrogen production. Keywords such as “anaerobic digestion”, “biorefinery”, and “enzymatic hydrolysis” emphasize the role of advanced biological and chemical processes in this area of research.

Furthermore, terms like “sugarcane bagasse”, “cellulose”, and “lignin” underscore the use of specific biomass feedstocks, and the challenges associated with breaking down complex materials. “Renewable energy” and “biochar” reflect the broader integration of biohydrogen within sustainable energy systems, while keywords such as “dark fermentation”, “gasification”, and “ionic liquid” point to various methodologies being explored to enhance production efficiency.

In conclusion, these keywords demonstrate a clear emphasis on sustainable and biological methods for hydrogen production. The interconnectedness of terms reflects a multidisciplinary approach, integrating concepts from biochemistry, renewable energy, and waste-to-energy processes. This highlights the ongoing efforts to improve efficiency, optimize processes, and utilize diverse organic feedstocks, contributing to advancements in clean and sustainable energy solutions. The integration of biohydrogen with other renewable energy sectors, such as bioethanol and methane production, illustrates a holistic approach to advancing clean energy solutions. Table 1 further emphasizes this multidisciplinary approach by associating these main keywords with the corresponding relevant articles, reflecting a strong emphasis on sustainability and environmental responsibility in biohydrogen technologies.

Table 1. Keywords related to biohydrogen production processes.

Related Keywords	Description	References
Anaerobic digestion	This process is a central area of study as it facilitates the conversion of organic materials into biohydrogen and biogas in the absence of oxygen. The references reflect efforts to enhance its efficiency and applicability.	[16–18]
Dark fermentation	Dark fermentation is widely studied due to its potential for sustainable hydrogen production using organic substrates without the need for light. The listed references focus on improving yields and understanding its biological mechanisms.	[18–31]
Hydrolysis	Research on hydrolysis addresses the challenges of breaking down complex biomass structures like cellulose into fermentable sugars. The studies cited explore advancements in enzymatic and chemical pretreatment methods.	[32–38]
Ethanol	Ethanol production from lignocellulosic biomass is a key area of research due to its potential as a sustainable biofuel. Efforts focus on enhancing fermentation efficiency, improving enzyme activity, and utilizing advanced pretreatment techniques. Integrated biorefineries co-producing ethanol and hydrogen with genetically engineered microorganisms represent a promising approach for maximizing resource utilization.	[39–41]
Wheat-straw	Wheat straw, an abundant agricultural residue, is a versatile lignocellulosic feedstock for bioethanol and biohydrogen production. Pretreatment techniques like enzymatic saccharification, laccase treatment, and molten oxalic acid processes enhance its conversion efficiency. These innovations facilitate its integration into biofuel systems and sustainable energy solutions.	[20,34,42,43]
Cellulose	As a major component of lignocellulosic biomass, cellulose plays a key role in biohydrogen production. Current studies investigate effective pretreatment methods to improve its conversion efficiency.	[32,44–48]
Methane	Methane production is often studied alongside hydrogen production, as both are integral components of renewable energy systems. The references examine integrated approaches and their potential applications.	[36,49–51]
Lignin	Despite its complexity, the lignin has been the focus of research for its potential to contribute to biohydrogen production. The studies highlight innovative methods for its utilization.	[8,43,52–55]
Rice straw	As an abundant agricultural residue, rice straw has become a valuable lignocellulosic feedstock for biohydrogen production. The references explore its pretreatment and conversion processes.	[56–61]
Biogas	Biogas production is frequently studied in connection with biohydrogen systems, with a focus on integrating both processes for more efficient energy recovery.	[62,63]
Bioethanol	Recent studies have emphasized the link between bioethanol and biohydrogen production, particularly the use of wastewater and other waste streams as feedstocks for sustainable energy production.	[59,64]

The studies reviewed point to a variety of pretreatment strategies, including acid, thermal, enzymatic, and hydrothermal treatments, that improve the conversion of lignocellulosic sugars into fermentable substrates. Mockaitis et al. (2020) focused on acidic and thermal pretreatments for enhancing the anaerobic digestion process and improving hydrogen and volatile fatty acid production from xylose, demonstrating the relevance of such approaches for lignocellulosic biomass, including sugarcane [16]. Likewise, Rawoof et al. (2021) reviewed the sequential production of hydrogen and methane through the

anaerobic digestion of organic wastes, underlining the potential of lignocellulosic materials like sugarcane for such applications [17].

Furthermore, Yang et al. (2021) explored the influence of calcium-containing alkali materials on dark fermentation, noting that such materials can stabilize fermentation processes, which is critical for improving biohydrogen yields from sugarcane biomass [18]. The integration of these pretreatments and the management of fermentation conditions are pivotal in enhancing the fermentability of sugarcane biomass, as emphasized by Srivastava et al. (2019), who highlighted the application of nanoengineering techniques to improve dark fermentation efficiency [19].

Zhu et al. (2023) extended this idea by investigating the enzymatic saccharification and dark fermentation of wheat straw, providing valuable insights into how similar processes can be applied to sugarcane biomass for higher biohydrogen production [20]. Similarly, Balakrishnan et al. (2023) optimized fermentable sugar production from Napier grass for biohydrogen generation, contributing to the broader understanding of how grasses and other lignocellulosic feedstocks can be utilized for biohydrogen production, including sugarcane [21].

Several studies have explored the synergy between pretreatment methods, with some focusing on the combination of acid, enzymatic, and oxidative treatments. Kucharska et al. (2020) investigated how alkaline and oxidative pretreatment of corn cob waste improved biohydrogen production through dark fermentation, with potential applications for sugarcane leaves and other agricultural residues [22]. Ahmad et al. (2024) provided a comprehensive review of recent trends in dark fermentation for biohydrogen production, emphasizing the need for optimizing the transition to a circular bioeconomy through sustainable biomass utilization [23].

The role of dark fermentation in biohydrogen production was further explored by Liu et al. (2020), who examined the microbial dynamics of dark fermentation and how the electron-equivalent balance can be optimized for lignocellulosic feedstocks, including sugarcane [24]. The interplay between microbial populations and the fermentation process is essential for maximizing biohydrogen yields. Sołowski et al. (2020) also studied biohydrogen production from cotton waste and found that adjusting fermentation conditions could significantly improve hydrogen yields, suggesting similar approaches for sugarcane biomass [25].

Moreover, the utilization of fruit and vegetable waste in dark fermentation was explored by Cieciora-Włoch et al. (2020), who demonstrated how biohydrogen can be efficiently produced from such organic wastes, further emphasizing the potential for integrating sugarcane biomass into similar biorefinery systems [26]. Their work reinforces the idea that diverse agricultural residues, including sugarcane, can be incorporated into integrated waste-to-energy processes that produce biohydrogen alongside other biofuels like biogas.

The integration of biohydrogen production with other renewable energy processes is another key theme in literature. Talapko et al. (2023) reviewed biological hydrogen production from biowaste, focusing on storage and transportation aspects, which are crucial for optimizing the biohydrogen supply chain [27]. This concept of multi-product biorefineries is increasingly relevant for sugarcane biomass, as it allows for the co-production of biohydrogen, bioethanol, and biogas, offering a more efficient use of agricultural residues.

Several studies have also emphasized the potential of optimizing pretreatment methods to enhance biohydrogen production. For example, Miftah et al. (2022) examined deep eutectic solvents and enzymatic hydrolysis to improve the fermentability of sugarcane leaves, leading to increased biohydrogen yields through dark fermentation [36]. This work aligns with the findings of Wang et al. (2022), who optimized alkaline and oxidative

pretreatment methods for biohydrogen production from sugarcane bagasse, highlighting the importance of pretreatment for maximizing sugar recovery [38].

