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Systematic Literature Review and Bibliometric Analysis on Low-Carbon Hydrogen: EESG Perspectives

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RESUMO: Este estudo conduz uma revisão sistemática da literatura e uma análise bibliométrica da cadeia de produção de hidrogénio de baixo carbono, abordando suas dimensões Económica, Ambiental, Social e de Governança (EESG). A procura foi realizada na base Scopus utilizando palavras-chave relacionadas a hidrogénio verde e sustentabilidade, resultando em um conjunto abrangente de publicações analisadas. A análise bibliométrica revelou uma ampla rede internacional de colaborações científicas, com destaque para a liderança de países como Estados Unidos, China, Alemanha, Reino Unido e Japão. Os resultados indicaram um foco predominante na dimensão ambiental, particularmente na redução das emissões de gases de efeito estufa, e na dimensão económica, abrangendo custos, potencial de mercado e investimentos em infraestrutura. Em contraste, as dimensões social e de governança receberam menor atenção, evidenciando lacunas significativas em aspectos como inclusão social, geração de empregos e regulamentações estáveis. Além disso, observou-se uma concentração das pesquisas na fase de produção do hidrogénio, enquanto as etapas de armazenamento, distribuição e consumo ainda carecem de investigações mais aprofundadas. Com base nesses achados, o estudo recomenda uma abordagem mais integrada das dimensões EESG, procurando equilibrar eficiência técnica, viabilidade económica, aceitação social e governança sólida. Conclui-se que a transição para o hidrogénio de baixo carbono exige políticas coordenadas e maior colaboração internacional para superar desafios tecnológicos e econômicos. Este trabalho fornece uma base sólida para pesquisas futuras e formulação de políticas públicas, contribuindo para um modelo energético mais sustentável e inclusivo.

PALAVRAS-CHAVE: Hidrogénio de Baixo Carbono; EESG; Revisão Sistemática da Literatura; Desenvolvimento Sustentável.

ABSTRACT: This study conducts a systematic literature review and a bibliometric analysis of the low-carbon hydrogen production chain, addressing its Economic, Environmental, Social, and Governance (EESG) dimensions. The search was performed in the Scopus database using keywords related to green hydrogen and sustainability, resulting in a comprehensive set of analyzed publications. The bibliometric analysis revealed a broad international network of scientific collaborations, highlighting the leadership of countries such as the United States, China, Germany, the United Kingdom, and Japan. The results indicated a predominant focus on the environmental dimension, particularly on reducing greenhouse gas emissions, and on the economic dimension, encompassing costs, market potential, and infrastructure investments. In contrast, the social and governance dimensions received less attention, revealing significant gaps in aspects such as social inclusion, job creation, and stable regulations. Additionally, research was found to be concentrated mainly on the hydrogen production phase, while the stages of storage, distribution, and consumption still lack deeper investigation. Based on these findings, the study recommends a more integrated approach to the EESG dimensions, aiming to balance technical efficiency, economic feasibility, social acceptance, and robust governance. It is concluded that the transition to low-carbon hydrogen requires coordinated policies and

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greater international collaboration to overcome technological and economic challenges. This study provides a solid foundation for future research and policy formulation, contributing to a more sustainable and inclusive energy model.

KEYWORDS: Low-Carbon Hydrogen; EESG; Sistematic Literature Review; Sustainable development.

RESUMEN: Este estudio realiza una revisión sistemática de la literatura y un análisis bibliométrico de la cadena de producción de hidrógeno de bajo carbono, abordando sus dimensiones Económica, Ambiental, Social y de Gobernanza (EESG). La búsqueda se llevó a cabo en la base de datos Scopus utilizando palabras clave relacionadas con el hidrógeno verde y la sostenibilidad, lo que resultó en un conjunto amplio de publicaciones analizadas. El análisis bibliométrico reveló una extensa red internacional de colaboraciones científicas, destacando el liderazgo de países como Estados Unidos, China, Alemania, Reino Unido y Japón. Los resultados indicaron un enfoque predominante en la dimensión ambiental, particularmente en la reducción de las emisiones de gases de efecto invernadero, y en la dimensión económica, abarcando costos, potencial de mercado e inversiones en infraestructura. En contraste, las dimensiones social y de gobernanza recibieron menos atención, lo que evidencia lagunas significativas en aspectos como inclusión social, generación de empleo y regulaciones estables. Además, se observó una concentración de las investigaciones en la fase de producción del hidrógeno, mientras que las etapas de almacenamiento, distribución y consumo aún requieren estudios más profundos.Con base en estos hallazgos, el estudio recomienda un enfoque más integrado de las dimensiones EESG, con el objetivo de equilibrar la eficiencia técnica, la viabilidad económica, la aceptación social y una gobernanza sólida. Se concluye que la transición hacia el hidrógeno de bajo carbono requiere políticas coordinadas y una mayor colaboración internacional para superar desafíos tecnológicos y económicos. Este estudio proporciona una base sólida para futuras investigaciones y la formulación de políticas públicas, contribuyendo a un modelo energético más sostenible e inclusivo.

PALABRAS CLAVE: Hidrógeno de Bajo Carbono; EESG; Revisión Sistemática de la Literatura; Desarrollo Sostenible.

1. Introduction

The global energy transition has been widely discussed in recent years, focusing on the urgent need to reduce carbon emissions and mitigate the impacts of climate change (Edwards et al., 2022; Kabeyi & Olanrewaju 2022). In this context, low-carbon hydrogen emerges as a promising solution, offering significant potential to decarbonize various sectors, including transportation, industry, and power generation (Butturi & Gamberini, 2022; Oliveira, Beswick & Yan 2021). For low-carbon hydrogen to be effectively integrated into the global energy system, key challenges must be addressed, and a comprehensive understanding of its production chain, as well as the Environmental, Economic, Social, and Governance (EESG) dimensions involved, are necessary (Zavarkó, 2023).

