

METHANOL, ETHANOL, AND GREEN HYDROGEN: TECHNOLOGICAL ROUTES AND ENGINEERING PERSPECTIVES FOR SUSTAINABLE FUEL PRODUCTION

**METANOL, ETANOL E HIDROGÊNIO VERDE: ROTAS TECNOLÓGICAS E
PERSPECTIVAS DA ENGENHARIA PARA A PRODUÇÃO DE COMBUSTÍVEIS
SUSTENTÁVEIS**

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ABSTRACT

The energy transition has driven the development of technological alternatives aimed at diversifying energy matrices and reducing the environmental impacts associated with fossil fuels. In this context, the general objective of this study is to comparatively analyze the main technological routes for methanol, ethanol, and green hydrogen production, considering their feedstocks, conversion processes, efficiency, sustainability, and prospects for industrial applications. This qualitative study is based on bibliographic and documentary research, drawing on scientific publications and technical documents issued by institutions specializing in the energy sector. The results indicate that methanol can be produced through conventional routes and alternative pathways based on renewable hydrogen and captured carbon dioxide. Ethanol is primarily obtained through the biochemical conversion of plant-based feedstocks, such as sugarcane and corn, whereas green hydrogen is produced through water electrolysis powered by renewable electricity. The comparison demonstrates that the sustainability and efficiency of these routes depend on feedstock origin, energy and water consumption, conversion technologies, and emissions associated with production processes. Furthermore, the suitability of each alternative for industrial applications depends on technical, environmental, and infrastructure conditions, while Engineering contributes to process optimization, renewable energy integration, and production scale-up. It is concluded that methanol, ethanol, and green hydrogen have complementary characteristics and can contribute to the energy transition, provided that their adoption accounts for the specific features of each production route and the requirements of their intended applications.

Keywords: Methanol; Ethanol; Green hydrogen; Energy transition.

RESUMO

A transição energética tem impulsionado o desenvolvimento de alternativas tecnológicas destinadas à diversificação das matrizes energéticas e à redução dos impactos ambientais associados aos combustíveis fósseis. Nesse contexto, o presente estudo tem como objetivo geral analisar comparativamente as principais rotas tecnológicas de produção de metanol, etanol e hidrogênio verde, considerando suas matérias-primas, processos de conversão, eficiência, sustentabilidade e perspectivas de aplicação industrial. A pesquisa caracteriza-se como qualitativa, de natureza bibliográfica e documental, fundamentada na análise de publicações científicas e documentos técnicos de instituições especializadas no setor energético. Os resultados evidenciam que o metanol pode ser produzido por rotas convencionais e alternativas baseadas em hidrogênio renovável e dióxido de carbono capturado; o etanol é obtido principalmente pela conversão bioquímica de matérias-primas vegetais, como cana-de-açúcar e milho; e o hidrogênio verde resulta da eletrólise da água com eletricidade de fontes renováveis. A comparação demonstra que a sustentabilidade e a eficiência dessas rotas dependem da origem das matérias-primas, do consumo energético e hídrico, das tecnologias de conversão e das emissões associadas aos processos produtivos. Evidencia-se, ainda, que a adequação de cada alternativa às aplicações industriais depende das condições técnicas, ambientais e de infraestrutura, enquanto a Engenharia contribui para a otimização dos processos, a integração de fontes renováveis e a ampliação da escala produtiva. Conclui-se que metanol, etanol e hidrogênio verde apresentam características complementares e podem contribuir para a transição energética, desde que sua adoção considere as particularidades de cada rota e os requisitos de sua aplicação.

Palavras-chave: Metanol; Etanol; Hidrogênio verde; Transição energética.

1. INTRODUCTION

The energy transition has intensified the search for alternatives capable of reducing dependence on fossil fuels and diversifying energy production and utilization. In this context, methanol, ethanol, and green hydrogen stand out because they involve different technological routes, feedstocks, and potential applications in energy systems and industrial processes. Although these fuels have distinct characteristics, they are associated with the development of energy conversion processes, the utilization of renewable resources, and the reduction of emissions from production activities. The production of these fuels involves different technological configurations and requires knowledge related to Engineering, process efficiency, the rational use of resources, and environmental sustainability. Methanol can be produced from different feedstocks through various synthesis processes, ethanol is primarily associated with biomass processing, and green hydrogen is produced through water electrolysis using electricity from renewable sources. Understanding these alternatives makes it possible to establish relationships between their production characteristics, applications, and contributions to the development of energy systems compatible with the transition toward a lower-carbon economy.

Within this context, this study is guided by the following research question: What are the main technological routes used to produce methanol, ethanol, and green hydrogen, and what are their characteristics, applications, and prospects for contributing to sustainable fuel production? To address this question, the general

objective was established as follows: to analyze the main technological routes for producing methanol, ethanol, and green hydrogen, considering their characteristics, applications, and prospects for sustainable fuel production. The specific objectives were to identify and characterize the main technological routes used to produce methanol, ethanol, and green hydrogen, considering the processes, technologies, and stages involved in their production; to evaluate the efficiency and sustainability characteristics of these routes, considering the feedstocks used, resource consumption, and environmental impacts associated with the processes; and to analyze the contributions of Engineering and technological innovations to the development and expansion of methanol, ethanol, and green hydrogen production routes within the context of the energy transition.