On the other hand, Dimitrellos et al. (2020) demonstrated that acid addition in liquid hot water pretreatment could significantly improve biohydrogen and biogas production from lignocellulosic biomass, including sugarcane bagasse [62]. Their findings point to the need for refining pretreatment processes to increase the accessibility of fermentable sugars, an essential step for improving biohydrogen production.

Zheng et al. (2022) reviewed the latest advances in pretreatment and hydrolysis technologies for biohydrogen production from straw biomass and other lignocellulosic materials, underlining the need for innovative methods to improve the hydrolysis process, which is crucial for sugarcane-based biohydrogen production [33]. Similarly, studies by Sivagurunathan et al. (2023) demonstrated the use of nano-metal doped calcium peroxide for biomass pretreatment, resulting in enhanced biohydrogen yields from rice straw, which could be applied to sugarcane and other agricultural residues [56].

In addition to pretreatment innovations, life cycle analysis (LCA) has been increasingly applied to assess the sustainability of biohydrogen production from biomass. Katakojwala et al. (2022) conducted an LCA of biohydrogen production from sugarcane bagasse, demonstrating that the environmental impacts can be minimized by optimizing both the pretreatment and fermentation processes [53]. This aligns with the research by Kumar Singh et al. (2023), who assessed the environmental impacts of biohydrogen production from rice straw and proposed integrated approaches that could reduce energy consumption and improve the sustainability of biohydrogen production from agricultural residues [57].

In conclusion, the reviewed literature underscores the immense potential of sugarcane biomass for biohydrogen production, emphasizing the importance of optimizing pretreatment processes, enhancing fermentation conditions, and integrating biohydrogen production with other bioenergy processes. By incorporating the latest advancements in pretreatment technologies, enzymatic hydrolysis, and microbial fermentation, researchers have made significant strides in improving the efficiency and sustainability of biohydrogen production from sugarcane. The future of biohydrogen production lies in the continuous improvement of these technologies, ensuring that sugarcane biomass can contribute effectively to the global transition toward a sustainable and circular bioeconomy. As we move forward to explore the energy landscape in Brazil, it becomes evident that the country, with its vast sugarcane production, holds a strategic position in implementing these technologies for the future of global energy.

3. Brazil's Energy Landscape and Electricity Mix: An Overview of 2023

According to the Brazilian Energy Balance released by the Empresa de Pesquisa Energética (2024), hydroelectric power continues to dominate Brazil's electricity generation, forming a significant proportion of the nation's energy matrix in 2023 [65]. This heavy reliance on hydropower underscores Brazil's advantageous position in renewable energy resources. It also highlights the necessity for strategic diversification into emerging renewable technologies such as solar and wind power to strengthen energy resilience and sustainability in the face of climate variability and growing energy demands.

3.1. The National Energy Supply in 2023

Examining Brazil's broader energy mix, as depicted in Figure 4, reveals the interplay between renewable and non-renewable sources. Non-renewable sources still represent a larger share of total consumption; however, Brazil distinguishes itself globally by maintaining an exceptionally high share of renewables in its energy matrix. Renewable sources—

comprising sugarcane products (16.9%), hydro (12.1%), firewood and charcoal (8.6%), black liquor and other renewables (7.2%), wind (2.6%) and solar (1.7%)—collectively contribute 49.1% to the nation’s energy matrix. This share is significantly above the global average, where dependence on renewables remains relatively modest.

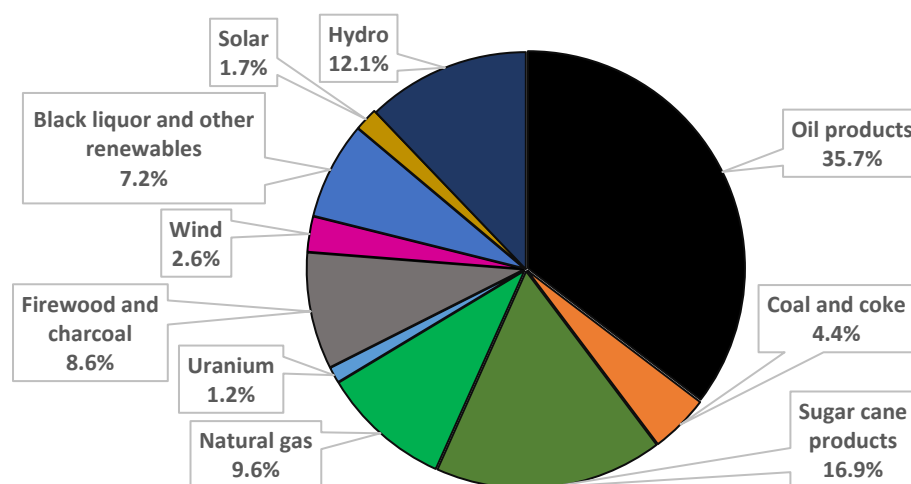


Figure 4. Internal energy supply by source 2023. Data source from [65].

Petroleum and oil remain the dominant sources in Brazil’s energy supply, accounting for the largest share at 35.7%. While these sources are critical to meeting current energy demands, they present challenges related to greenhouse gas emissions and energy security. In contrast, coal and coke make up only 4.4% of the supply, reflecting Brazil’s relatively lower reliance on these carbon-intensive resources. To complement this fossil-based energy matrix, renewables play an increasingly important role, as detailed in Figure 5, which illustrates the supply breakdown of “Black liquor and other renewables”.

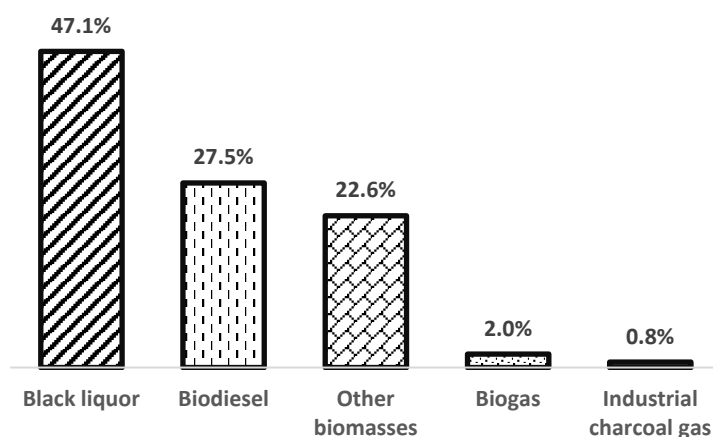


Figure 5. The supply breakdown of “Black liquor and other renewables”. Adapted from [65].

The figure illustrates the distribution of energy supply from black liquor and other renewable sources. Black liquor represents the largest share at 47.1%, followed by biodiesel (27.5%), other biomasses (22.6%), biogas (2.0%), and industrial charcoal gas (0.8%). The category “other biomasses” includes solid biomass, organic waste, secondary biofuels, and other forms of energy derived from organic materials not specified in the other categories. This breakdown highlights the significant role of black liquor, a byproduct of the pulp and paper industry, alongside the contribution of other renewable sources to the energy supply.

Brazil’s energy mix, therefore, presents a dynamic scenario, reflecting the ongoing balance between renewable and non-renewable energy sources. On one hand, the substantial

reliance on renewable resources like hydropower and bioenergy demonstrates the country's leadership in sustainable energy practices. On the other hand, the continued dependence on fossil fuels such as oil and natural gas highlights areas for improvement, particularly considering global efforts to transition to low-carbon energy systems. The data underscores both Brazil's potential to lead in renewable energy adoption and the pressing need to address the challenges associated with non-renewable sources in its energy landscape.

Brazil's energy mix has undergone significant evolution over the past two decades, as illustrated in Figure 6. Between 2004 and 2023, renewable energy sources consistently represented a substantial portion of the nation's Internal Energy Supply (OIE). This ongoing prominence of renewables, reaching 49.1% in 2023, reflects Brazil's proactive approach to energy transition, including the integration of emerging renewable sources such as wind and solar energy [65]. The diversification within the renewable energy portfolio has ensured high levels of sustainability in the OIE, even amidst fluctuations in hydropower and other traditional renewable sources. Such diversification highlights the nation's commitment to enhancing energy security and sustainability in the face of dynamic energy demands and environmental challenges.