Currently, the incorporation of EESG criteria in the production of low-carbon hydrogen is essential to ensure long-term sustainability and viability. Recent research highlights the importance of adopting EESG principles to increase transparency, foster stakeholder trust, and promote sustainable practices throughout the hydrogen value chain. Studies show that low-carbon hydrogen, produced via renewable energy sources, can significantly reduce greenhouse gas emissions and contribute to the decarbonization of various industries (Lau & Tsai, 2022; Oliveira et al., 2021). Additionally, the inclusion of social aspects, such as community engagement and equitable job creation, along with robust governance frameworks, ensures that the hydrogen economy develops in a way that benefits all stakeholders and supports global climate goals (Dillman & Heinonen, 2023; Zavarkó 2023).

The global energy matrix based on fossil fuels presents significant limitations, particularly regarding environmental impacts and dependence on finite resources, which hinder efforts to reduce carbon emissions (Hou et al., 2023). Although technologies associated with fossil fuels, such as oil, coal, and natural gas, have been extensively developed and optimized over more than a century, their use remains the primary driver of greenhouse gas emissions, intensifying climate change and accelerating environmental degradation (Wen et al., 2021). This dependency creates a pressing need for a transition to sustainable and renewable energy

alternatives to achieve long-term climate goals and ensure a cleaner and more resilient energy future (Chenic et al., 2022; Lv, 2023).

In the current literature, the production of low-carbon hydrogen is extensively studied, particularly in relation to its potential to contribute to the global energy transition. However, many studies tend to examine the economic, environmental, social, and governance (EESG) dimensions in isolation, without adequately integrating these aspects into a comprehensive framework. This study addresses this gap by providing a detailed analysis that incorporates all EESG dimensions, thereby offering a holistic perspective on the state

of low-carbon hydrogen production. Through a systematic literature review and bibliometric analysis, this research identifies not only the trends and significant scientific contributions but also the existing gaps in the field. While systematic literature reviews are often utilized to understand the current state of research (Zhou, 2022), this study goes further by combining it with a bibliometric analysis, which reveals the geographical distribution of research, institutional collaborations, and the key players involved (Donthu et al., 2021). This integrated approach contributes to a more complete understanding of the challenges and opportunities associated with low-carbon hydrogen, thus providing a solid foundation for future research and policy-making in this critical area (Gorji, 2023).

Therefore, through the combination of these two methodologies, the study contributes to research by addressing underexplored social and governance aspects (Blohm & Dettner, 2023; Dillman & Heinonen, 2023; Zavarkó, 2023), mapping gaps in the hydrogen value chain (Chapman et al., 2020; Rampai et al., 2024), and identifying global collaborations and funding sources (Fan et al., 2021; Kar et al., 2023; Song et al., 2022), thereby providing support for strategic decision-making and the development of integrated policies aimed at the sector's sustainable growth. What distinguishes this article from other bibliometric studies is the combined use of a systematic literature review and bibliometric analysis to integrate the EESG dimensions across the entire low-carbon hydrogen value chain. This dual approach not only reveals research trends and collaboration networks but also highlights underexplored stages such as storage, distribution, and consumption, providing actionable insights for academia, policymakers, and industry.

In light of these considerations, this study addresses the challenges and opportunities of the global energy transition, emphasizing the importance of integrated policies and a holistic approach to promoting the adoption and scalability of low-carbon hydrogen. Ultimately, it seeks to provide a solid foundation for researchers, policymakers, and stakeholders, contributing to a cleaner and more sustainable energy future. This paper is an extended version of the work presented at the VIII Ibero-American Congress on Entrepreneurship, Energy, Environment, and Technology (CIEEMAT 2024), titled *Systematic Literature Review and Bibliometric Analysis on Low-Carbon Hydrogen: EESG Perspectives* (Ramos, Penalva Santos, & Boloy, 2024). The remainder of this paper is organized as follows: Section 2 describes the methodological approach, including the systematic literature review process and bibliometric analysis procedures. Section 3 presents the results, outlining the main research trends, collaboration networks, and identified gaps in the field. Finally, Section 4 provides the main conclusions and suggests directions for future research, followed by the list of references used in the study.

2. Methods

The analysis presented in this paper was conducted using a search in the Scopus database with the following Boolean search string: (("low-carbon hydrogen" OR "green hydrogen") AND ("sustainability" OR "corporate social responsibility" OR "corporate governance")). The Scopus database was selected due to its relevance and extensive coverage of high-impact journals. The initial search yielded 598 documents, which were refined by applying filters to include only open-access journal articles published in English between 2020 and 2024, reducing the total to 185 articles. Next, a screening process based on title analysis and abstract reading was conducted to select only studies that directly and objectively addressed the specific research topic. After this stage, 27 articles met the eligibility criteria for analysis. Finally, after a full-text review, 16 articles were deemed fully aligned with the study's scope and included in the meta-analysis.

A combined bibliometric and systematic review approach was adopted to provide an in-depth analysis of the management of the low-carbon hydrogen production chain, focusing on environmental, economic, social, and governance dimensions.