Regarding the methodological procedures, this study adopts a qualitative approach, combining a literature review with documentary research. The literature review was based on theses, monographs, scientific articles, and books related to the subject, while the documentary research covered technical, scientific, and institutional documents addressing hydrogen, energy technologies, and ethanol. The combined use of these procedures made it possible to integrate knowledge from the scientific literature with documentary information to examine the technological routes for producing methanol, ethanol, and green hydrogen, considering aspects related to efficiency, sustainability, innovation, and the energy transition. The article is organized into four sections: Introduction, which presents the research context, question, objectives, and methodological overview; Theoretical Framework, which discusses the production routes, efficiency, sustainability, and technological innovations associated with methanol, ethanol, and

green hydrogen; Methodology, which describes the research approach and procedures; and Final Considerations, which summarizes the main results, assesses the achievement of the objectives, and outlines prospects for future research.

2. THEORETICAL FRAMEWORK

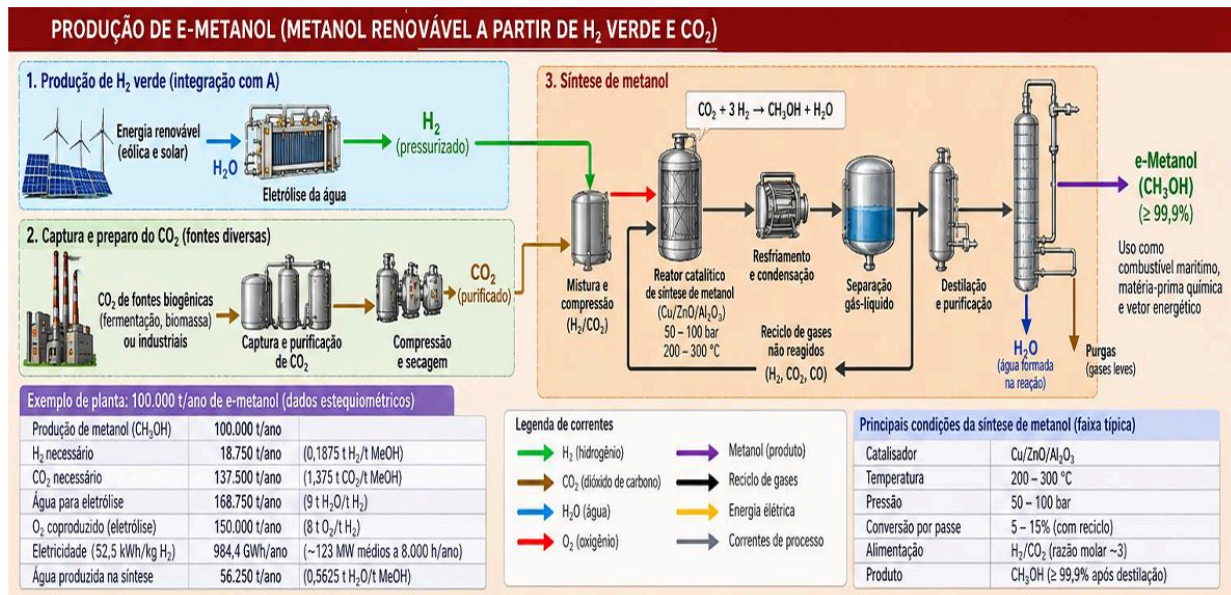
2.1. Technological Production Routes

Methanol is widely used both as a chemical feedstock and as a fuel, and its production routes depend on various feedstocks and industrial configurations. Conventional methods involve processes ranging from syngas production from carbonaceous resources to catalytic synthesis and purification. At the same time, routes combining renewable hydrogen with captured CO₂ are being explored as an alternative for integrating fuel production, carbon utilization, and renewable energy sources (Motaharia; Moorjanib; Rahimpoura, 2025; Marques, 2020).

Industrial methanol production generally involves several stages, including feedstock preparation, syngas production and treatment, catalytic synthesis, separation, and purification. The selection of catalysts and reactors is closely related to operating conditions and process efficiency. According to Motaharia, Moorjanib, and Rahimpoura (2025), technological advances in methanol production involve the interaction between conversion processes, catalysts, and reactor configurations, while Marques (2020) addresses the production structure of methanol in the industrial sector. In this regard, Figure 1 illustrates how carbon capture and reuse can be integrated into hydrogen and methanol production, indicating the feasibility of using carbon dioxide as a feedstock for generating

compounds of interest to the energy and chemical sectors. The representation also connects renewable energy, carbon conversion, and the production of methanol derivatives, providing an integrated view of the technological value chain.