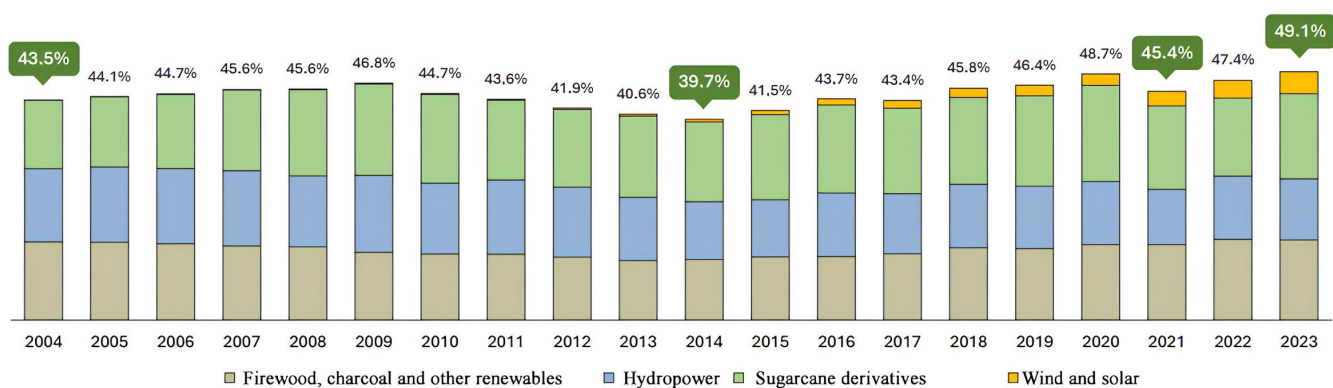


Figure 6. Evolution of the share of renewable energy in the internal energy supply over the last 20 years. Adapted from [65].

Referring to the data in the figure, it becomes evident that the period witnessed notable advancements in renewable energy diversification. Initially reliant primarily on hydropower and biomass (sugarcane derivatives and firewood), Brazil gradually integrated wind and solar power into its energy matrix, as seen in the modest but increasing representation of these sources from 2015 onward. By 2023, the inclusion of these new renewable options contributed to maintaining the robust share of renewables in the OIE despite hydropower's variable contributions due to climatic factors. This shift underscores the strategic value of expanding Brazil's renewable energy mix, ensuring adaptability and resilience within its energy framework while progressing toward a low-carbon future.

3.2. The National Electricity Mix in 2023

In 2023, Brazil's electricity generation from public service plants and self-producers reached 708.1 TWh, representing a 4.6% increase compared to 2022 [65]. Renewable energy sources dominated the electricity generation mix, accounting for 89.2% of the total. Among these, hydroelectric power remained the cornerstone of Brazil's electricity supply, contributing approximately 60.2%, as illustrated in Figure 7. Wind energy followed with 13.6%, reflecting the rapid expansion of this resource in recent years. Solar energy accounted for 7.2%, and sugarcane bagasse provided 8.2%, underscoring the role of bioenergy in the country's energy strategy. The growing share of wind and solar energy indicates a gradual diversification within Brazil's renewable portfolio, even as hydropower continues to maintain a central position.

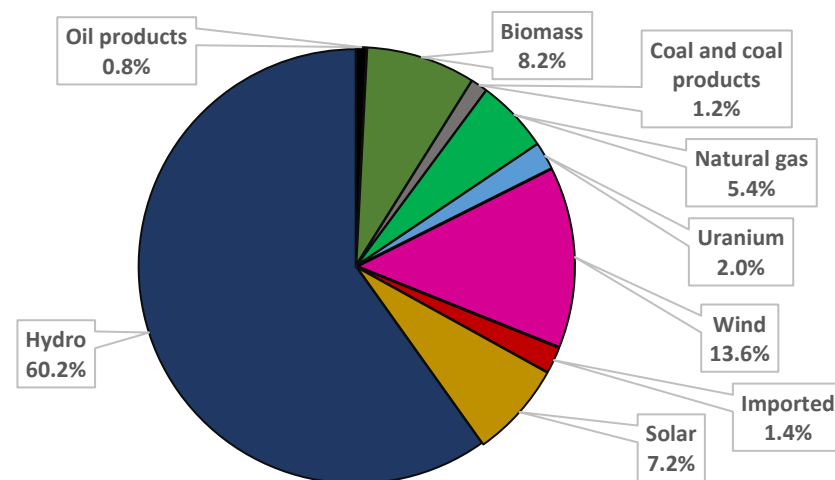


Figure 7. Total electricity supply by source in 2023. Data source from [65].

When compared to the global energy landscape, Brazil stands out as having one of the most renewable-intensive electricity matrices in the world. The country's leadership in biofuel production further underscores its renewable energy credentials. These favorable conditions, combined with Brazil's rich natural resources and biodiversity, provide an ideal foundation for advancing emerging technologies such as green hydrogen production via electrolysis. Green hydrogen represents a significant opportunity for Brazil to leverage its abundant renewable resources to meet both domestic and international clean energy demands.

Despite these achievements, the potential for further growth in renewables remains substantial. Investments in wind and solar energy, in particular, could help mitigate the vulnerabilities associated with Brazil's heavy dependence on hydropower, which is susceptible to climatic fluctuations. Figure 7 highlights the relatively small contributions of non-renewable sources such as oil products (0.8%), coal and coal products (1.2%), and uranium (2.0%) to the electricity mix, reflecting a notable shift toward cleaner energy sources. However, these contributions emphasize the importance of continuing to diversify and stabilize the energy matrix through strategic renewable investments.

Over the past two decades, the share of renewable sources in Brazil's electricity matrix has consistently exceeded 70%, a level notably higher than global averages [65]. This sustained performance underscores Brazil's proactive energy policies, which have fostered diversification and resilience within the electricity supply. Strategic incentives for wind and solar power generation have played a pivotal role in maintaining renewability in the internal electricity supply, even during periods of significant hydric stress. These efforts highlight Brazil's commitment to reducing emissions and bolstering energy security through the continuous expansion of renewable energy capacity [65]. Figure 8 illustrates the dynamic composition of Brazil's electricity matrix, highlighting the dominance of hydropower alongside the growing contributions of wind and solar energy.

While hydropower's share has fluctuated due to climatic variability, the steady rise in wind generation (an increase of approximately 14 TWh in 2023) and solar photovoltaic generation (a growth of more than 20 TWh in 2023) underscores the importance of diversifying the electricity supply [65]. Such advancements demonstrate Brazil's sustained progress in its energy transition, aligning with global decarbonization efforts and reinforcing the nation's leadership in renewable energy adoption.

In conclusion, Brazil's energy matrix in 2023 reflects both notable progress and areas for continued development. While hydropower remains the predominant source, the growing contributions of wind, solar, and bioenergy highlight encouraging steps toward a

more diversified energy portfolio. Brazil's strengths, including its vast renewable resources and well-established biofuel infrastructure, provide a solid basis for advancing innovative technologies such as green hydrogen. These factors underscore the country's potential to maintain a leadership role in global sustainable energy initiatives. Building on this context, the following section will explore the specific role of sugarcane biomass in supporting Brazil's energy transition and its prospects for green hydrogen production.