The bibliometric analysis, conducted using the Bibliometrix software, enabled the mapping of trends

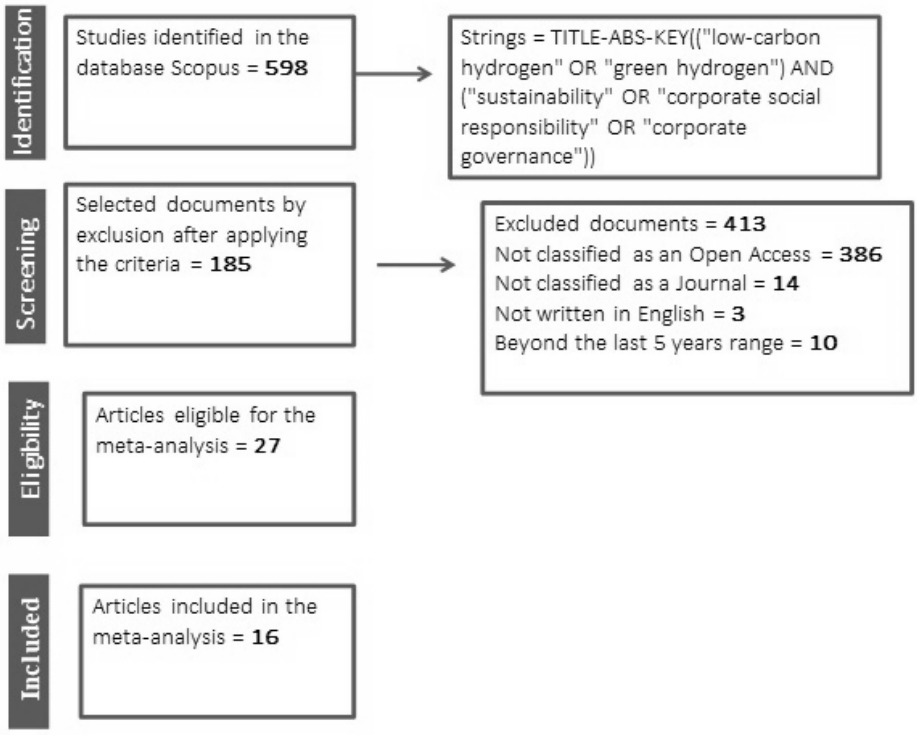
and gaps in the literature based on general quantitative data, that is, from the initial search performed in the Scopus database before applying any filters. This approach followed the recommendations of Donthu et al. (2021) and provided a comprehensive overview of the academic production on the topic.

Additionally, a systematic literature review was conducted using the PRISMA method (Zhou, 2022), ensuring transparency and methodological rigor in the review process while also providing qualitative support for the analysis. This method, which includes the identification, screening, eligibility, and inclusion phases, ultimately resulted in the selection of 16 articles for the meta-analysis, as shown in Figure 1.

Based on the collected data, key questions were formulated for qualitative analysis: 1) At which stage of the hydrogen production chain does the study focus? 2) What type of analysis was used? 3) Which EESG dimensions (economic, environmental, social, and governance) are addressed in the study? 4) What are the main impacts of the EESG dimensions?

Figure 1

PRISMA Flow Diagram – Screening.



(Source: Developed by the authors).

3. Results and Discussion

The presentation and discussion of the results are organized into two subtopics, aiming to explore each methodological approach in detail. Section 3.1 addresses the results of the bibliometric study, based on the 598 articles initially retrieved from the Scopus database using the predefined search string. This stage highlights critical points and gaps in the literature, identified from the collected data. Subsequently, Section 3.2 focuses on the systematic review, providing an in-depth analysis of the articles selected for the meta-analysis, with an emphasis on the application of the PRISMA method.

3.1. Bibliometric study

3.1.1. Word Cloud

The word cloud is an effective tool for identifying emerging themes, topics of current interest, and areas with the highest scientific production within a field of study. This analysis was conducted using the Bibliometrix

software, as illustrated in Figure 2.

Figure 2
Word Cloud.

(Source: Developed by the authors using the Bibliometrix software).

It can be observed in Figure 2 that the term green hydrogen is highlighted as it represents a strategic vector for sustainable energy transition (Blohm & Dettner, 2023; Kovač, et al., 2021). Other important terms emphasized within this context include: “electrolysis,” “water electrolysis,” and “electrolyzers,” reflecting the primary role of electrolysis in green hydrogen production. However, it is important to note that if the energy used in electrolysis originates from non-renewable sources, the resulting hydrogen will not be considered sustainable.

Among renewable energy sources, the most significant for green hydrogen production are solar energy, as evidenced by terms such as “solar power generation” and “solar energy,” followed by “wind power” and, to a lesser extent, “biomass.” These results align with the scientific focus on renewable energy sources for sustainable hydrogen production (Kakoulaki et al., 2021; Nurdiawati & Urban, 2022; Wu et al., 2022).

The association of green hydrogen with terms such as “renewable energies,” “sustainability,” “carbon dioxide,” “clean energy,” “climate change,” “emission control,” “gas emissions,” and “global warming” underscores its role in addressing climate change and reducing emissions. Furthermore, the term “hydrogen storage” highlights the critical importance of efficient storage technologies for enabling the use of green hydrogen on a broader scale (Qudaih et al., 2024).

Economic aspects are also prominent, as reflected in terms like “cost benefit analysis,” “costs,” “cost effectiveness,” and “investments,” which indicate the financial challenges and opportunities associated with green hydrogen systems (Jovan & Dolanc, 2020). Additionally, terms like “hydrogen fuels,” “fuel cells,” and “fossil fuels” suggest applications in fuel cells, vehicles, and energy systems, showcasing the wide-ranging potential of green hydrogen technologies (Peksen, 2021).