Figure 1. E-Methanol Production Cycle



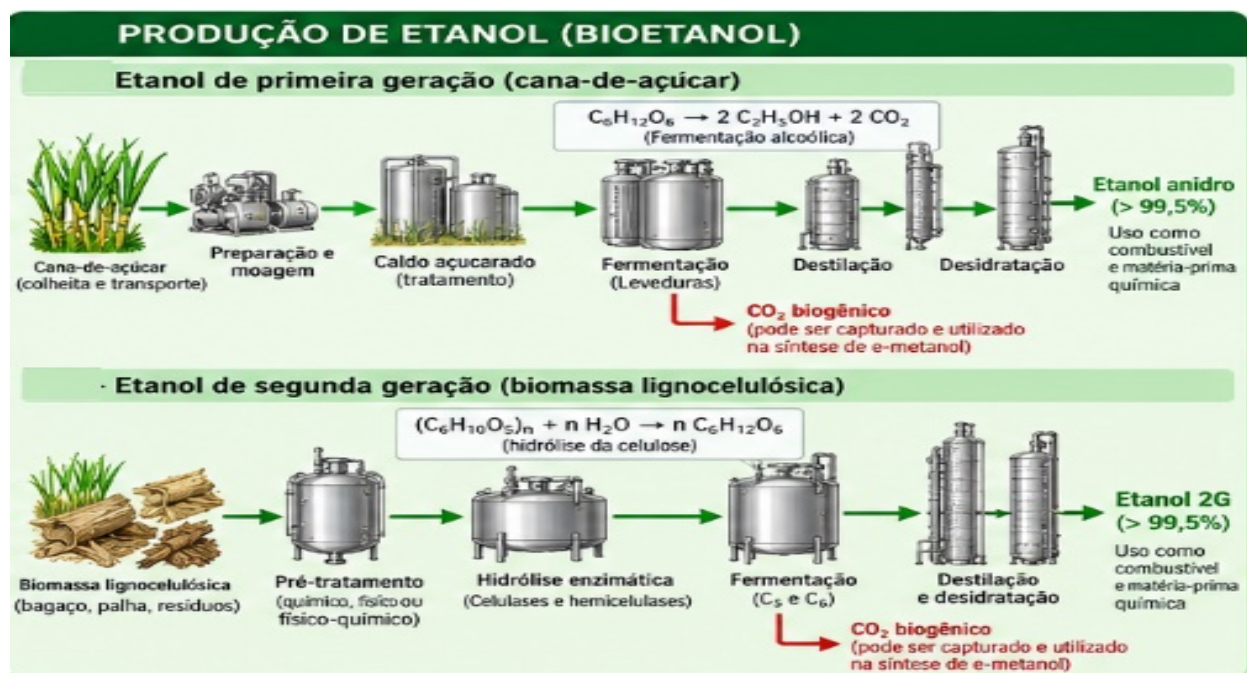
Source: Prepared by the authors with the assistance of ChatGPT (OpenAI, 2026).

The use of CO₂ as a feedstock diversifies methanol production routes by establishing a link between carbon capture, hydrogen, and chemical synthesis. Goeppert et al. (2018) discuss this approach within the methanol economy, in which the compound can be used for energy storage, fuel production, and chemical manufacturing. This configuration aligns methanol production with carbon utilization strategies and the integration of renewable energy systems into industrial processes. Regarding ethanol, technological production routes are largely determined by feedstock characteristics and the processes used to release sugars for fermentation. Sugarcane processing relies on the availability of fermentable sugars, whereas corn production involves converting starch into sugars that can subsequently be fermented. Industrial operations include feedstock reception, storage, milling or

processing, and stages such as saccharification, fermentation, separation, distillation, and product storage (Brito et al., 2024; Ribeiro, 2023).

Corn-based ethanol production has specific characteristics related to starch conversion, involving milling, gelatinization, liquefaction, and saccharification before fermentation. After ethanol production, separation and purification stages ensure that the product meets the requirements of its various applications. While Mohanty and Swain (2019) discuss bioethanol production from corn and wheat, emphasizing the relationship between food, fuels, and sustainability, Ribeiro (2023) focuses on the specific characteristics of corn ethanol production in Brazil. Figure 2 illustrates the stages involved in ethanol production, beginning with feedstock reception and proceeding through preparation, fermentation, separation, distillation, storage, and transportation. It demonstrates how the different production stages are interconnected, as well as how coproducts generated during processing can be utilized, highlighting the complexity of the ethanol production chain.

Figure 2. Representation of Ethanol Production



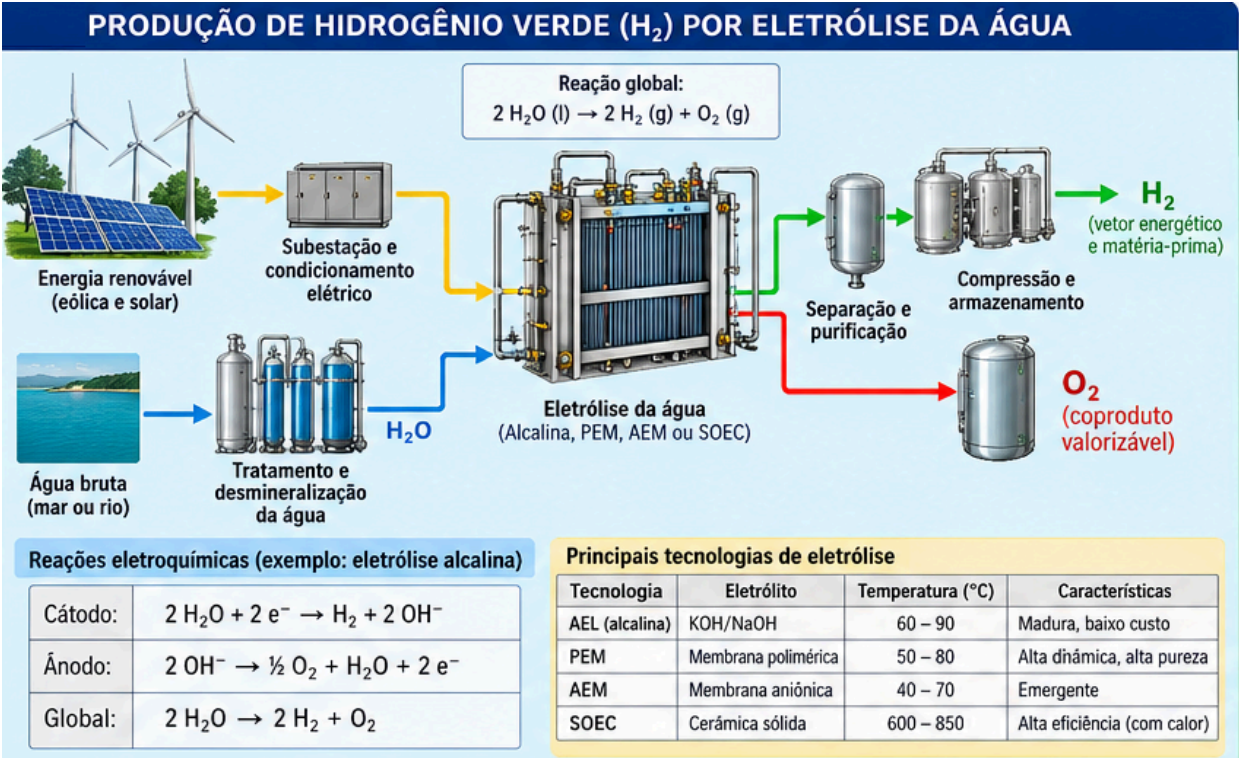
Source: Prepared by the authors with the assistance of ChatGPT (OpenAI, 2026).