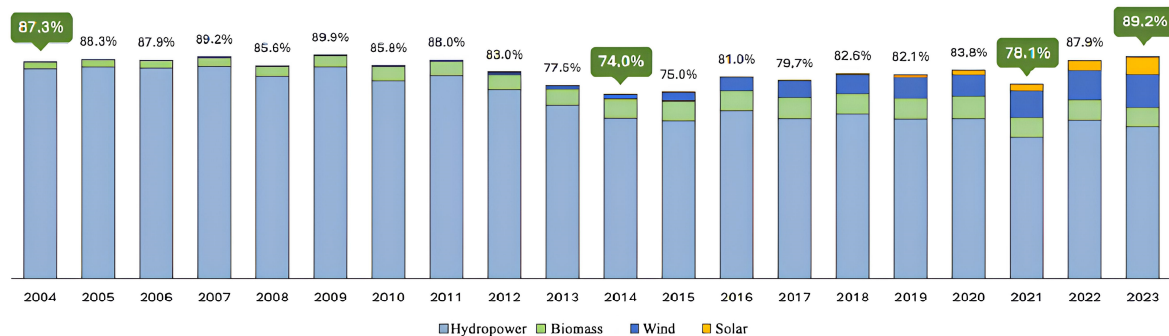


Figure 8. Evolution of the share of renewable energy in the internal electricity supply over the last 20 years. Adapted from [65].

3.3. Evolution of Sugarcane Biomass in Brazil's Energy Systems

Sugarcane biomass has played a dynamic role in Brazil's energy systems, showcasing both its historical significance and its potential to address contemporary energy challenges. As highlighted in Figure 9, the contribution of bioelectricity—largely derived from sugarcane bagasse (63.3%) and black liquor (26.1%)—to electricity generation has remained consistently high, with a peak of 58,742 GWh in 2020 and sustained production at 57,825 GWh in 2023 [65]. This trend underscores the resilience of sugarcane-derived bioelectricity in meeting energy demands and reflects its strategic importance in Brazil's broader transition to renewable energy. However, the temporal variability of sugarcane biomass as a source of electricity highlights its adaptability to policy and market shifts, particularly in response to hydropower fluctuations during periods of climatic stress.

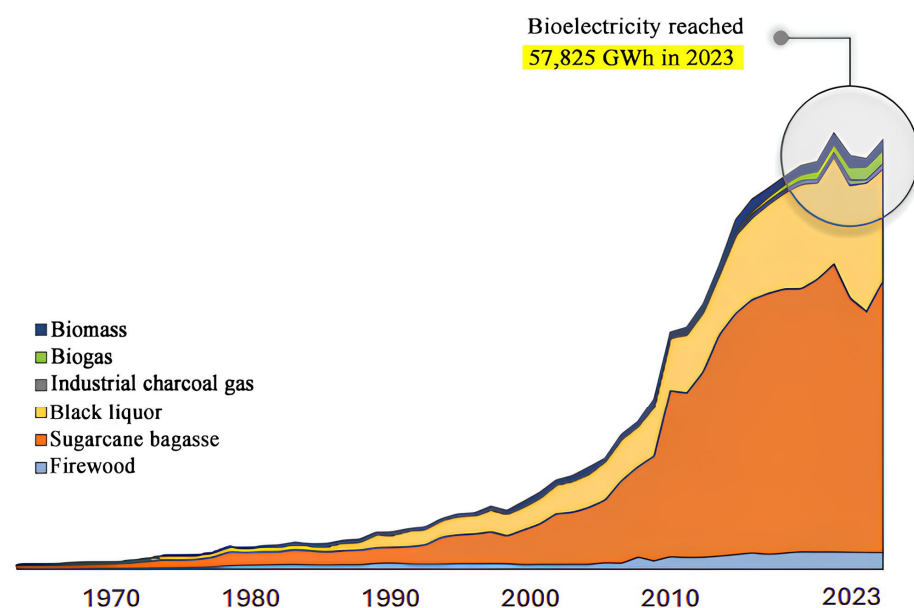


Figure 9. Historical growth of bioelectricity production in Brazil (1970–2023). Adapted from [65].

Figure 10 provides a broader perspective on the time variability of Brazil's primary energy production, emphasizing the growing role of sugarcane-derived energy in relation

to other sources over recent decades. While hydropower and petroleum have historically dominated the energy matrix, sugarcane-based bioelectricity has demonstrated consistent growth, solidifying its position as a critical renewable resource. This consistent contribution not only stabilizes the energy supply but also offers potential synergies with emerging technologies, such as hydrogen production.

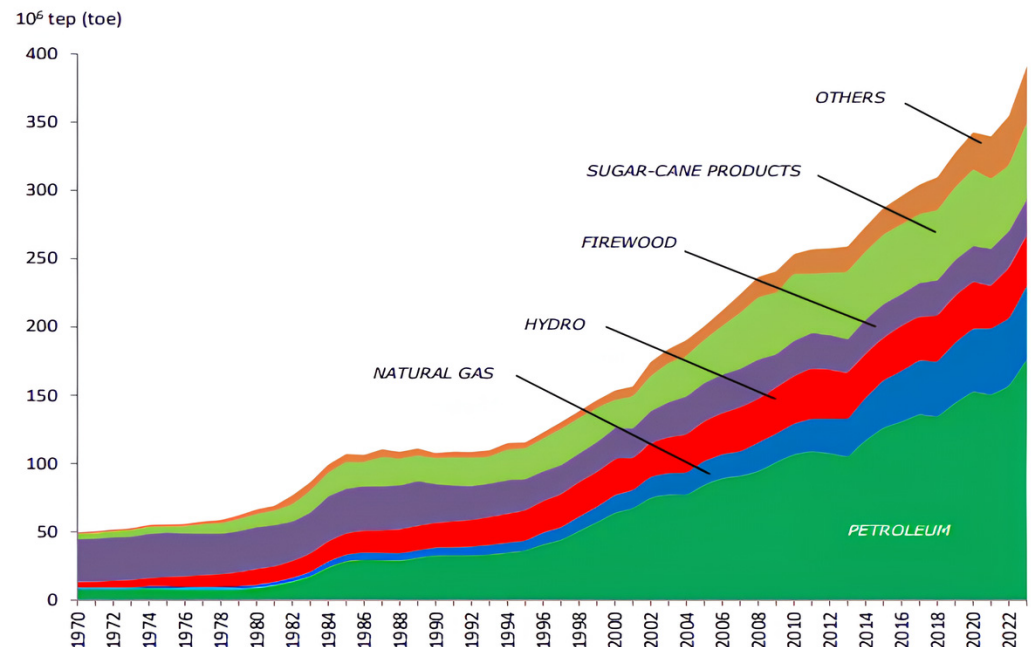


Figure 10. Contribution of sugarcane and other energy sources to Brazil's primary energy production (1970–2022). Adapted from [65].

In conclusion, the evolution of sugarcane biomass in Brazil's energy systems demonstrates its significant contribution to electricity generation and its strategic role in diversifying the energy matrix. While hydropower continues to dominate, sugarcane-derived energy has proven to be a reliable and adaptable resource, particularly in mitigating the impacts of hydrological variability. Its stable contribution over recent decades underscores its importance as both a renewable energy source and a foundation for future innovations, such as hydrogen production. Moving forward, integrating sugarcane biomass with emerging technologies could further enhance its value, positioning Brazil as a global leader in sustainable energy practices.

4. Sugarcane Production in Brazil

Brazil leads global sugarcane production, ranking as the top producer and a dominant force in the manufacture of sugar and ethanol. Its processing facilities include mills that produce both sugar and ethanol, as well as autonomous distilleries focused solely on ethanol production. In both setups, significant quantities of biomass are generated, including sugarcane straw (SS) from mechanized harvesting and sugarcane bagasse (SB) from the crushing process. Currently, SS and SB are primarily utilized for cogeneration, with bagasse combustion serving as the main energy source for Brazil's sugar and ethanol plants [66].

According to the fourth survey of sugarcane production in Brazil conducted by the National Supply Company (Conab), during the 2023/2024 harvest, more than 400 mills in the country processed approximately 713.2 million metric tons of sugarcane. From this, around 45.68 million metric tons of sugar and 29.69 billion liters of first-generation ethanol

were produced [66]. These numbers highlight Brazil's key position in the global sugar and ethanol markets, demonstrating the scale and productivity of its sugarcane industry.

