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Evolving sustainable energy technologies and assessments through global research networks: advancing the role of blue hydrogen for a cleaner future

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Considering the interest in innovations in the energy sector and government policies that seek an energy system free of polluting agents, blue hydrogen, whose production takes place through fossil fuels with the capture of CO_2, is seen as a way to offer economic opportunities for production with a reduced amount of unwanted by-products. Thus, in blue hydrogen research, the United States leads in the number of publications (16) and the number of citations and H-index, closely followed by England, Norway, and China. However, when considering the number of institutions involved in research in this field, the United Kingdom has a prominent place, the main one being Research Libraries UK (RLUK), with 10 articles published. Also notable is the participation of South Korea in the ranking of active development agencies (8%). Thus, advanced bibliometric analysis techniques were implemented in this study, using the Web of Science website, to understand the cooperative relationships between authors, countries, institutions, and agencies in developing research on blue hydrogen, establishing parameters to understand future trends and the main derived subfields. Thus, it is possible to verify the role of the United States as the primary research center today and to identify which topics involve hydrogen production. Future research will address storage routes due to their relevance in integrating blue hydrogen into the energy matrix.

Sustainability spotlight

The sustainable advancement highlighted in this work on blue hydrogen research demonstrates a significant commitment to the United Nations Sustainable Development Goals (SDGs). By focusing on the production of hydrogen with reduced emissions, the study is in line with SDG 7 (Clean and Affordable Energy), contributing to the global energy transition. Furthermore, by highlighting cooperation between countries and institutions, it promotes SDG 17 (Partnerships and Means of Implementation), fostering international collaboration to address environmental challenges. The research also anticipates future hydrogen storage issues, linking to SDG 9 (Industry, Innovation and Infrastructure) by driving technological advancements. Thus, this study not only advances scientific knowledge, but also stands out as a relevant contribution to a more sustainable future, in line with the principles of the UN 2030 Agenda.

1. Introduction

The search for the integration of new sustainable technologies in the energy market has accelerated in recent decades, even in the face of a global context still primarily dominated by fossil fuels in the energy matrix.[1–3] Therefore, transitioning to a matrix based on renewable sources still encounters resistance to investment and security of economic returns from projects of this size.[4,5] That said, hydrogen production has proven to be an essential process for developing an economy integrated with clean and sustainable energy, considering that it is a versatile fuel capable of replacing fossil fuels in various sectors, such as transport and industry.[6–8] Hydrogen can be regarded as a clean alternative because when used in fuel cells, it only produces H_2O and does not emit polluting gases such as carbon dioxide and nitrogen oxides.[9] In this scenario, we have the blue category of hydrogen production emerging as one of the most promising technologies to meet the growing demand for hydrogen in the market and help reduce the emission of greenhouse gases.[10,11]

Before delving into the more specific characteristics of blue hydrogen, a brief explanation of the differences between other classes of this product, such as grey and green, is necessary. To

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differentiate them, it is required to highlight their production routes, where blue hydrogen is produced from natural gas (methane) in a process called steam reforming that results in the capture and storage of carbon, thus contributing to a reduction in gas emission that worsens the greenhouse effect. Grey hydrogen differs from blue hydrogen as it does not capture carbon, making it a more polluting production route. Finally, green hydrogen is an environmentally friendly production route, as it uses the electrolysis of water generated from energy from renewable sources, such as wind and solar. Therefore, in the process of generating green hydrogen, carbon is not released into the atmosphere.

The production of blue hydrogen is based on carbon capture and storage (CCS),[12] a technology that involves capturing the carbon dioxide (CO_2) obtained during the hydrogen production process and storing it in geologically safe places, such as underground reservoirs of oil and gas.[13] This process begins with natural gas reforming, a chemical reaction that transforms natural gas into hydrogen and carbon dioxide.[14] The hydrogen is then separated from the carbon dioxide and purified, and the CO_2 is captured and stored securely.[15] This technology allows hydrogen to be produced with almost zero carbon emissions, presenting itself as a way to decarbonize the energy matrix.[16]

While blue hydrogen production could offer a low-carbon option for the industry and other applications, there are also concerns about the high cost involved in producing it.[17,18] One of the main challenges is ensuring that this type of hydrogen production is economically viable and competitive with other renewable energy sources.[19] In addition, concerns regarding the availability of natural gas sources, the fuel used to produce blue hydrogen, and the feasibility of carbon capture and storage limit its large-scale application.[20,21] It is also essential to ensure that blue hydrogen production is environmentally sustainable, as capturing and storing carbon can have significant environmental impacts.[22,23] Therefore, it is necessary to carefully evaluate investments in blue hydrogen production and ensure they are viable and sustainable in the long run.[24]

Thus, the implementation of this category of hydrogen on a commercial scale is still seen as ambitious.[25] However, introducing blue hydrogen into the energy system presents favourable parameters.[26,27] An organized and equipped infrastructure is essential to efficiently guarantee management from the initial production processes to this fuel's safe storage and distribution.[28]