The efficiency of the ethanol production chain also involves the energy and economic utilization of by-products generated during processing. Residues and coproducts from sugarcane ethanol production can be integrated into energy generation, aligning biofuel production with resource utilization. Brito et al. (2024) associate innovation with sugarcane ethanol production, while Lima, Castro, and Rocha (2022) discuss the operational structure of an ethanol plant and its relationship with renewable energy production. Green hydrogen production relies on a specific technology: water electrolysis powered by electricity from renewable sources. In this process, electrical energy is used to split water molecules, producing hydrogen and oxygen. The technological configuration involves integrating renewable energy generation with an electrolysis system, forming a production chain that differs from conventional routes based on fossil feedstocks (Nóbrega et al., 2022; Ronceros et al., 2025).

The production stage is not the only component of the green hydrogen technological chain, which also includes conditioning, storage, transportation, and end use. Different options can be

adopted depending on the physical state of hydrogen, transportation distance, available infrastructure, and intended application. While De Castro et al. (2023) discuss the role of hydrogen in the energy transition and the opportunities emerging in Brazil, Gomes et al. (2025) examine storage methods, economic feasibility, regulatory barriers, and certification. Figure 3 illustrates the green hydrogen cycle, from the use of electricity generated by renewable sources and hydrogen production through electrolysis to storage, transportation, and end use.

Figure 3. Green Hydrogen Production Cycle



Source: Prepared by the authors with the assistance of ChatGPT (OpenAI, 2026).

The figure illustrates various applications of hydrogen in transportation, the chemical industry, power generation, industrial processes, and agriculture, helping to demonstrate the breadth of its integration into current energy value chains.

2.2. Efficiency, Sustainability, And Feedstocks

Comparing methanol, ethanol, and green hydrogen solely in their final fuel form provides limited insight into the efficiency and sustainability of each production route. These attributes depend on a combination of interrelated factors throughout the entire value chain, including the feedstocks used, energy and water requirements, processing conditions, and emissions associated with each production stage. This integrated perspective, encompassing the product, inputs, and processes, makes it possible to relate technological performance to resource availability and the environmental implications of the respective production chains.

In the case of methanol, the diversity of feedstocks is a key factor distinguishing its technological routes. Conventional processes rely on fossil resources, whereas more recent alternatives use renewable feedstocks and combinations of hydrogen and carbon dioxide. Deka et al. (2022) emphasize that fuel assessment requires simultaneous consideration of production, use, and techno-economic aspects. Andrade (2024), in turn, highlights the importance of jointly evaluating chemical processes, energy consumption, and environmental impacts within a single analytical framework.

Diversifying feedstocks for methanol production represents an important opportunity to restructure the production chain of this chemical compound, particularly in view of the growing need to reduce dependence on fossil resources, which are associated with environmental impacts and finite reserves. This transformation may create opportunities for more sustainable alternatives, promoting more responsible and efficient resource utilization. Reddy and Seodigeng (2026) explore the transition from conventional feedstocks to renewable sources, emphasizing the importance of diversifying the materials used in production.

This diversity is regarded as an important factor in maintaining the sustainability and efficiency of current production methods, reflecting a growing trend in modern industries. Such a transition is directly related to the need to assess not only feedstock availability but also its relationship with energy consumption, process efficiency, and emissions associated with different production options. This assessment is necessary to understand the overall environmental impacts and sustainability of these operations.

Regarding ethanol, feedstock characteristics influence both the configuration of the production process and its environmental efficiency. The properties of the raw material determine the structure of the production system and its resulting environmental impacts. Sugarcane and corn, in turn, involve substantially different technological value chains, resulting in distinct processing operations and approaches to utilizing their various components. Throughout their production chains, each crop requires specific methods and techniques that reflect its characteristics and the available resources used in feedstock conversion and utilization. Sousa (2026) states that ethanol production in Brazil is directly associated with the use of renewable feedstocks, highlighting the relevance of these resources to sustainable production. Conversely, Januario et al. (2024) emphasize the importance of assessing CO₂ emissions resulting from ethanol combustion, including in contexts where ethanol is combined with green hydrogen.

Ethanol sustainability depends on both feedstock origin and energy efficiency throughout the production chain. Renewable resources can help reduce dependence on fossil fuels. However, environmental assessments must consider all stages of fuel production, processing, and consumption.

Comparisons between production routes should therefore account for the full range of resources consumed and emissions associated with the production cycle rather than relying solely on assessments of the fuel's properties during use.