One metric ton of crushed sugarcane generates 276 kg of fresh sugarcane bagasse with 50% moisture and 165 kg of sugarcane straw with 15% moisture [67]. Considering that sugarcane has 75% moisture before harvest, 713.2 million metric tons of sugarcane correspond to 178.4 million metric tons of sugarcane dry matter, represented by 120.4 million metric tons of sucrose, 25.0 million metric tons of SB and 25.0 million metric tons of SS.

Figure 11 illustrates the integration of first-generation (1G) and second-generation (2G) ethanol production, providing a detailed overview of the main steps in the production processes. It highlights the generation and reuse of byproducts, along with the consumption of water, energy, and chemicals.

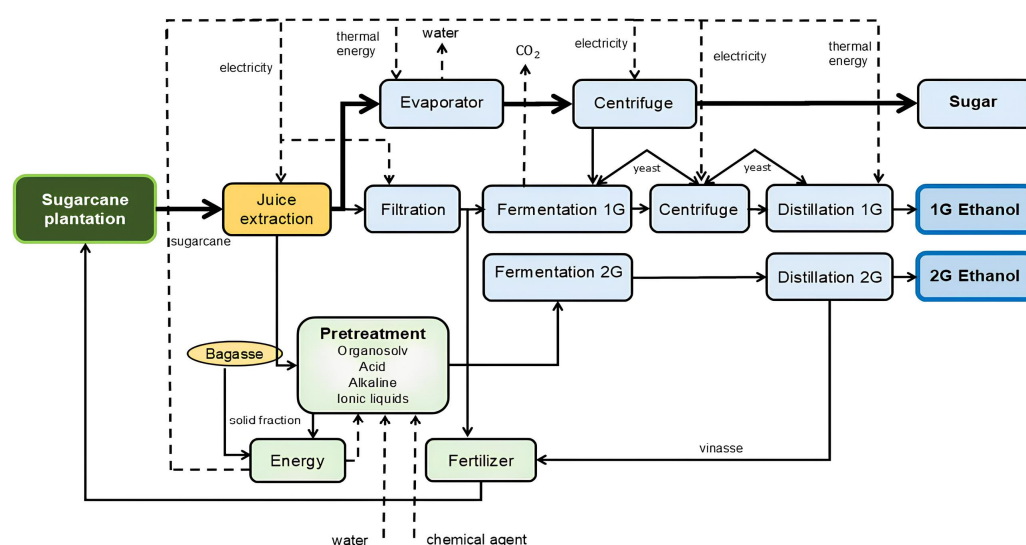


Figure 11. Processing of sugarcane and sugarcane bagasse to produce 1G and 2G ethanol, along with the byproducts generated. Adapted from [68].

As shown, the production of 1G ethanol follows the biorefinery model, where both solid and liquid residues from sugarcane processing are utilized in various applications. These byproducts play a crucial role in the generation of thermal and electrical energy, contributing to the sustainability of the overall process [68]. This is especially important considering the growing global demand for electricity, which presents challenges as the use of fossil fuels declines and becomes more restrictive [5]. Additionally, these residues serve as valuable components in the production of fertilizer, further emphasizing the multifaceted and resource-efficient nature of the biorefinery approach within the sugarcane ethanol production cycle.

In the study by Orlando Jr. et al. (2021), the influence of chemical interactions on gas holdup and flow regimes in bubble columns was thoroughly analyzed. Their findings indicate that the presence of salts, surfactants, and polymers significantly alters gas retention and flow behavior, which are critical parameters in optimizing gas–liquid systems. These insights could inform the development of more efficient hydrogen production systems, particularly in biorefineries utilizing sugarcane biomass [69].

Table 2 provides a comprehensive comparative analysis of the 1G and 2G ethanol production processes. It summarizes their main characteristics, including feedstocks, key processing steps, byproducts, challenges, and energy efficiency. This comparison underscores the technological maturity of 1G ethanol production, and the developmental challenges faced by 2G processes, particularly in terms of pretreatment complexity and scale-up feasibility.

Table 2. Comparative analysis of 1G and 2G ethanol production processes.

Aspect	1G Ethanol	2G Ethanol
Feedstock	Sugarcane juice	Lignocellulosic biomass (e.g., bagasse and straw)
Main processes	Filtration, fermentation, and distillation	Pretreatment, enzymatic hydrolysis, and fermentation
By-products	Vinasse, CO ₂	Lignin and hydrolyzed residues
Challenges	Scale-up limitations	Complexity of pretreatment
Energy efficiency	High (relatively mature technology)	Moderate (under development with technical challenges)

Currently, approximately 60% of ethanol is produced from corn, 25% from sugarcane, 2% from molasses, 3% from wheat, and the remaining amount from other grains, cassava, or sugar beets [70]. Domestically, ethanol is obtained mostly from sugarcane and corn. At present, using sugarcane for ethanol production is recognized as a key option in the global market, given its favorable energy balance and carbon reduction potential compared to other alternatives [71]. In this scenario, with the increasing pressure on the control of polluting emissions imposed by new climate policies and the introduction of targets for the reduction of greenhouse gas emissions in the transport sector, biofuels are becoming an increasingly promising solution.

According to Coelho (2019), as ethanol production rises, the cost of biofuel production is expected to decrease significantly, and at present, ethanol is considered economically competitive with gasoline without the need for subsidies [71]. This trend highlights the growing viability of ethanol as a sustainable and cost-effective alternative to traditional fossil fuels in the energy market.

Biofuels (e.g., bioethanol and biodiesel) are derived from biomass. The international biofuel sector is strongly influenced by national policies that have three main objectives: supporting farmers, reducing greenhouse gas emissions and/or enhancing energy independence [70,72]. A further increase in oil prices could intensify competition between sugar and sugarcane-based ethanol, which would have a significant impact on Brazil, the leading exporter of sugar, and have broader effects on the global sugar market [71]. These dynamics underscore the complex interplay between biofuel production, market competition, and national energy policies, highlighting the potential for significant global economic and environmental implications.

5. Environmental Impacts and Sustainable Solutions

To address a gap in the existing literature and explore new environmental perspectives, a study was conducted on sustainable alternatives for green hydrogen production using 2G ethanol as a carrier. The focus is on evaluating the environmental sustainability of different sugarcane biomass pretreatment methods, specifically in terms of their future potential. Producing green hydrogen from sugarcane biomass involves extracting hydrogen from a water–ethanol mixture. The pretreatment of bagasse for 2G ethanol production requires heating the biomass and a chemical mixture to temperatures ranging from 30 °C to 195 °C, with alkaline processing using milder conditions and organosolv pretreatment involving more extreme conditions [68].

Bioenergy that combines biological resources to produce heat, electricity, fuel, and chemicals with little or no carbon emissions is considered one of the most promising renewable energy sources [73]. The energy sustainability of 2G ethanol production is largely driven by using thermal and electrical energy from renewable sources in the biomass

processing stage. This makes it a key player in the transition to more sustainable and low-carbon energy systems.

5.1. 2G Ethanol Production

Brazil is recognized for producing 1G sucrose ethanol at the lowest cost globally (USD 0.3396 L⁻¹) and utilizing bioelectricity as a proven, cost-efficient technology (USD 360 GJ⁻¹). 2G technology, in addition to being a robust process, is expected to maintain low costs and deliver an attractive energy balance [74]. To evaluate the energy potential of emerging biomass technologies, it is relevant to compare the energy output from the complete combustion of sugarcane biomass (17.33 MJ kg⁻¹) with that of its primary cell wall components: cellulose polysaccharides (44%), hemicellulose (25%), and the hydrophobic, aromatic macromolecule lignin (28%). These components hold potential for both ethanol production and energy generation [67].