On the other hand, this category of hydrogen production offers a solution for reducing greenhouse gas emissions, encouraging the development of new technologies to meet the growing energy demand in the most diverse sectors of the global market.[29–31] Thus, the blue hydrogen produced can be used in several applications, such as producing electricity in power plants, transporting vehicles powered by fuel cells, and producing fertilizers and chemical products.[32]

In addition, we can use blue hydrogen in an integrated manner with other alternative energy sources. This is possible through storage of hydrogen energy, which can be used when wind and solar energy are unavailable.[33] Despite offering many benefits, there is still a need for investments in CO_2 storage infrastructure, as well as the lack of government policies to encourage the adoption of this technology and its implementation in the world's energy matrix in a more expressive way.[34]

For this study, bibliometric analysis is a research technique that uses quantitative indicators to assess scientific production in a given area of knowledge.[35–37] The objective is to identify patterns and trends in the scientific literature and map the main contributions and authors in a field of study.[38–40]

Thus, through advanced bibliometric analysis of the Web of Science (WoS) site database, this study proposes to evaluate and present the development of the scientific production process of research aimed at the challenges and opportunities in producing blue hydrogen. Therefore, we seek to understand the current research scenario for this hydrogen category and the future trends in this area. In this way, this analysis focuses on investigating advancements, updates, and trends in improving processes for obtaining this hydrogen category.

This study contributes to the description of available technologies and provides the possibility to evaluate diverse applications of this fuel and explore innovative opportunities for its use in sustainable processes. Consequently, this study offers a solid foundation for future research and represents an important step toward transitioning the industry towards a circular economy in the context of blue hydrogen production.[41] In addition, the following questions are sought to be answered:

• RQ1 How has scientific production developed in research on the challenges and prospects of blue hydrogen production?

• RQ2 Who are the main authors in blue hydrogen production research?

• RQ3 What are the main emerging subfields of research on blue hydrogen production in recent literature?

• RQ4 What are the main hotspots used in the literature search?

2. Methodology

2.1 Data source

At the heart of this study, we have bibliometric analysis as a fundamental tool to determine the number of scientific productions in a clear and detailed way, an accessible alternative to collecting and evaluating these data.[42–48] Thus, this analysis covers authors, citations, journals, institutions, and other emerging scientific productions in blue hydrogen production. Therefore, to carry out the bibliometric analysis, we have as a crucial part of this study the use of the database obtained through the publications gathered in the collection of the Web of Science website, currently owned by Clarivate Analytics, which has around 74.8 million academic productions, according to 2020 data.[49] Therefore, as an essential and highly regarded source of data in the educational field for developing the proposed analysis, this platform was used to access many productions in the scientific literature within the theme addressed.[50–54]

2.2 Data collection

Initially, academic data referring to scientific publications focused on the production of blue hydrogen were obtained from the use of the keywords "hydrogen", "production," and "blue hydrogen" in a survey carried out on May 14, 2023, using the period 2012–2023 for the quantitative survey of productions in the area. Thus, the research was limited to using these terms and English as the language to avoid the impacts of updating bias in the database and, in this way, to develop a concrete synthesis of the scientific production in the proposed theme considering the current scenario. Therefore, the information obtained through the adopted database is described in Fig. 1.

2.3 Data extraction

After collecting and obtaining the database that would be used as a subsidy for the continuation of the study, all the material gathered was imported into the Microsoft Excel 2023 software (Microsoft Corporation, Redmond, Washington, WA, United States), where, later, it would be processed and analyzed to present statistical results. All information considered for the development of this analysis includes the frequency of citations, the relevant countries in the area of study and scientific production on blue hydrogen, the authors, the number of annual publications, agencies involved in financing the projects, and the institutions. Thus, the data considered here for the qualitative analysis were extracted using the Journal website Citation Reports (JCR) (**https://www.thomsonreuters.com/journal-citationreports/**). During the development of this analysis, the collected data were filtered and processed manually in Excel.

2.4 Data visualization and analysis

The descriptive statistical analysis of the adopted database Excel 2023 software was used, using the cited parameters ranging from the authors and institutions to the number of citations and occurrence of their publications in other works. With this, it was possible to carry out a detailed analysis of the data extracted from the selected articles, allowing an accurate and reliable evaluation of the performance of the publications in the proposed area of study. The descriptive statistical analysis developed in this research is an important technique that identifies patterns and trends in the data, helping interpret results and decision-making.[55,56]

The qualitative data of the publications present in the database and the impact factor (IF) of the productions were taken into account, as well as the category (Q1, Q2, Q3, and Q4) in which each of the journals and articles is inserted since these indices are responsible for presenting the most relevant productions in a given area of knowledge.[57–59] In addition, another critical parameter to be considered for this study is the H index, an indicator used to evaluate the scientific production of researchers, research groups, institutions, and countries. It measures the quantity and quality of a researcher's works, considering the number of citations these publications receive.[60,61]