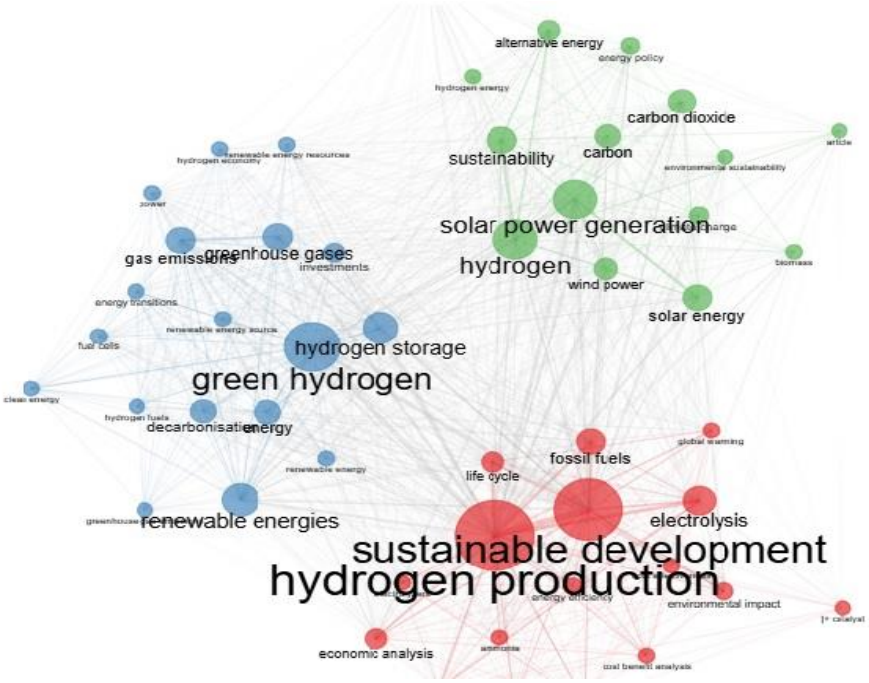
The production of hydrogen via electrolysis powered by renewable energies emerges as a crucial technological focus for decarbonization (Kakoulaki et al., 2021; Nurdiawati & Urban, 2022; Wu et al., 2022). However, the relevance of hydrogen in the global energy scenario depends on overcoming challenges related to costs and scalability, which require robust public policies and efficient governance to ensure its widespread adoption (Chapman et al., 2020; Fazioli & Pantaleone, 2021).

3.1.2. Co-occurrence network of words

Keywords can be analyzed based on the number of occurrences and co-occurrence with other keywords, presenting connections with various thematic dimensions, as shown in Figure 3.

Figure 3

Co-occurrence of keywords.



(Source: Developed by the authors using the Bibliometrix software).

The presented image highlights sustainable hydrogen production as the central theme and its correlation with issues such as sustainability, renewable energy, and decarbonization. The terms *sustainable development* and *hydrogen production*, present in the red clusters, stand out, emphasizing the need to replace fossil fuels with cleaner alternatives, such as green hydrogen, while addressing economic and technological challenges (Sgarbossa et al., 2022; Sgarbossa et al., 2023; Weidner et al., 2023).

The surrounding clusters reflect complementary approaches: the blue cluster emphasizes *green hydrogen* and its connection to *renewable energy*, highlighting its role in reducing *greenhouse gas emissions* and decarbonizing critical sectors. Meanwhile, the green cluster focuses on energy sources such as *solar and wind*, reinforcing their importance in the sustainable production of hydrogen with a low *carbon* footprint. These themes underscore the interdependence between environmental sustainability, economic feasibility, and technological innovation.

Finally, the three clusters depicted in the co-occurrence network are interconnected through cross-cutting themes that reinforce a systemic approach to sustainable hydrogen development. The red cluster underscores the strategic importance of aligning technological advancements with sustainability goals, as evidenced by terms such as "sustainable development" and "hydrogen production," which highlight the transition from fossil fuels to cleaner alternatives like green hydrogen. This cluster serves as the central axis for envisioning a decarbonized energy future.

The blue cluster focuses on renewable energy sources, such as solar energy, wind power, and greenhouse gas emission reductions, providing practical insights into the resources required for green hydrogen production. Additionally, the term "hydrogen storage" appears prominently in this cluster, signifying its critical role in advancing green hydrogen systems. However, despite its importance, hydrogen storage remains an underexplored topic in current scientific research, leaving space for future advancements and innovation (Rampai et al., 2024).

In contrast, the green cluster highlights broader environmental dimensions, emphasizing themes such as "sustainability," "carbon," and "solar energy." This cluster reflects the intersection of environmental

concerns and renewable energy technologies, providing a complementary perspective to the technological and resource-oriented focus of the other clusters.

Together, these clusters create an integrated panorama, reinforcing the conclusions of Chapman et al. (2020), who argued that the success of sustainable hydrogen depends on a holistic approach. Such an approach must effectively connect resources, technologies, and policies into a unified global decarbonization agenda, bridging gaps between scientific advancements and their practical and policy-driven applications.