According to experimental data reported by Oliveira et al. (2020), it is possible to estimate that the volume of 2G ethanol produced from 1 metric ton is equivalent to 24.6 L (594 MJ). During the pretreatment stage, 122 kg·ton⁻¹ of solid fraction (comprising cellulose and lignin) is processed. Of this, 40 kg·ton⁻¹ is consumed during fermentation, while the remaining 82 kg·ton⁻¹, composed of solid lignin residue, is utilized in the cogeneration process, contributing 1705 MJ. This energy is subsequently reused in the sugarcane juice extraction process.

The energy content of 2G ethanol was calculated using the total volume produced and the density of hydrated ethanol, determined to be 0.809 kg·L⁻¹ [75]. This results in a higher heating value of 29.85 MJ·kg⁻¹ [76], translating to an energy yield of 594 MJ·ton⁻¹ of processed biomass. These values underscore the significant energy potential of 2G ethanol as a renewable fuel. Figure 12 provides an overview of the sugarcane processing pathway for 2G ethanol production.

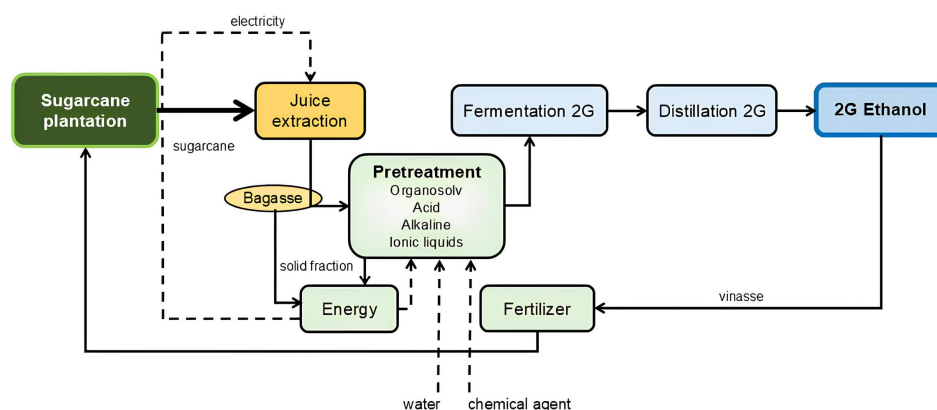


Figure 12. Sugarcane processing to produce 2G ethanol. Adapted from [68].

As observed in Figure 2, after harvesting, sugarcane undergoes a grinding process to extract SB. Typically, SB is utilized to produce high-pressure steam and generate electricity, serving as a crucial energy source in cogeneration plants. This practice ensures energy self-sufficiency and reduces the environmental impacts of industrial operations [68]. Additionally, a portion of the SB is diverted for pretreatment steps, such as organosolv, acid, alkaline, or ionic liquid processes, which facilitate the breakdown of biomass into components for 2G ethanol production. The solid fraction remaining from the pretreatment stage contributes to energy generation and fertilizer production, further enhancing the efficiency and sustainability of the sugarcane processing system.

The solid fraction of sugarcane bagasse that is diverted from direct energy production, which is rich in lignin—the most abundant aromatic polymer in nature—can still be used

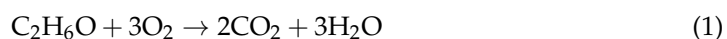
for energy generation to support industrial self-sufficiency. However, the energy surplus is reduced, as lignin constitutes approximately 1/5 to 1/3 of SB [77]. Due to its high storage content of phenolic compounds, lignin is considered an alternative source to produce various polymers and biomaterials [78]. Thus, while lignin in sugarcane bagasse reduces the energy surplus, it offers significant potential for producing valuable polymers and biomaterials.

The chemical pretreatment of sugarcane bagasse, a widely used method for breaking down lignocellulose into its monomeric and oligomeric units for bioconversion into ethanol, involves the use of dilute acids, alkaline solutions, organosolv processes, and ionic liquids [68]. As one of the largest bioindustries, the ethanol sector—particularly with the emergence of 2G ethanol—faces a growing need for technological advancements and sustainable approaches. In response, research is increasingly focused on developing eco-friendly pretreatment methods using green chemicals, emphasizing the recovery and reuse of chemical agents as well as their replacement with environmentally sustainable solvents.

5.2. Second-Generation Ethanol as a Sustainable Pathway for Green Hydrogen

It is well-established that during the combustion of C_2H_6O , complete combustion produces CO_2 and water (H_2O) (Reaction (1)). Considering the molar masses of carbon (12 g/mol), hydrogen (1 g/mol), and oxygen (16 g/mol) from the periodic table, we can infer that each mol of ethanol (46 g) produces two moles of CO_2 (88 g) during the process. Therefore, while 2G ethanol is a renewable biofuel, its combustion is not entirely environmentally friendly, as it releases CO_2 into the atmosphere. This highlights the need to convert C_2H_6O into another fuel whose complete combustion is green, i.e., which results in no pollutant emissions.

Reaction (1):



To address the issue of CO_2 emissions from ethanol combustion, there is the potential to produce green hydrogen, which is widely regarded as a key solution for the future renewable energy landscape. This can be achieved through parallel processes involving 2G ethanol. Hydrogen, in addition to being a clean and alternative fuel—since the only byproduct of its combustion is water (Reaction (2))—can be used to generate low-carbon renewable energy for applications such as urban transportation and stationary energy needs. Furthermore, it serves as a valuable raw material in industries such as steel, chemicals, petrochemicals, agriculture, and food production, among many others.

Reaction (2):



Based on a review of the existing literature on methods for producing green hydrogen, a diagram was created to summarize the main approaches for obtaining biohydrogen using second-generation ethanol or integrated processes (Figure 13). The diagram highlights that ethanol-based methods involve two primary pathways from a water–ethanol mixture: electrocatalytic reforming using a Ni–Cu bilayer of hollow microtubes and a plasma reactor driven by spark discharge, which is resistant to coking. For integrated production, three main approaches involving lignocellulosic biomass are outlined: fermentation coupled with energy generation technologies, the use of nanomaterials alongside established processing methods, and anaerobic bacterial cultivation with the addition of iron nanoparticles. Additionally, two other distinct approaches are noted: biohydrogen production within the framework of a circular biorefinery and through xylose conversion via acidogenesis.

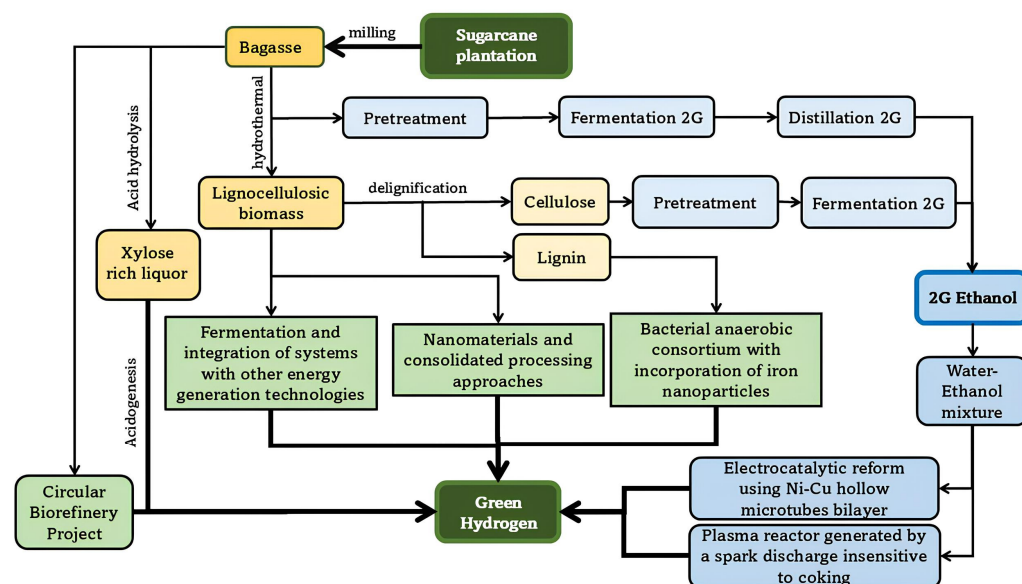


Figure 13. Pathways for green hydrogen production using 2G ethanol and integrated processes.