The sustainability of green hydrogen production is closely linked to the source of electricity used to power water electrolysis. The process requires both water and electricity, and the hydrogen is classified as green when the electricity is supplied by renewable sources, subject to the applicable sustainability and certification criteria.

Santana et al. (2023) describe different production methods and electrolyzer categories, while Almeida et al. (2023) establish a connection between green hydrogen, the expansion of renewable energy sources, and the restructuring of energy systems.

The use of hydrogen across multiple sectors increases the need for an integrated assessment of its production chain, encompassing production, storage, transportation, and end-use applications.

IRENA (2025) emphasizes the relationship between green hydrogen and international trade in hydrogen and related products, while ComCiência (2021) highlights the challenges associated with the sustainable production of this energy carrier. In this regard, Figure 4 illustrates the various categories of hydrogen applications, highlighting its use in residential, industrial, and transportation sectors, as well as other economic activities.

Figure 4. Hydrogen Applications by Category



Source: ComCiência (2021)

The three production routes differ in terms of feedstocks, resource requirements, and the efficiency and sustainability dimensions discussed in this section. Board 1 summarizes these differences by comparing methanol, ethanol, and green hydrogen in terms of the factors that determine the technological performance and environmental impacts of each process.

Board 1 – Comparative Characteristics of Methanol, Ethanol, and Green Hydrogen Production Routes

Fuel	Main Feedstocks or Resources	Characteristics of the Production Route	Efficiency Aspects	Sustainability Dimensions
Methanol	Fossil resources, renewable feedstocks, hydrogen,	Feedstock conversion, intermediate formation, and	Dependent on conversion conditions, catalysts,	Feedstock diversification, CO ₂ utilization, and reduced

	and CO ₂ , depending on the production route	methanol synthesis	reactors, and process integration	dependence on fossil resources
Ethanol	Sugarcane, corn, and other feedstocks containing fermentable sugars or carbohydrat es	Feedstock processing, sugar extraction, fermentatio n, and ethanol separation	Associated with conversion yield, feedstock processing, and energy utilization	Use of renewable feedstocks, coproduct utilization, and assessment of emissions associated with production and use
Green Hydrogen	Water and electricity from renewable sources	Water electrolysis, followed by conditioning , storage, transportati on, and utilization	Related to electrolyzer performanc e and the availability of renewable electricity	Use of renewable energy sources, reduction of production- related emissions, and integration with different energy sectors

Source: Prepared based on ComCiência (2021), Almeida et al. (2023), Santana et al. (2023), Andrade (2024), Deka et al. (2022), IRENA (2025), Reddy and Seodigeng (2026), Sousa (2026), and Januário et al. (2024).

The analysis reveals that efficiency and sustainability are interrelated aspects whose assessment must account for the specific

characteristics of each technological route. While methanol and ethanol offer several alternatives in terms of feedstock diversification and coproduct utilization, green hydrogen relies on the synergy between water, renewable electricity, and electrolysis technologies. The interaction among these elements provides the basis for discussing, in the next section, how engineering, technological innovation, and these fuels contribute to the energy transition.

To complement the qualitative comparison presented in Board 1, Table 1 brings together quantitative indicators of energy efficiency, water consumption, and greenhouse gas emissions for representative production routes of methanol, ethanol, and green hydrogen, including information on their technological maturity. The values are presented according to the data available in the literature, taking into account differences in feedstocks, process configurations, and assessment boundaries. This approach enables a more detailed discussion of the energy and environmental performance of these alternatives without assuming that results obtained under different conditions are directly comparable.

Table 1. Quantitative Indicators of Energy Efficiency, Water Consumption, Emissions, and Technological Maturity of Sustainable Fuel Production Routes

Fuel and Production Route	Energy Efficiency	Water Consumption	Carbon Footprint	Technological Readiness Level (TRL)
Conventional methanol, produced from natural gas	No single percentage applies to all configurations	Depends on the industrial configuration and the	Approximately 90–100 g CO ₂ -eq/MJ, based on life	TRL 9, established industrial route

		assessment boundary considered	cycle assessment	
Renewable methanol, produced by hydrogenation of CO ₂ with renewable H ₂	Depends on electrolysis efficiency and process integration	Depends on H ₂ production, CO ₂ capture, and auxiliary systems	Approximately 0.5–33.1 g CO ₂ -eq/MJ, depending on the route and assessment assumptions	Commercial routes available, with differences in maturity across configurations
First-generation ethanol, produced from sugarcane	Energy balance of 17.7 MJ of liquid energy per liter of ethanol, in a specific study	Water footprint of 1,115 L/L of ethanol, in a specific study	38.5 g CO ₂ -eq/MJ, in a specific study	TRL 9, established commercial production
First-generation ethanol, produced from corn	Energy balance of 11.2 MJ of liquid energy per liter of ethanol, in a specific study	Water footprint of 541 L/L of ethanol, in a specific study	44.9 g CO ₂ -eq/MJ, in a specific study	TRL 9, established commercial production
Green hydrogen, produced by alkaline electrolysis	Up to 70%, based on the lower heating value (LHV)	22.3 L/kg of H ₂	Depends on the electricity source and life cycle boundary; no universal value is available	TRL 9, established commercial technology

Green hydrogen, produced by PEM electrolysis	Up to 85%, based on the LHV	17.5 L/kg of H ₂	Depends on the electricity source and life cycle boundary; no universal value is available	TRL 9, commercially available technology
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Source: Prepared based on IRENA (2023), a study on the efficiency assessment of green hydrogen published in Renewable Energy (2024), a study on the water, energy, and carbon footprint of bioethanol published in Environmental Science & Technology (2018), and a review of methanol production routes published in 2026.