VOSviewer (**https://www.vosviewer.com**) was used to build these networks,[62] which synthesized the data from scientific productions in the blue hydrogen area. In this way, to relate these categories, analysis techniques can be used to build and present the connections between them. Citation analysis is

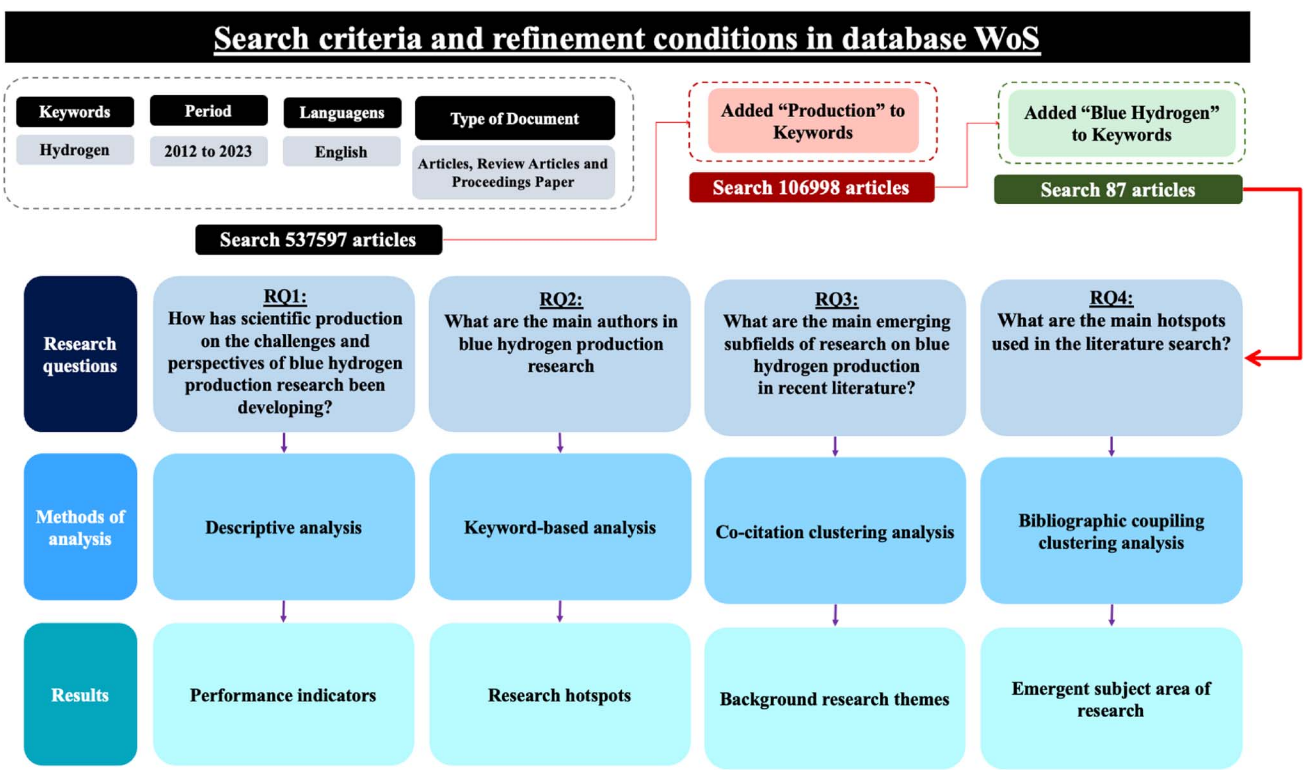

Fig. 1 Representation of the study methodology search criteria and refinement condition in the WoS database.

a technique used in bibliometrics to assess the relevance and impact of a scientific publication and identify relationships between different publications. It is based on counting the number of times an article is cited by other articles.[63] However, to analyze co-citations and co-occurrences, the associations between articles, how they are referenced, and the quantity of that occurrence must be kept in mind.[64] Furthermore, there is also co-authorship analysis, a technique used to define collaboration relationships between authors.[65] For this bibliometric analysis, VOSviewer software was used to perform (i) citation analysis by country/region, (ii) citation analysis by institution, (iii) analysis of co-authorship and co-citation of authors, (iv) journal co-citation analysis, and (v) keyword co-occurrence analysis.