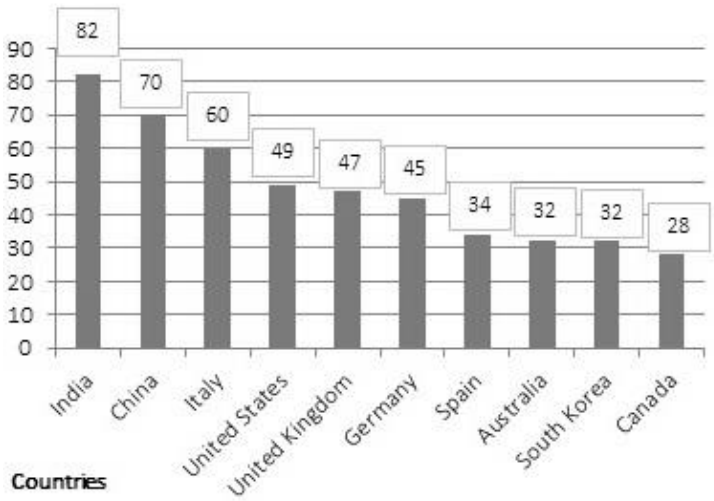
3.1.3. Documents by country

In Figure 4, based on the overall results from Scopus, the 10 countries with the highest number of publications on the topic are presented. Notably, India, China, and Italy lead in the number of published documents, with 82, 70, and 60 publications, respectively. The prominence of these countries is associated with national strategies aimed at decarbonization, robust investments in innovation, and a favorable energy infrastructure. China, with its carbon neutrality target set for 2060, is heavily investing in hydrogen technologies and leads in the number of patents in the field (Fan et al., 2021). India, through the National Hydrogen Mission, seeks to reduce its dependence on fossil fuels and strengthen international partnerships (Kar et al., 2023). Meanwhile, Italy, driven by European Union guidelines, focuses on the development of electrolysis and storage technologies, consolidating its position in advancing the hydrogen economy (Fragiacomo & Genovese, 2020).

The United States, the United Kingdom, and Germany stand out in low-carbon hydrogen research, with a significant volume of publications (between 49 and 45 documents), reflecting their well-established scientific infrastructures, well-structured energy policies, and strong financial incentives, such as the Hydrogen Shot in the U.S. and the National Hydrogen Strategy in Germany (Miller, 2022; Nunes & Quitzow, 2024). In contrast, countries like Canada (28 publications) and South Korea (32) exhibit lower academic representation, a consequence of distinct strategic challenges: while Canada prioritizes green hydrogen production and export, South Korea focuses on industrial implementation, which limits emphasis on fundamental research (Gupta & Trivedi, 2023; Lee & Kim, 2021). Spain (34 publications) and Australia (32) occupy an intermediate position, driven by investments in renewable energy and promising industrial initiatives, yet they still lack a more robust structure for fostering scientific research (Li et al., 2020; Sorman et al., 2020). Thus, differences in publication volume not only highlight each country's level of engagement in the energy transition but also reveal their ability to align research, innovation, and technological development with decarbonization strategies.

Figure 4

Documents by country.



(Source: Developed by the authors using Microsoft Excel).

3.1.4. Documents by funding sponsor

Figure 5 highlights the leadership of the European Commission, with 32 funded documents, reflecting the European Union's commitment to leading the sustainable energy transition. China follows closely, with 30 documents funded by the National Natural Science Foundation and 18 by the Ministry of Science and Technology, reinforcing its strategic position in the development and export of low-carbon hydrogen technologies. South Korea also stands out, with 19 documents funded by its National Research Foundation. Furthermore, India, with 11 documents funded by its Department of Science and Technology, demonstrates its interest in integrating low-carbon hydrogen into its sustainable growth and emissions reduction strategies, consolidating its relevance among developing countries in this field, as highlighted by Song et al. (2022).

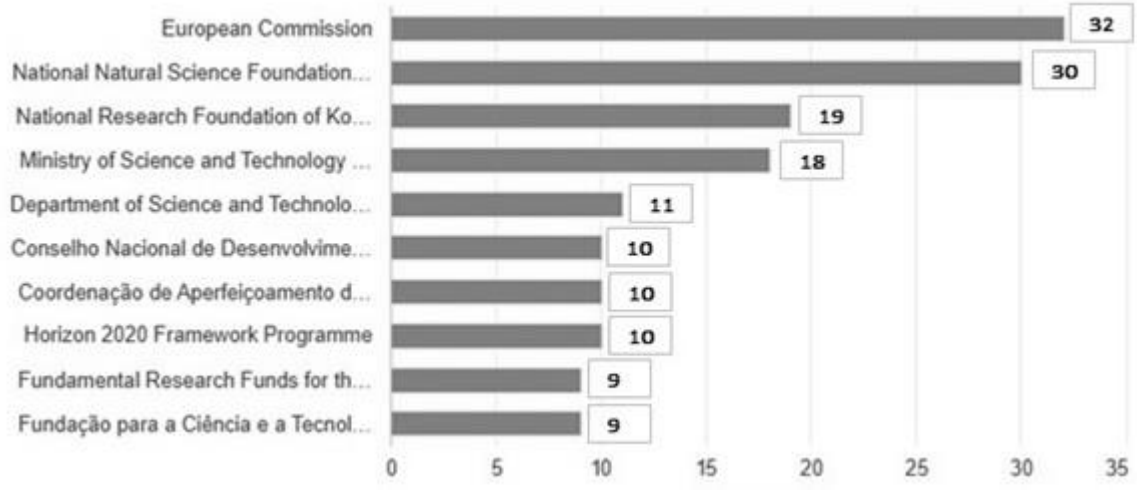
In the case of Brazil, institutions such as the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) each account for 10 documents, highlighting their limited participation. Despite the existence of funding agencies, the low number of publications in Brazil may be associated with challenges such as fragmented investments, reliance on sporadic public funding calls, and difficulties in translating research into high-impact publications. Additionally, bureaucratic obstacles, the need for greater international cooperation, and a limited culture of scientific dissemination may restrict the visibility of advancements in hydrogen technologies. These factors hinder Brazil's consolidation as a globally relevant player in the sector (Goés et al., 2021).

Other initiatives, such as the European Union's Horizon 2020 program (10 documents) and Fundação para a Ciência e a Tecnologia from Portugal (9 documents), further reinforce the European focus on scientific collaborations aimed at decarbonization (Bairrão et al., 2023).

The data highlight a concentration of funding in regions with greater economic capacity and technological infrastructure, while developing countries face barriers to competing in this sector.

Figure 5

Documents by funding sponsor.