To further elucidate the key methods depicted in Figure 13, Table 3 provides a detailed comparison of the seven approaches for biohydrogen production. The table highlights the techniques, reported yields, advantages, and limitations associated with each method. This comparative analysis consolidates state-of-the-art knowledge while highlighting the unique contributions and practical implications of each approach. By summarizing the strengths and challenges of these methods, the table offers a comprehensive perspective on their potential applications and suitability for different contexts.

Table 3. Comparison of seven methods for biohydrogen production.

Method	Technique Used	Results	Advantages	Limitations
Fermentation (2G)	Biological fermentation of lignocellulosic biomass	Biohydrogen yield depends on feedstock and enzymes used	Environmentally friendly, scalable	Requires pretreatment, complex optimization
Electrocatalytic reform	Reforming with Ni–Cu hollow microtubes bilayer	High conversion efficiency	Insensitive to cooking, efficient process	High initial setup cost
Plasma reactor	Plasma discharge-based hydrogen production	Enhanced hydrogen output, robust performance	Resistant to fouling	Requires advanced technology
Fermentation with iron nanoparticles	Anaerobic bacterial consortium with iron nanoparticles	Increased microbial activity and hydrogen yield	Improves fermentation efficiency	The stability of nanoparticles can be a challenge
Nanomaterial-assisted processes	Nanomaterials and consolidated processing approaches	Improved catalytic and conversion efficiency	Innovative, enhance existing methods	High cost of nanomaterials
Pretreatment and delignification	Acid hydrolysis, hydrothermal processes	Releases fermentable sugars	Essential for lignocellulosic biomass processing	Energy-intensive, possible inhibitor formation
Integration with energy systems	Coupling fermentation with other energy generation technologies	Maximized energy recovery and hydrogen output	Efficient resource utilization	Complex system design

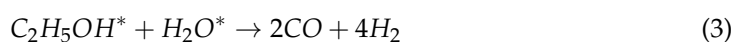
5.2.1. Green Hydrogen Production from 2G Ethanol

Second-generation ethanol can be an excellent raw material to produce green hydrogen, since it is produced from the fermentation of sugarcane biomass and is a zero-emission method. However, despite substantial research efforts, no economically viable method for converting ethanol into green hydrogen has been achieved. The primary challenge lies in the formation of coke, which leads to catalyst deactivation during the process.

Ongoing studies aim to address this issue by exploring methods to mitigate catalyst deactivation caused by coke formation. One example is a study published in the *International Journal of Hydrogen Energy* [79], which investigates the electrochemical synthesis of Ni–Cu bilayer hollow microtubes for the electrocatalytic reforming of ethanol. In this method, external potential facilitates the oxidation of ethanol at the anode and the reduction of protons at the cathode, resulting in hydrogen production. Hydrogen, as an efficient energy carrier, can subsequently be used in fuel cells to generate electricity [80]. The study focuses on understanding the synthesis processes of Ni and Cu hollow tubes (NC-HT) and evaluating their effectiveness as electrocatalysts in hydrogen evolution reactions from water–ethanol solutions.

According to a study involving efficient plasma technology to produce green hydrogen from ethanol and water, the use of excess water reduces coke, but requires more energy to heat water, making the hydrogen production process unprofitable [81]. This research proposed an alternative approach, utilizing a plasma reactor driven by spark discharge, which is resistant to coke formation (Reaction (3)). The spark reactor demonstrated high operational flexibility and the capability to supply hydrogen to fuel cells, even under varying energy demands.

Reaction (3):



5.2.2. Production of Green Hydrogen Parallel to Bioethanol

Green hydrogen can also be produced from lignocellulosic biomass through fermentation combined with integration into other energy generation systems. A key step in this approach involves the chemical pretreatment of sugarcane bagasse, which is a conventional method for breaking down lignocellulose into its mono- and oligomeric units. These units can subsequently be bioconverted into ethanol. Commonly used agents for this pretreatment include dilute acids, alkaline solutions, organosolv reagents, and ionic liquids [68]. These pretreatment methods play a critical role in optimizing the conversion process, making it a promising pathway for sustainable hydrogen production.

Lignocellulosic biomass is an abundant and cost-effective renewable resource that holds significant promise for biohydrogen production [80]. Predominantly derived from sugarcane bagasse and straw, these materials are rich in cellulose, hemicellulose, and lignin, with smaller amounts of extractives and ash [82]. This composition underscores its potential as a sustainable substrate for hydrogen production, paving the way for innovative bioenergy solutions.

Lignin, a compound obtained from the delignification of lignocellulosic biomass, also plays a critical role in biohydrogen production. A study published in the *International Journal of Hydrogen Energy* demonstrated that biohydrogen yield can be enhanced through the incorporation of lignin-mediated iron nanoparticles (FeNPs) into the fermentation medium. The study revealed that these magnetic nanoparticles significantly improved microbial activity, fostering more efficient pathways for hydrogen production compared to non-magnetic nanoparticles [83]. These findings highlight the transformative potential of nanotechnology in optimizing the biohydrogen production processes.

Despite technological advancements, challenges remain in scaling up biohydrogen production from lignocellulosic biomass. According to research in the Science of The Total Environment, pretreatment methods are often inefficient and costly, leading to by-products that inhibit microbial growth and reduce hydrogen yield. For industrial viability, it is essential to redirect carbon flow towards hydrogen production while minimizing the synthesis of inhibitory by-products [84]. For biohydrogen production to be feasible, it is crucial to redirect the carbon flow toward hydrogen generation, thereby minimizing the formation of inhibitory by-products.

A recent development in the application of lignocellulosic biomass involves nanoparticles with enzymatic mimetic properties, known as nanozymes. These nanozymes are increasingly being explored as enzyme substitutes across various fields, including agriculture and biofuel production [85]. According to a study published in Bioresource Technology, it is possible to develop a sustainable process for hydrogen production through the implementation of nanotechnology in combination with the consolidated bioprocessing approach from lignocellulosic biomass [86]. In this study, it was found that the combination of nanomaterials and consolidated bioprocessing approaches for hydrogen production would definitively prove commercial viability, which is an urgent need today.

Another innovative approach involves the co-production of green hydrogen and bioethanol from sugarcane bagasse within a circular biorefinery framework. An article in *The Chemical Engineering Journal* presented an integrated strategy to fully utilize raw materials for producing biohydrogen and bioethanol alongside organic agriculture. Through experiments conducted in three phases, the study demonstrated the viability of biohydrogen production using pure xylose and raw materials sourced from agricultural fields [87]. By converting xylose into biohydrogen, the process maximizes resource recovery from biomass, minimizing waste and optimizing the biorefinery system [88]. The results showed a great potential to integrate bioprocesses to obtain maximum resources from the agrobiomass raw material without leaving residues in the biorefinery structure.

6. Discussion

To highlight the originality and relevance of this study, a comparative analysis with similar reviews and experimental studies was conducted. Table 4 summarizes key findings from the most related works in the literature and contrasts them with the contributions of the present study. This comparison emphasizes the innovative aspects of this review, particularly its focus on sugarcane biomass in the Brazilian context and its comprehensive evaluation of sustainability.

Brazil's prominence in sugarcane production, particularly in leveraging sugarcane bagasse and straw for bioenergy, highlights its potential to lead advancements in green hydrogen production. While 2G ethanol derived from sugarcane biomass is a renewable resource, its direct combustion is not entirely carbon neutral. This limitation underscores the importance of converting 2G ethanol into green hydrogen as a more sustainable alternative.