In order to build a visual structure capable of presenting the desired parameters and establishing the correlations between each of them, figures were created in VOSviewer to provide a reliable statistical approach combined with a more transparent and objective presentation of the results obtained. Thus, some graphic representations were developed to visualize these data, such as user nodes, to represent keywords, articles, regions, and institutions, where each node can be distinguished by colour according to the time of occurrence. Furthermore, these nodes' size and position relative to the centre of the map indicate relevance. To display the connections between each of the chosen parameters, some lines connect the nodes, showing how the publications are related to each other, and the thickness of the lines indicates how strong this relationship is, using the total link strength of the connection (TLS) to assess the connection between works quantitatively.[66]

The CiteSpace Java program, a visualization and analysis tool for bibliometric data to identify trends, patterns, and relationships in large citation datasets, was also used.[67] It allows the analysis of citations, co-citations, and co-occurrences of keywords. It also provides resources to identify co-authorship networks and institutions and analyze the geographic distribution of these works.[68,69] Based on the information collected, CiteSpace produces interactive charts and maps that help users identify emerging research areas and the prominent researchers and institutions involved in a field of study. That said, through this software, it was possible to perform (i) co-authorship analysis of institutions, (ii) analysis of co-authorship and co-citation of authors, (iii) journal co-citation analysis, (iv) overlapping of journal double maps, and (v) analysis of co-citation of references.

Therefore, the graphical representations built with the help of the VOSviewer and CiteSpace software make it possible to categorize the correlations between the academic data recovered in the Web of Science. The nodes in a map represent the type of study being considered, and their size is defined concerning the number of times it was cited. The connections between nodes represent the strength of collaborations, co-citations, or co-occurrences between studies. In these visualization maps, clusters that refer to a group of highly connected articles through citations can also be observed.

In order to visualize these data for the bibliometric analysis developed here, it is essential to reiterate that different parameter configurations were considered for this study. Some of the main parameters that can be configured in VOSviewer include the source of terms (title, abstract, plus keyword and author keyword), node type (institution, author, cited author, reference or keyword), selection criteria (top 50) and pruning of segmented networks. The CiteSpace software also allows us to adjust the temporal division, where we consider the time interval of publications made between 2012 and 2022. There is also term selection, node type, selection criteria, pruning, and visualization.

Therefore, VOSviewer and CiteSpace were used to analyze the entire database and elaborate correctly directed discussions. In the main text of this study, we present all the results obtained through these advanced bibliometric tools. It is essential to highlight that data analysis through different tools can provide unique and complementary insights into the trends and patterns in a given field of research.

3. Results

3.1 Trend of global publications and citations

After collecting the database from WoS, 87 publications, including articles, review articles, and conference papers, were obtained between 2012 and 2023, as shown in Fig. 1. Analysis of Fig. 2 reveals that, although data collection encompassed publications since 2012, the trend of global scientific productions related to blue hydrogen research had a significant start in 2020. In 2020, only three articles were published on the subject, but this number grew to 37 articles in 2022. Additionally, these publications were cited approximately 1.119 times as of the date of this research.

3.2 Contributions of countries/regions

The provided results in this section address the first RQ:

• RQ1 How has scientific production developed in research on the challenges and prospects of blue hydrogen production?

To visualize the distribution of published works, we have a world map (Fig. 3A), created after processing the data using Excel as a tool. It is possible to analyze the density of these publications in each country through colours. In order to present how the distribution of published articles occurred throughout the analyzed period (2012–2023), Fig. 3B shows the contribution of the top 10 most relevant countries in blue hydrogen research, demonstrating the increasing number of articles and other works. For this, the period from 2019 to 2023 was used, as no articles were published in the field of study in previous years. As shown in Fig. 3C, the United States leads scientific production in the field, with 16 articles (18.39%) out of the 87 articles obtained from the database, followed by England with 13 publications (14.94%). Fig. 3D shows the number of citations per country, where the United States has been cited 216 times for these articles, followed by Canada with 201 citations, contributing to 1.242 citations across 24 collaborating countries. Analyzing the H-index of the leading countries through Fig. 3E, it is possible to verify that the United States and England stand out from the others, both presenting an H-index equal to 5.

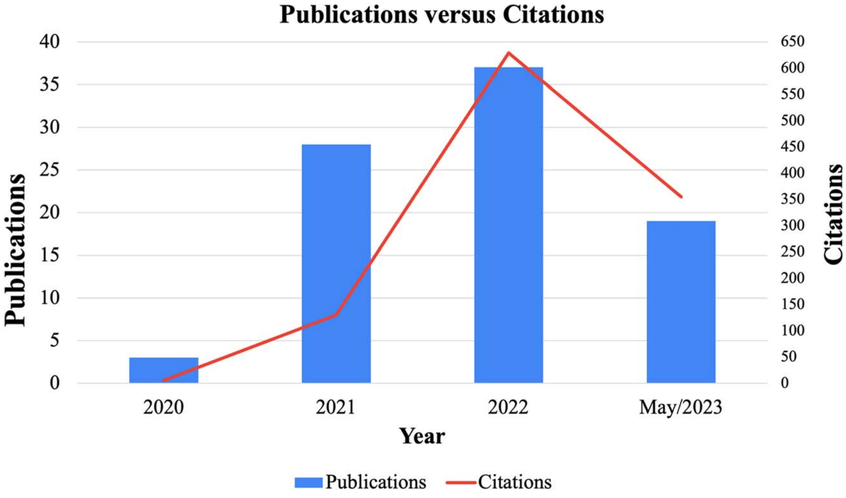

Fig. 2 Global trend of annual publications and citations related to blue hydrogen production research from 2020 to 2023.