The energy and environmental performance of each production route varies according to the technology employed and the conditions under which production takes place. Consequently, comparing ethanol, green hydrogen, and methanol side by side is more complex than it may initially appear. In the case of ethanol, the selected study identifies clear differences between the sugarcane and corn production routes in terms of both energy balance and water and carbon footprints, indicating that the differences are not confined to a single indicator. For green hydrogen, efficiency and water consumption vary depending on the electrolysis technology adopted, whereas emissions are primarily influenced by the electricity supply and the number of process stages included in the assessment. A similar pattern is observed for methanol, for which the origin of the feedstock and the actual integration of renewable hydrogen with CO₂ capture are the main factors determining the carbon intensity of each route. Therefore, any comparison must account for the assessment boundaries adopted and the specific

characteristics of each process. Drawing conclusions from an isolated indicator entails a risk that is clearly demonstrated by the values themselves.

2.3. Engineering, Innovation, And Energy Transition

The energy transition transforms energy generation, conversion, storage, and use systems, requiring Engineering to balance technical performance, process efficiency, and the reduction of emissions associated with productive activities. In this context, advances in conversion technologies and industrial supply chains associated with sustainable fuels ultimately depend on coordination among scientific knowledge, technological development, and the effective ability to scale these advances to industrial production (Oliveira; Guimarães, 2026; International Energy Agency, 2024).

In the case of methanol, ethanol, and green hydrogen, Engineering is involved not merely at a single stage but throughout the entire supply chain. Its activities begin with feedstock selection and preparation and extend through conversion, separation, conditioning, storage, and product distribution. Optimizing these operations involves improving equipment, control systems, and conversion processes, as well as establishing energy recovery strategies that reduce losses and enhance the overall performance of industrial plants (Oliveira et al., 2024).

Technological innovation broadens this scope by integrating new materials, automated systems, monitoring techniques, and methods for interconnecting different industrial processes. Digitalization also enables the monitoring of operational variables and data-driven decision-making, thereby increasing control over production

processes. Consequently, the relationship between Engineering and innovation represents a significant dimension in the development of energy solutions aimed at reducing carbon intensity (Abreu et al., 2026).

Another issue within the scope of Engineering concerns the integration of renewable energy sources into fuel production. Electricity generated from renewable sources can be combined with hydrogen production through electrolysis and, in certain configurations, incorporated into synthetic fuel production chains. Infrastructure must be planned, equipment adapted, and energy availability aligned with industrial demand, while accounting for the operational characteristics of each facility (Gomes et al., 2026; International Energy Agency, 2024).

Technological innovations must overcome the experimental or pilot-project stage and become large-scale solutions within industrial systems. In this regard, factors such as equipment reliability, input availability, integration between units, operational safety, and logistics infrastructure begin to influence technology adoption. Engineering therefore serves as the means through which technological innovations are converted into production arrangements that meet the technical and economic requirements of industry (Oliveira; Guimarães, 2026; Abreu et al., 2026).

To summarize how these various dimensions are interconnected, Board 2 systematically presents the main contributions of Engineering and technological innovation to the methanol, ethanol, and green hydrogen production routes.

Board 2 – Contributions of Engineering and Technological Innovation to Methanol, Ethanol, and Green Hydrogen Production Routes

Technological Area	Engineering Contributions	Technological Innovations and Applications	Relationship with the Energy Transition
Process Optimization	Improvement of reactors, equipment, separation systems, control systems, and operational integration	Automation, variable monitoring, and advanced process control	Reduction of losses and improvement of production system performance
Renewable Energy Integration	Integration of renewable generation with energy conversion units	Electrolysis, hybrid systems, and integration between energy generation and consumption	Expansion of renewable energy use in fuel production
Energy Efficiency	Energy recovery, thermal integration, and operational optimization	Energy management systems and heat recovery technologies	Reduction of specific energy consumption and associated emissions
Expansion of Production Capacity	Equipment sizing, process engineering, infrastructure, and industrial safety	Development of equipment and systems suitable for large-scale production	Expansion of the supply of sustainable fuels
Methanol	Integration of synthesis, separation, and feedstock utilization stages	Routes associated with hydrogen and carbon utilization	Diversification of alternatives for producing fuels and chemical feedstocks

Ethanol	Improvement of processing, fermentation, separation, and energy utilization stages	Automation, industrial integration, and coproduct valorization	Greater efficiency in biofuel production chains
Green Hydrogen	Design and integration of electrolyzers, electrical systems, storage, and infrastructure	Electrolysis powered by renewable sources, control systems, and sectoral integration	Production of an energy carrier associated with the decarbonization of hard-to-electrify sectors
Innovation and Intellectual Property	Development, protection, and incorporation of technological solutions	Patents, technology transfer, and cooperation between research institutions and industry	Stimulation of innovation and technological competitiveness

Source: Prepared based on Oliveira and Guimarães (2026), Gomes et al. (2026), Oliveira et al. (2024), Abreu et al. (2026), Gondim and Matias (2024), Hamasu and Souza (2024), and International Energy Agency (2024).

In the Brazilian context, green hydrogen occupies a prominent position in the energy transition debate for two straightforward reasons: it can be integrated with renewable energy sources and used across a wide range of sectors.

However, moving from discussion to large-scale deployment requires much more than electrolyzers. Infrastructure, regulation, operational safety, and, in a way that ties all these elements

together, the establishment of conditions that enable the implementation of production chains are also required. Gondim and Matias (2024) address this issue by linking green hydrogen development to the institutional and regulatory advances that Brazil still needs to achieve.