Emerging technologies, such as electrocatalytic reforming and plasma reactors, combined with the utilization of lignocellulosic biomass, offer promising pathways for sustainable hydrogen production. These approaches not only align with Brazil's established role in bioenergy innovation but also support the global transition toward a cleaner and more sustainable energy matrix. This convergence establishes Brazil as a leader in green hydrogen technologies.

Table 4. Comparison of relevant studies on biohydrogen production and the contributions of this review.

Reference	Main Focus	Methodological Approach	Key Findings
[29,30]	Photofermentation of lignocellulosic biomass for biohydrogen production	Experimental and literature review	Identified optimal light conditions for biomass conversion
[7,8,20,24]	Biohydrogen production through dark fermentation using lignocellulosic biomass	Experimental and review	Highlighted technical barriers in pretreatments and dark fermentation processes
[32,85,86]	Sustainable strategies for converting lignocellulosic materials into biohydrogen	Experimental and literature review	Demonstrated the potential of nanobiotechnology to enhance fermentation efficiency
[16]	Impact of physical and thermal pretreatments on biohydrogen production	Experimental approach	Identified efficiency improvements through optimized pretreatment techniques
[8,9,18,19]	Sustainable biohydrogen production from biomass using integrated metabolic pathways	Critical review of biological pathways	Proposed integration of dark and photofermentation approaches
[11,12,33]	Favorable conditions for lignocellulosic biomass saccharification for biohydrogen production	Experimental and literature review	Demonstrated improved biohydrogen production under specific conditions
[13,29]	Integrated biorefinery systems for biohydrogen and biochar production	Experimental and literature review	Identified synergies between biohydrogen production and byproduct utilization
This study	Use of sugarcane biomass for biohydrogen production	Literature review and integrated approach with regional data	Comprehensive and innovative analysis for Brazil

6.1. Brazil's Growing Role in Biohydrogen Research

Recent analyses highlight Brazil's increasing contributions to biohydrogen research, driven largely by the abundant availability of sugarcane biomass. The strategic use of sugarcane biomass for biohydrogen production aligns with global efforts to utilize agricultural residues for sustainable energy, positioning Brazil as a competitive player in this rapidly evolving sector.

Brazil's focus on sugarcane biomass aligns with global trends in biohydrogen research, where the use of diverse lignocellulosic materials has gained traction. Countries like South Korea and Malaysia, with its emphasis on biomass-based renewable energy, highlight the opportunities for emerging players to contribute to a rapidly evolving landscape. Brazil's efforts stand out for leveraging one of the world's most abundant biomass resources in innovative ways.

6.2. Advances in Sugarcane Biomass Utilization

Research into the effective utilization of sugarcane bagasse and straw has demonstrated significant advancements in biohydrogen production. The integration of innovative pretreatment strategies, such as acid hydrolysis, oxidative treatments, and enzymatic saccharification, has proven essential in enhancing sugar recovery and the efficiency of fermentation processes. Studies on the sequential production of hydrogen and methane, as well as the use of microbial dynamics to optimize fermentation, further underscore the versatility of sugarcane as a biohydrogen feedstock.

For example, advancements in nano-engineered catalysts and alternative solvents have shown promise in improving the pretreatment process, reducing energy demands, and maximizing yield. These developments contribute to the growing recognition of sugarcane biomass as a key player in biohydrogen production, particularly when integrated with complementary renewable energy technologies, such as bioethanol and biogas production in biorefinery systems.

6.3. Strategic Opportunities and Challenges

Despite its strong renewable energy foundation, Brazil faces challenges in reducing its reliance on hydropower, which remains susceptible to climate variability. While hydropower accounted for 60.2% of electricity generation in 2023, diversifying the energy mix through the expansion of wind, solar, and bioenergy sources is critical to ensuring energy security. Sugarcane bagasse, currently contributing 8.2% of electricity generation, exemplifies the untapped potential of bioenergy resources within Brazil's energy strategy.

The global shift toward biohydrogen represents an opportunity for Brazil to leverage its extensive sugarcane infrastructure. However, realizing this potential requires addressing technological and logistical barriers, including the optimization of supply chains, development of advanced conversion technologies, and expansion of research collaborations. By investing in these areas, Brazil can strengthen its role in shaping the future of biohydrogen production.

7. Future Perspectives

Brazil's leadership in sugarcane production offers significant potential for advancing green hydrogen technologies. While 2G ethanol is renewable, its combustion is not fully carbon neutral, highlighting the need for more sustainable alternatives like green hydrogen. Future research should focus on optimizing the conversion of 2G ethanol to green hydrogen through emerging technologies, such as electrocatalytic reforming and plasma reactors, combined with lignocellulosic biomass. Brazil's established bioenergy infrastructure provides a strong foundation for scaling these innovations. Research should also explore advanced pretreatment strategies, microbial dynamics, and anaerobic processes to improve efficiency and yield. Overcoming technological and logistical challenges, such as optimizing supply chains and scaling up production, will be crucial for advancing biohydrogen production. Collaborative efforts will help address these barriers, while integrated systems combining green hydrogen with other renewable energy technologies will strengthen Brazil's energy independence and contribute to global sustainability goals.

8. Conclusions

Brazil's prominent role in renewable energy is strengthened by its well-established bioethanol industry, particularly through the large-scale utilization of sugarcane biomass. In the 2023/2024 harvest, the country processed over 713.2 million metric tons of sugarcane, reaffirming its status as a global leader in first- and second-generation ethanol production. In addition to their domestic impact, sugarcane-based biofuels play a crucial role in the global energy transition by providing a renewable alternative to fossil fuels. When considering per capita production, Brazil remains a dominant contributor, further emphasizing its strategic position in sustainable bioenergy. However, despite the potential of 2G ethanol as a feedstock for green hydrogen, large-scale implementation still faces challenges, particularly regarding catalyst deactivation and process efficiency, which must be addressed to enhance technological viability.

Sugarcane, a highly productive and abundant crop, plays a central role in this dynamic. Its cultivation avoids direct CO₂ emissions, further solidifying Brazil's global leadership in

sugarcane production. This compound can be converted into valuable fuels and chemicals through thermochemical and biochemical conversion processes, solidifying Brazil's role as a key player in bioenergy. Beyond ethanol, sugarcane biomass offers immense potential for conversion into valuable fuels and chemicals through thermochemical and biochemical processes, enhancing Brazil's bioenergy capabilities.

Although 2G ethanol derived from sugarcane biomass is a renewable resource, its combustion is not entirely carbon neutral. Therefore, it is critical to explore conversion processes that generate cleaner energy, such as green hydrogen, which offers a more environmentally friendly alternative. Green hydrogen is seen as a vital component of the future renewable energy matrix.

This study identifies two promising methods for producing green hydrogen from a water–ethanol mixture: electrocatalytic reforming using Ni–Cu bilayer hollow microtubes and plasma reactors driven by spark discharge, which are resistant to coke formation. Additionally, three pathways using lignocellulosic biomass are outlined: fermentation integrated with other power generation systems, the use of nanomaterials and consolidated processing techniques, and anaerobic bacterial cultivation combined with iron nanoparticle incorporation. Finally, hydrogen can also be produced from a circular biorefinery project or through xylose via acidogenesis.

In conclusion, while Brazil is well-positioned to lead the transition to green hydrogen production, challenges remain in optimizing these processes for large-scale implementation. Further research should focus on improving the efficiency and economic viability of these hydrogen production methods, addressing the technical limitations in catalyst performance and by-product formation. Exploring the integration of these technologies with Brazil's existing bioenergy infrastructure will be crucial for advancing sustainable energy solutions. Future studies should also explore the potential of combining green hydrogen production with other renewable energy technologies to maximize the country's energy independence and contribute to global climate goals.

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