Regarding the international cooperation among countries, Fig. 4A aims to provide a visualization of co-authorship analysis. Thus, the United States, England, and Canada show a robust collaborative relationship in research in this hydrogen category. As for the information presented in Fig. 4B, the contribution of 24 countries is indicated, considering that each country should have at least one document for analysis in VOSviewer, where each "node" represents the countries that have contributed to the scientific community in recent years. Furthermore, with the visual map presented by the software, it can be observed that Canada has the highest TLS (TLS = 27).

3.3 Contributions of institutions

Analyzing institutions that contributed to scientific production in this field revealed 207 institutions involved in research and publications. Research Libraries UK (RLUK) led the publication with 10 documents, followed by SINTEF (Norway) and N8 Research Partnership with 6 and 4 records, respectively. Table 1 provides an objective overview of the top 10 institutions based on the number of published works, highlighting those that have had greater relevance in this area in recent years. Fig. 5A shows, using a low-density network map, the collaboration relationships between the institutions, where a density = 0.0626 was obtained. To perform a citation analysis of the prominent institutions, Fig. 5B was prepared, considering a minimum number of 10 citations. Thus, the contribution network map reveals the presence of 31 nodes and 50 links, among which the 3 institutions that most stood out concerning TLS were the University of Calgary (TLS = 19), Vienna University of Technology (TLS = 18) and the Swiss Federal Institutes of Technology Domain (TLS = 15).

3.4 Contributions of funding agencies

The top 10 funding agencies worldwide that supported research in this field are listed in Table 2, based on the number of their contributions to the scientific community. Among them, three South Korean agencies collectively account for 7 studies. However, the Research Council of Norway individually published 4 research papers, highlighting their significant involvement in advancing blue hydrogen research.

3.5 Contributions of authors

The findings of this section address the second RQ:

• RQ2 Who are the main authors in blue hydrogen production research?

For the visualization of the top 20 emerging authors in blue hydrogen research, we have Fig. 6A, which ranks them according to the number of publications between 2012 and 2023. In this way, it was observed that the author with the highest number of published works was Cloete S from Norway, with 6 articles published, accounting for 6.89% of the total articles in the field. We have Del Pozo from Spain, with 3 published articles. The remaining authors considered here had 2 publications each, but they are ranked in order of relevance. The last author had only one publication. Fig. 6B graphically shows the co-citation relationship between the authors. Thus, the constructed visualization map presented considerable Q value and silhouette values ($Q = 0.597$; silhouette = 0.8463), indicating a certain homogeneity between the publications and the themes addressed. In addition, 8 clusters were identified: "SMR with CCUS" (#0), "CO_2 reduction" (#1), "techno-economic" (#2), "greenhouse gases" (#3),"sorption enhanced reforming" (#4), "methane catalytic" (#5), "methane pyrolysis" (#6) and "CO_2 sequestration" (#7).

3.6 Journal analysis

After data collection, 42 journals were identified as prominent in research within this field in recent years. Thus, Table 3 was prepared, ranking the top 10 journals that have contributed the most to the literature on blue hydrogen. These journals account for 60.92% of the total article production in this area, with the *International Journal of Hydrogen Energy* being the foremost contributor, producing the majority of works (13), and contributing to 14.94% of the publications. *Energies and Energy*