(Source: Developed by the authors using Scopus database and adapted in Microsoft Excel).

3.1.5. Documents by year

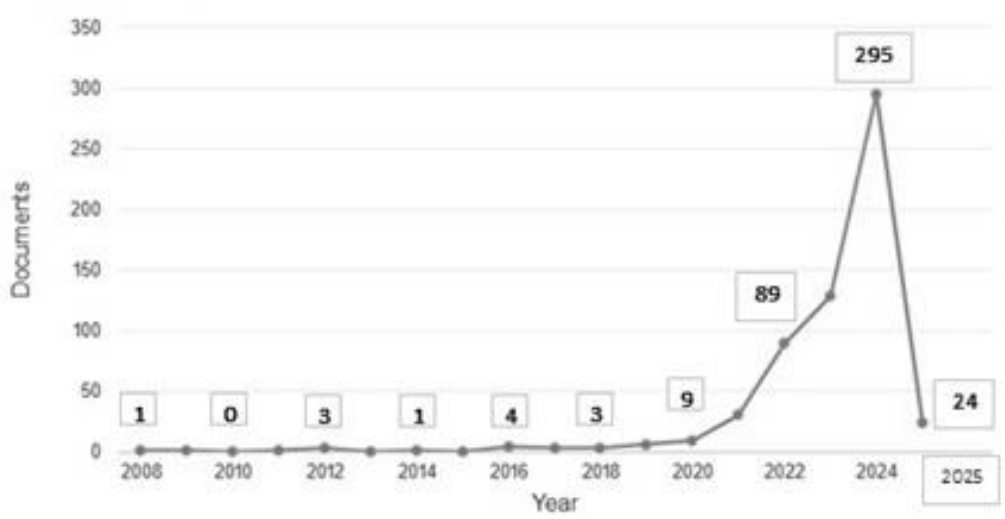
Based on general data from Scopus, the analysis covers the period from 2008 to 2025, providing an overview of the evolution of annual publications on the topic. During the period analyzed in Figure 6, the limited number of publications between 2008 and 2020 can be attributed to the initially low interest and the still incipient development of green hydrogen, as well as the prioritization of other renewable energy sources (Marouani et al., 2023). During this period, only 21 publications were recorded in total, with a very low annual frequency.

From 2022 onwards, there was a significant increase, with 89 publications recorded, culminating in a peak of 295 publications in 2024. This growth may have been driven by global policies, such as the Paris Agreement, increased investments in clean technologies, and growing awareness of climate change (Andresen et al., 2021). Additionally, geopolitical crises, such as the energy crisis, may have intensified interest in green hydrogen research (Noussan et al., 2020).

In 2025, 24 publications have been recorded so far. However, since the data was collected on January 10, 2025, this number is still partial, as the year is ongoing and new publications may be added throughout the period.

Figure 6

Documents by year.



(Source: Developed by the authors using Scopus database and adapted in Microsoft Excel).

3.2. PRISMA meta-analysis

Table 1 below presents the PRISMA meta-analysis, considering the article title and authors, keywords, stage of the hydrogen production chain, EESG dimensions addressed, and main EESG impacts.

Table 1

PRISMA meta-analisys.

Article Title / Authors	Keywords	Stage of Hydrogen Production Chain	EESG Dimensions Addressed	Main EESG Impacts
A decarbonization Roadmap for Taiwan and Its Energy Policy Implications (Lau & Tsai, 2022)	Taiwan; decarbonization roadmap; energy transition; carbon capture and storage; renewable energies.	Production	Environmental	Energy & Carbon Cycle
Accelerating sustainability transitions: the case of the hydrogen agenda in the North West region of England (Edwards et al., 2022)	Decarbonization; hydrogen; sustainability; policy; transition	Hydrogen production; Hydrogen storage; Hydrogen distribution; Carbon capture and storage (CCS) technologies.	Environmental	Pollution Risks & Safety
Challenges and opportunities in green hydrogen supply chain through metaheuristic optimization (Gorji, 2023)	consumption, green hydrogen, metaheuristic optimization, production, storage, transportation.	production; storage; transportation; consumption.	Economic; Social; Environmental; Governance.	Energy & Carbon Cycle
Decarbonising the refinery sector: A socio-technical analysis of advanced biofuels, green hydrogen and carbon capture and storage developments in Sweden (Nurdiawati & Urban, 2022)	Industrial decarbonisation; Sustainability transition; Innovation system; CCS; Hydrogen; Biofuel.	Production	Economic; Social; Environmental; Governance.	Pollution Risks & Safety
Deep decarbonization of the Indian economy: 2050 prospects for wind, solar, and green hydrogen (Song et al., 2022)	Deep decarbonization; Indian economy; Wind energy; Solar energy Green hydrogen.	Power Generation Sector, Industrial Sector, and Transport Sector.	Environmental	Energy & Carbon Cycle