The industrial dimension of the energy transition is also connected to innovation policies and technological development strategies. In Brazil, the implementation of decarbonization projects and productive modernization depends on coordination among industrial policy, science, technology, and innovation financing. Hamatsu and Souza (2024) associate this coordination with the Nova Indústria Brasil initiative and funding mechanisms aimed at technological development and the energy transition itself.

Engineering also contributes through the development, adaptation, and protection of technological solutions capable of meeting the requirements of emerging production chains.

In this context, intellectual property helps structure technological development strategies, register solutions applied to industrial processes, and facilitate knowledge transfer between research institutions and companies. The integration of innovation, technological development, and industrial property can therefore strengthen the productive and technological capabilities associated with renewable energy sources and sustainable fuels (Gomes et al., 2026; Oliveira et al., 2024).

The expansion of methanol, ethanol, and green hydrogen production routes consequently depends on the convergence of

process improvement, technological innovation, industrial infrastructure, and development policies.

This coordination makes it possible to consider not only the efficiency of conversion technologies but also the conditions required for their implementation at different scales and in different production contexts.

From this perspective, Engineering provides a framework for integrating technical knowledge, innovation, and the organization of production systems, thereby contributing to the consolidation of energy alternatives compatible with the transition toward lower-carbon systems (Hamatsu; Souza, 2024; International Energy Agency, 2024).

2.3.1. Environmental Impacts Of Production Routes

The environmental impacts of the fuels analyzed depend on feedstocks, the energy mix, production scale, and the boundaries adopted to account for each stage. Therefore, life cycle assessment (LCA), with an explicitly defined functional unit and system boundaries, enables comparisons of greenhouse gas emissions and other indicators without assuming that a renewable production route is automatically free of environmental impacts.

In the case of methanol, the conventional route based on fossil resources generates emissions associated with feedstock extraction and industrial conversion. Routes based on biomass, waste, or synthesis using captured CO₂ may reduce greenhouse gas intensity, but the outcome depends on the carbon source, the energy used to produce hydrogen, and the method employed to allocate impacts among coproducts. Recent LCA studies highlight significant

differences among feedstocks and production configurations (Badger et al., 2024; Masum et al., 2025).

In ethanol production, in addition to energy and water consumption during agricultural and industrial stages, land use and land-use change, fertilizer application, and emissions associated with cultivation must also be considered. Land expansion may place pressure on ecosystems and increase competition for land. Conversely, productivity gains, improved management practices, and coproduct utilization may reduce the intensity of environmental impacts. For sugarcane production in Brazil's Center-South region, LCA indicates that increased productivity and precision agriculture are alternatives for limiting territorial expansion and reducing emissions (Sanchez et al., 2023).

For green hydrogen, climate performance depends primarily on the use of electricity that is genuinely renewable and has a low carbon intensity. Electrolysis also requires water and equipment whose manufacturing involves materials and energy. Consequently, impacts on resources, water use, toxicity, and land occupation may occur throughout the supply chain. The prospective analysis by Wei et al. (2024) highlights the climate benefits of electrolysis as electricity generation becomes decarbonized, while also emphasizing the need to assess potential indirect effects and trade-offs among environmental impact categories.

Taken together, this evidence indicates that comparisons among methanol, ethanol, and hydrogen should employ LCA with consistent system boundaries, assumptions, and functional units, covering emissions, water use, land use, and material resources. This approach avoids conclusions based solely on the fuel use phase and

enables the identification of mitigation measures appropriate to each production route.

3. METHODOLOGY

This study investigates methanol, ethanol, and green hydrogen, focusing on technological routes and Engineering perspectives for sustainable fuel production. The topic is situated within a context of transformation in energy systems and the search for alternatives capable of reconciling production efficiency, sustainability, and technological innovation. Addressing such a subject, which spans several fields of knowledge, requires greater methodological care because the information comes from different sources and must be systematically compiled and interpreted. This underscores the importance of defining a coherent research strategy from the outset to ensure organization, consistency, and rigor throughout the study (Alexandre, 2021; Risemberg; Wakin; Shitsuka, 2026).

A qualitative approach was adopted, prioritizing the systematic interpretation of information related to technological routes, feedstocks, production processes, sustainability, and the contributions of Engineering. Qualitative research is widely used in scientific studies because it enables complex phenomena to be understood in terms of their characteristics, relationships, and contexts, supporting well-grounded interpretations of aspects that cannot be adequately examined through the simple measurement of variables alone. Alexandre (2021) argues that different methodological strategies should be combined according to the nature of the research problem, while Risemberg, Wakin, and Shitsuka (2026) emphasize the importance of scientific methodology in organizing and developing academic research.

Two research procedures were employed: a literature review and documentary research. The literature review involved examining theses, monographs, scientific articles published in journals, and books retrieved from academic and institutional repositories, scientific journals, and platforms for publishing and accessing scientific knowledge. This procedure made it possible to compile studies on methanol, ethanol, and green hydrogen production, covering technological, energy-related, environmental, and Engineering aspects. Bibliographic research is characterized by the systematic use of existing theoretical literature on a given subject, enabling researchers to engage in an organized manner with previously established knowledge (Sousa; Oliveira; Alves, 2021).