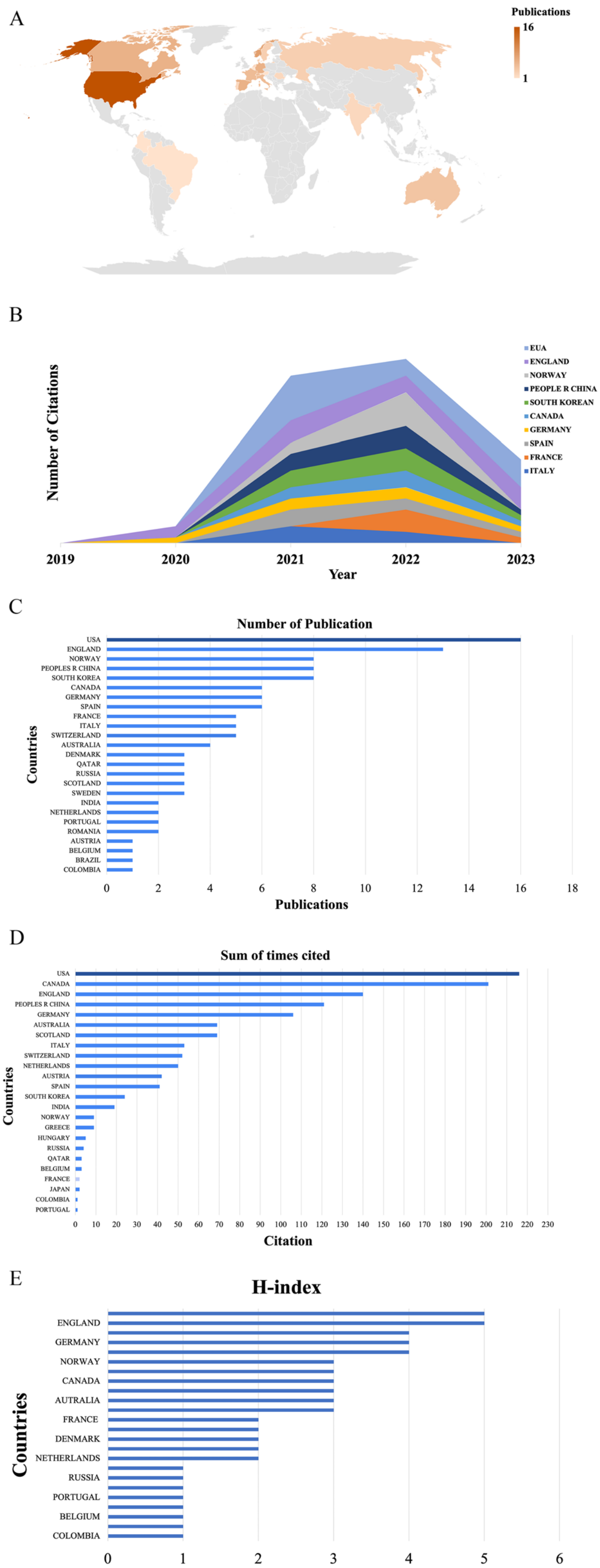

Fig. 3 (A) World map displaying the global distribution of blue hydrogen research. (B) Growth trends in the publication quantity of the top 10 countries/regions in blue hydrogen research from 2019 to 2023. (C) Total number of publications in this field. (D) Sum of total citations. (E) H-index of 24 countries.

Conversion and Management are presented with 9 articles each. Following the JCR 2021 standards, the ranking reveals that 7 of these journals were classified as Q1, two as Q2, and only one as Q3. Furthermore, through a dual-map overlay of the journals related to blue hydrogen research, Fig. 7 presents ten citation pathways. Still, the published studies mainly targeted journals in just one of them: (v) physics, materials, and chemistry.

3.7 Reference analysis

The results obtained in this section address the third RQ:

• RQ3 What are the main emerging subfields of research on blue hydrogen production in recent literature?

Table 4 lists the ranking of the top 10 most cited papers and their basic information, such as the journal of publication, author, and year of publication. It was revealed that all ranked articles were published in 2020, with the majority being from 2021. The most impactful paper in terms of citation count was written by Howarth *et al.* (2021),[15] with 165 citations, followed by the article written by Yu *et al.* (2021),[12] with 113 citations. In third place was the paper produced by Fan *et al.* (2021),[70] which received 79 citations. Regarding the number of authors per published article, it was observed that all articles in the top 10 had co-authors, with an average of 4.9 authors per article.

A co-citation network was built through CiteSpace on a visualization map to establish the co-citation relationship, as shown in Fig. 8A. The citation network obtained comprises 160 nodes, and to facilitate the analysis of the data presented by it, we can group them into 11 main subclusters. Through the software, it is possible to access the Q value of modularity, a quality measure of the grouping of nodes in communities or modules in a network, which can vary between −1 and 1 in the presented structure (Fig. 8A). The Q modularity value was 0.5913, suggesting that the nodes are substantially connected within their communities. Furthermore, it is also possible to see that the weighted average silhouette value between subclusters #0 and #10 was 0.7967, indicating the quality of the relationship between the clusters. In order to present a view of the relationships of the co-citation network of references in a temporal way, Fig. 8B reveals the characteristics of the hot spots for current and future research in this field. The most relevant cluster for this study was "assessing economy" (#0), the second largest was "low-emission hydrogen" (#1), and the third was "steam methane" (#2). Suggesting that there was an earlier development about the other clusters, cluster 4 (hydrogen) initially focuses on hydrogen production. It can also be considered that cluster 2 (low-emission hydrogen) is currently a research hot spot. Thus, it can be observed that there is an increase in the contextual bias of publications based on the theme of hydrogen production with low pollutant emissions.

3.8 Keyword analysis

The provided results in this section address the fourth RQ:

• RQ4 What are the main hotspots used in the literature search?