Article Title / Authors	Keywords	Stage of Hydrogen Production Chain	EESG Dimensions Addressed	Main EESG Impacts
Energy Decarbonization via Green H2 or NH3? (Wu et al., 2022)	Decarbonization; Green Hydrogen (H2); Green Ammonia (NH3); Renewable Energy; Energy Storage.	Production	Economic	Value Added & Decouple Growth
Environmental sustainability assessment of large-scale hydrogen production using prospective life cycle analysis (Weidner et al., 2023)	Hydrogen economy; Absolute environmental; sustainability; Green hydrogen.	Production	Environmental	Energy & Carbon Cycle and Pollution Risks & Safety
Green Hydrogen and Energy Transition: Current State and Prospects in Portugal (Bairrão et al., 2023)	carbon footprint; electrolysis; green hydrogen; renewable energy; sustainability.	Production	Environmental	Energy & Carbon Cycle
Green hydrogen production: Integrating environmental and social criteria to ensure sustainability (Blohm & Dettner, 2023)	Green hydrogen; Just transition Measurable criteria; Social sustainability; Sustainability criteria.	Production	Social	"Jobs", "Human Rights", "Skills & Labour Standards"
Green Hydrogen Value Chain in the Sustainability for Port Operations: Case Study in the Region of Valparaiso, Chile (Masip Macía et al., 2021)	green hydrogen; chain value; port operations; renewable energy.	Final consumption	Environmental	Pollution Risks; Carbon Cycle; Energy; Resources; Safety; Policy Commitment & Engagement.
Logical Analysis on the Strategy for a Sustainable Transition of the World to Green Energy—2050. Smart Cities and Villages Coupled to Renewable Energy Sources with Low Carbon Footprint (Chenic et al., 2022)	Climate neutrality; fossil fuels; global warming; greenhouse gases; wind and solar photovoltaic energy; CCUS: carbon capture, use and storage.	Production	Environmental	Pollution Risks; Carbon Cycle; Jobs; Skills; Value Added; Trade; Policy Commitment & Engagement.

Article Title / Authors	Keywords	Stage of Hydrogen Production Chain	EESG Dimensions Addressed	Main EESG Impacts
Macroeconomic Factors Influencing Public Policy Strategies for Blue and Green Hydrogen (Fazioli & Pantaleone, 2021)	Blue hydrogen; green hydrogen; carbon capture; sustainability; energy transition.	Formulation of Public Policies and Strategies.	Economic	Infraestruture & Public Finance; Pollution Risks; Carbon Cycle; Stability; Regulatory Quality.
Renewable hydrogen supply chains: A planning matrix and an agenda for future research (Sgarbossa et al., 2023)	Renewable hydrogen supply chain; Green hydrogen; Supply chain management; Supply chain planning; Literature review.	Supply of raw materials, production, storage, distribution, and final applications.	Economic	Value Added; Jobs; Pollution Risks; Policy Commitment.
Reprint of: Renewable hydrogen supply chains: A planning matrix and an agenda for future research (Sgarbossa et al., 2022)	Renewable hydrogen supply chain; Green hydrogen; Supply chain management; Supply chain planning; Literature review.	Production	Economic	Value Added; Jobs; Pollution Risks; Policy Commitment.
The potencial of hydrogen technologies for low-carbon mobility in the urban-industrial symbiosis approach (Butturi & Gamberini, 2022)	Climate change mitigation; green hydrogen; sustainable mobility; symbiosis; urban-industrial.	Production and storage	Environmental	Value Added; Pollution Risks; Policy Commitment; Health & Safety.
Towards a Safe Hydrogen Economy: An Absolute Climate Sustainability Assessment of Hydrogen Production (Dillman & Heinonen, 2023)	Hydrogen economy; absolute sustainability; safe operating space; hydrogen policy; hydrogen certification	Production	Economic	Public Finance; Human Rights; Pollution Risks; Stability; Regulatory Quality.

(Source: Developed by the authors using the Microsoft Excel).

The following section provides a detailed qualitative analysis of each question individually, offering complementary insights to enrich the bibliometric study.

1) At which stage of the hydrogen production chain does the study focus?

The study predominantly focuses on the hydrogen production phase, highlighting its relevance in the transition to a low-carbon economy. The systematic and bibliometric analysis revealed that most research emphasizes production processes, particularly electrolysis powered by renewable sources, such as solar and wind, due to its potential to mitigate greenhouse gas emissions. Additionally, economic aspects, including infrastructure costs, market feasibility, and necessary investments, were widely discussed. In contrast, the subsequent stages of the hydrogen value chain, such as storage, distribution, and consumption, still lack deeper investigation, revealing gaps that may hinder the scalability and widespread adoption of hydrogen. Therefore, the study underscores the importance of an integrated approach that balances technological efficiency, economic feasibility, and environmental sustainability, while also reinforcing the need for public policies and international collaborations to overcome structural challenges and accelerate the consolidation of hydrogen as a sustainable energy carrier.

2) What type of analysis was used?

The analysis was based on the PRISMA method, which, after applying the selection criteria, resulted in the inclusion of 16 articles for the meta-analysis. The results revealed a predominance of environmental and economic dimensions, focusing on emission reduction and the costs of production and infrastructure for low-carbon hydrogen. Social and governance aspects were less explored, highlighting gaps in social inclusion and sector regulation. Most studies focused on the production phase, while storage, distribution, and consumption received little attention. Quantitative and qualitative methodologies were used, including life cycle assessment, economic modeling, and public policy analysis. The study reinforces the need for an integrated approach, balancing economic viability, environmental sustainability, social inclusion, and regulatory governance, ensuring the scalability of hydrogen as a sustainable energy carrier.

3) Which EESG dimensions (environmental, economic, social, governance) are addressed in the study?

The studies analyzed cover various combinations of EESG dimensions, with a dominant emphasis on environmental aspects. Nearly all articles highlight the environmental dimension, focusing on the potential for greenhouse gas reduction and alignment with global climate targets. The economic dimension is also extensively discussed, particularly in terms of the costs, market potential, and infrastructure investments required for low-carbon hydrogen.

The social dimension, while less frequently addressed, emerges in discussions on equitable job creation, skill development, and community engagement. Articles emphasizing governance explore the regulatory frameworks, policy stability, and the need for comprehensive legislation to support sustainable hydrogen production. The disparity in focus among the EESG dimensions highlights the need for a more integrated approach, particularly to strengthen social and governance considerations.

4) What are the main impacts of the EESG dimensions?