The literature review was particularly relevant to this investigation because it provided a conceptual and scientific foundation for understanding the different production routes analyzed. It enabled the examination of contributions addressing production processes, feedstocks, conversion technologies, efficiency, sustainability, innovation, and the energy transition. The selection of different types of academic publications also made it possible to bring together perspectives from undergraduate and graduate research, scientific journals, and specialized books. Sousa, Oliveira, and Alves (2021) emphasize that bibliographic research is based on the theoretical contributions of other authors and requires the appropriate organization of sources used in the construction of scientific knowledge.

The second procedure was documentary research, which was used to complement the information obtained from the scientific literature through the analysis of technical and institutional documents related to the subject under investigation. The

documents examined were ComCiência, Challenges in Sustainable Hydrogen Production (2021); the International Energy Agency (IEA), Energy Technology Perspectives 2024; the International Renewable Energy Agency (IRENA), Analysis of the Potential for Green Hydrogen and Related Commodities Trade (2025); and the Renewable Fuels Association, 2021 Ethanol Industry Outlook. The selection of these materials made it possible to incorporate information produced by organizations and entities specializing in the energy, hydrogen, and biofuel sectors.

Documentary research is important in scientific investigations because it enables the analysis of records produced in different institutional contexts, provided that their selection and interpretation are conducted systematically and consistently with the research problem. Alves et al. (2021) emphasize that documentary analysis is a research method in which documents should not be selected randomly. Rather, their relevance to the study's objectives must be considered. In the present study, this procedure made it possible to complement the academic literature with technical and institutional information directly related to the energy technologies and fuels examined.

The documents were analyzed in conjunction with the literature review, considering information on technological routes, feedstocks, production processes, applications, efficiency, sustainability, innovation, and the energy transition. The use of technical and institutional documents complemented the knowledge synthesized from articles, books, theses, and monographs, establishing a relationship between academic research and information provided by specialized institutions. This approach is consistent with the methodological perspective of Alexandre (2021), according to which

the selection of research strategies should be aligned with the nature of the problem and the established objectives.

The combined use of these two procedures was appropriate to the aims of the study because the literature review provided the scientific foundation necessary to understand the technological routes and their characteristics, while documentary research added technical and institutional information concerning contemporary developments in the sectors analyzed. The complementarity of these strategies enabled a more comprehensive qualitative approach by integrating established academic knowledge with specialized documents. Thus, the methodological choices remained consistent with the research question and the established objectives, strengthening the coherence of the analysis conducted (Sousa; Oliveira; Alves, 2021; Alves et al., 2021; Alexandre, 2021).

4. FINAL CONSIDERATIONS

Based on the theoretical framework, it was established that the assessment of production routes cannot be limited to the final product. It must also account for the origin of feedstocks, energy and water consumption, process yields, resource utilization, and emissions at each stage of production. Since sustainability characteristics depend on technological configurations and operating conditions, only integrated assessments allow for fair comparisons among the available alternatives. Within this balance, the abundance of renewable resources, together with the efficiency with which they are converted, plays a significant role in determining the most appropriate production strategies for each situation.

The third component of the theoretical framework demonstrated that Engineering plays a cross-cutting role throughout the production chains investigated, from equipment development and optimization to process automation and control, as well as energy integration, renewable energy utilization, and production scale-up. New technologies improve the coordination of the different stages of these chains and can thereby enhance the functional performance of the systems. In other words, technological advancement and industrial integration go hand in hand with the expansion of sustainable fuel production options.

However, scaling up these production routes faces challenges clearly identified in the analysis: reducing production costs, ensuring the availability of feedstocks and renewable electricity, improving process efficiency, and developing adequate infrastructure for fuel storage, transportation, and distribution. The relative importance of these challenges varies according to the technology employed, production scale, and regional implementation conditions. This alone rules out the assumption that a single technological solution could independently meet all the requirements of the energy transition. Methanol, ethanol, and green hydrogen have distinct characteristics in terms of inputs, conversion processes, infrastructure requirements, applications, and integration into energy systems. Therefore, selecting and scaling up these alternatives necessarily depends on the technical and environmental characteristics of each route, the resources available, existing infrastructure, and the conditions for integration across different end-use sectors.

This study was limited to organizing and cross-referencing information on methanol, ethanol, and green hydrogen production

routes by bringing together three complementary dimensions: the technological characteristics of each route, process efficiency and sustainability, and the role of Engineering in improving these processes. Examining these three dimensions together avoids reducing the fuels to an exclusively energy-related or environmental perspective and highlights the need to align technological development, innovation, and industrial planning in the development of alternatives for lower-carbon energy systems.

Nevertheless, several aspects remain beyond the scope of this study, particularly technical, economic, and environmental comparative assessments of the production routes incorporating indicators of energy consumption, water use, greenhouse gas emissions, costs, and conversion efficiency. Further research could also include life cycle assessments, regional feasibility analyses for different parts of Brazil, and investigations into the integration of renewable energy sources, hydrogen production, methanol synthesis, and ethanol coproduct utilization. Experimental studies and pilot-plant analyses would also help bridge the gap between theoretical results and actual industrial operating conditions.

Ultimately, sustainable fuel production depends on a combination of appropriate technological routes, efficient and responsible use of feedstocks and resources, process efficiency, innovation, and the Engineering expertise that supports these elements, as demonstrated by this study. Despite their differences, methanol, ethanol, and green hydrogen can contribute to distinct strategies for transitioning energy systems. By bringing these dimensions together in a single comparative analysis, this research systematizes existing knowledge about the technological alternatives examined and identifies the technical, environmental, and infrastructural

conditions that influence their expansion, albeit qualitatively. Complementary quantitative investigations conducted under consistent methodological criteria will be necessary to compare the performance of these routes and bring theoretical assessments closer to the actual conditions of industrial application.

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