Keyword co-occurrence analysis plays a critical role in bibliometric analysis. By conducting this procedure, it is possible

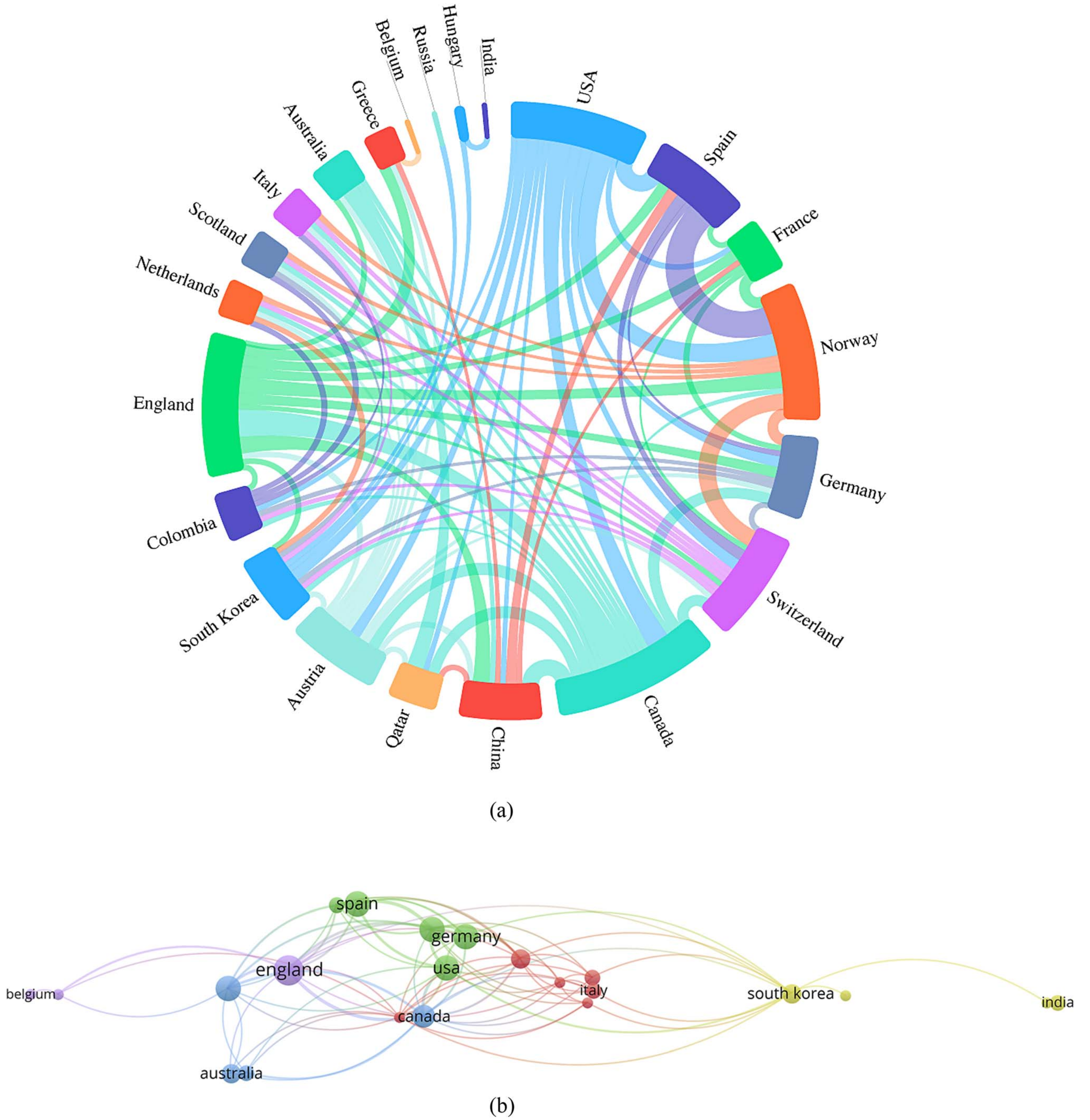

Fig. 4 (A) Distribution and international cooperation of countries/regions involved in blue hydrogen research. (B) Citation map of countries/regions on blue hydrogen research. The nodes with closer proximity exhibit higher numbers of citations among the countries.

to visualize knowledge networks, observe relationships between concepts, and identify emerging trends in scientific literature. Thus, Fig. 9 was created to present a map containing the density of keyword frequency based on the selected database. The analysis revealed that 327 keywords were identified across the 87 obtained articles. Furthermore, keywords with the highest number of occurrences are represented as hotspots. Table 5 provides a list of the top 20 keywords based on their frequency of occurrence. Notably, "blue hydrogen" and "hydrogen production" were the most frequent, with 18 and 12 occurrences, respectively. However, the remaining keywords primarily refer to the main processes involved in blue hydrogen production and other types of hydrogen, such as CO_2 capture and methane reforming.