Considering the EESG indicators, the information analyzed to answer these questions included:

The environmental dimension is prominently discussed in the analyzed studies, emphasizing the substantial reduction of greenhouse gas emissions and the mitigation of pollution risks as key benefits of low-carbon hydrogen production. These impacts highlight the role of hydrogen in achieving climate targets, reducing the carbon footprint, and improving air quality. In addition, the environmental advantages extend to the promotion of cleaner energy systems that contribute to global sustainability goals.

The economic dimension focuses on the creation of value-added opportunities and the decoupling of economic growth from carbon emissions. The studies highlight the potential of hydrogen to drive innovation, foster the development of new industries and markets, and enhance competitiveness. Moreover, the necessity of large-scale investments in infrastructure for production, storage, and distribution is underscored

as a critical aspect of establishing a resilient hydrogen economy.

The social dimension, although less frequently explored, reveals meaningful impacts related to job creation, workforce skill development, and improved labor standards. Low-carbon hydrogen initiatives are seen as opportunities for generating employment, particularly in regions transitioning from fossil fuels, and for fostering social inclusion by engaging local communities and ensuring equitable distribution of the benefits derived from hydrogen projects.

Finally, the governance dimension emerges as a crucial factor for the sustainable development of the hydrogen sector. The studies emphasize the need for a stable and robust regulatory framework to support the scalability of low-carbon hydrogen technologies. Effective governance ensures compliance with environmental standards, maximizes economic returns, and promotes equitable social outcomes. Furthermore, policy stability and quality are identified as essential to attracting long-term investments and fostering confidence among stakeholders in the hydrogen value chain.

4. Conclusions

In summary, this study underscores the critical importance of a comprehensive and detailed approach to analyzing the low-carbon hydrogen production chain, integrating environmental, economic, social, and governance (EESG) dimensions. The systematic literature review and bibliometric analysis identified key trends, research gaps, and significant scientific contributions. Notably, most studies focus primarily on the hydrogen production phase, while the subsequent stages, storage, distribution, and consumption, remain relatively underexplored. This predominant emphasis on production is largely driven by the pressing need to curb carbon emissions and enhance the economic feasibility of hydrogen technologies. However, the limited attention given to storage and distribution poses challenges to the large-scale deployment of hydrogen as a sustainable energy carrier, highlighting the need for a more holistic and integrated research agenda.

The results also indicate a predominant emphasis on environmental and economic dimensions, while social and governance dimensions are often underestimated. This imbalance suggests that, although environmental sustainability and economic viability are recognized as crucial, there is a significant gap in considering social impacts and the need for robust governance structures. In the long term, the success of the low-carbon hydrogen transition depends not only on technical efficiency and economic viability but also on social acceptance and the adequacy of regulatory policies. Therefore, a more balanced approach that integrates all EESG dimensions is essential to ensuring sustainable development.

This study highlights that research on low-carbon hydrogen remains primarily focused on the production phase, while the stages of storage, distribution, and consumption remain underexplored. The bibliometric analysis revealed a significant increase in the number of publications over the years, with India, China, and Italy standing out as the leading countries in terms of study volume, driven by national decarbonization strategies and investments in innovation. The United States, the United Kingdom, and Germany also demonstrate strong academic output, supported by well-structured policies and financial incentives aimed at advancing the hydrogen economy. The keyword co-occurrence analysis confirmed the predominance of topics related to production and decarbonization, but also revealed significant gaps in storage and distribution technologies. These findings underscore the need for a more balanced and integrated approach, encouraging research that addresses all stages of the hydrogen value chain and fosters its adoption as a sustainable energy carrier.

In this context, this study makes a significant contribution by providing a solid foundation for future research and policy formulation to bridge these gaps. The proposed recommendations seek to enhance the integration of EESG dimensions, ensuring that social and governance aspects are considered alongside technical and economic challenges. In particular, greater attention should be directed toward job creation, skills development, and the implementation of fair labor standards, as well as the strengthening of governance policies that ensure a stable and predictable environment for investments in the hydrogen sector. The keyword co-occurrence analysis and the growing number of international publications highlight the strategic role of global research and innovation networks in accelerating scientific and technological advancements in this field.

The conclusions of the studies included in the PRISMA meta-analysis reinforce these observations. Most of the reviewed articles highlight the importance of emerging technologies and the need for specific policies to accelerate the transition to a green hydrogen economy. Despite the promising potential of green hydrogen, the studies point to significant barriers in terms of costs and technological development, which demand supportive policies throughout the entire innovation cycle, from research and development to the creation of competitive markets.

The studies also suggest that policies tailored to the specific needs of each sector and region may provide better results in terms of decarbonization and sustainability, rather than a one-size-fits-all approach. This diversity of strategies is essential to effectively address the different industrial and regional realities.

Based on these findings, it is recommended that future studies explore more deeply the social and governance dimensions in low-carbon hydrogen production. The analysis of integrated approaches that holistically consider the economic, social, environmental, and governance impacts will be crucial to ensuring an energy transition that is not only effective in reducing emissions but also fair and inclusive. Additionally, it is vital that new research focuses on the application of hydrogen technologies in various industrial sectors and the exploration of best practices for developing policies that encourage the adoption and scalability of low-carbon hydrogen. These initiatives will contribute to the continuous advancement of the field and the realization of a more sustainable and resilient global economy.

Contributions

FABIANA DE O. RAMOS: Conceptualization, Methodology, Formal Analysis, Investigation, Writing – original draft. DANIEL DE C.L. e PENALVA SANTOS: Conceptualization, Methodology, Formal Analysis, Investigation, Writing – original draft. RONNEY A. MANCEBO BOLOY: Conceptualization, Methodology, Writing – review & editing, Supervision.

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