The visualization map obtained through VOSviewer indicated 6 clusters, where all the keywords identified in the data collection could be divided into the following categories: "blue hydrogen study", "hydrogen production study", "green

Table 1 Top 10 institutes that contributed to publications about blue hydrogen

Rank	Institutions	Countries/regions	Count
1	Research Libraries UK (RLUK)	United Kingdom	10
2	SINTEF	Norway	6
3	N8 Research Partnership	United Kingdom	4
4	Universidad Politécnica de Madrid	Spain	4
5	University of Calgary	Canada	4
6	ETH Zurich	Switzerland	3
7	Swiss Federal Institutes of Technology Domain	Switzerland	3
8	University of Manchester	United Kingdom	3
9	Aarhus University	Denmark	2
10	Boston University	EUA	2

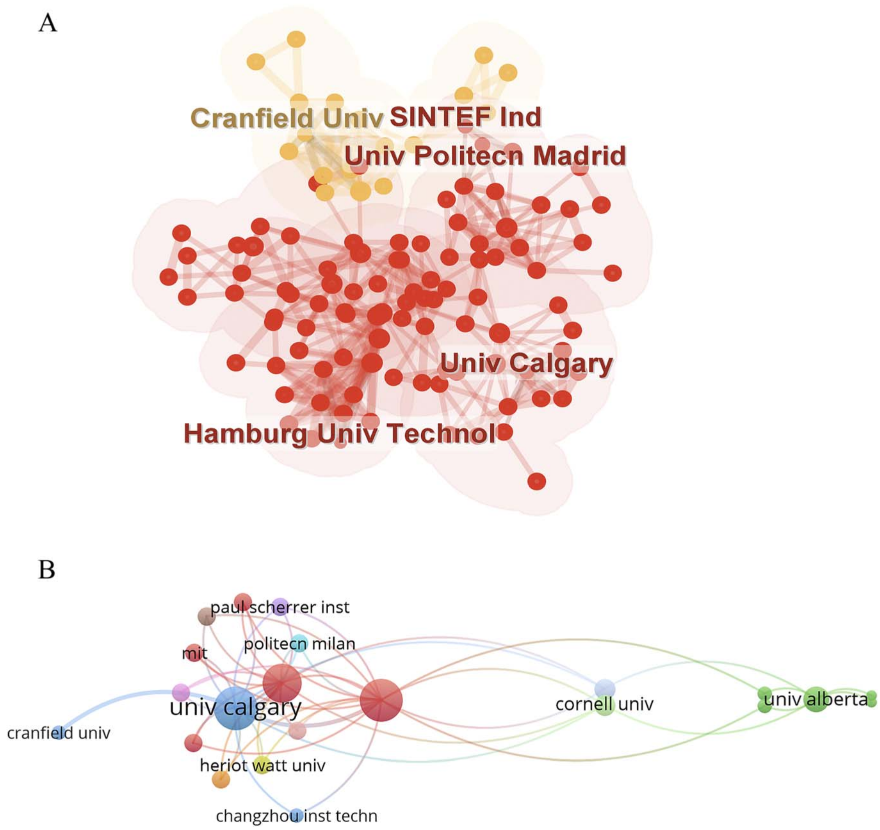

Fig. 5 (A) This network map, generated by CiteSpace, highlights co-authorship within the institution, where closer clusters indicate thematic affinity and more intensive collaborations among researchers. (B) Mapping of citation analysis among 207 identified institutions on blue hydrogen research, depicted in VOSviewer. The proximity of specific nodes reflects the strength of citation connections, indicating closer ties and more significant influence between institutions.

hydrogen production study", "CO_2 capture and storage study", "techno-economic study" and "technological study" as shown in Fig. 10A. The purpose of presenting the current scenario in blue hydrogen research is to analyze the prominent topics up to the present moment. In the "blue hydrogen study" cluster, the main keywords assigned are "coal", "challenges", and "gas". As for the "hydrogen production study" cluster, the most relevant keywords are "hydrogen economy", "methane pyrolysis", and "carbon dioxide capture". In the "green hydrogen production study" cluster, the most frequent keywords are "renewable energy", "cost", and "ammonia". The "CO_2 capture and storage study" cluster commonly includes terms such as "chemical looping", "optimization" and "design". The "techno-economic study" cluster mainly features "liquid hydrogen" and "economic analysis". The sixth cluster, "technologies", has keywords with higher frequencies, such as "process intensification" and "partial oxidation".

Fig. 10B was created based on the Average Article Year (AAY), displaying the frequency at which the gathered keywords were cited in articles from 2020 to 2023. By using different colours in the overlay visualization map, occurrences of these terms can be delimited. It can be observed that the publications in 2020 were

Table 2 Top 10 related funding agencies

Funding agencies	Countries/regions	Count	Percentage (%)
Research Council of Norway	Norway	4	4.59
National Research Foundation of Korea	South Korea	3	3.44
Qatar National Research Fund (QNRF)	Qatar	3	3.44
Spanish Government	Spanish	3	3.44
Australian Research Council	Australia	2	2.29
Canada First Research Excellence Fund	Canada	2	2.29
China Scholarship Council	China	2	2.29
European Commission	European Union	2	2.29
Korea Institute of Energy Technology Evaluation Planning (KETEP)	South Korea	2	2.29
Ministry of Science, ICT and Future Planning, Republic of Korea	South Korea	2	2.29

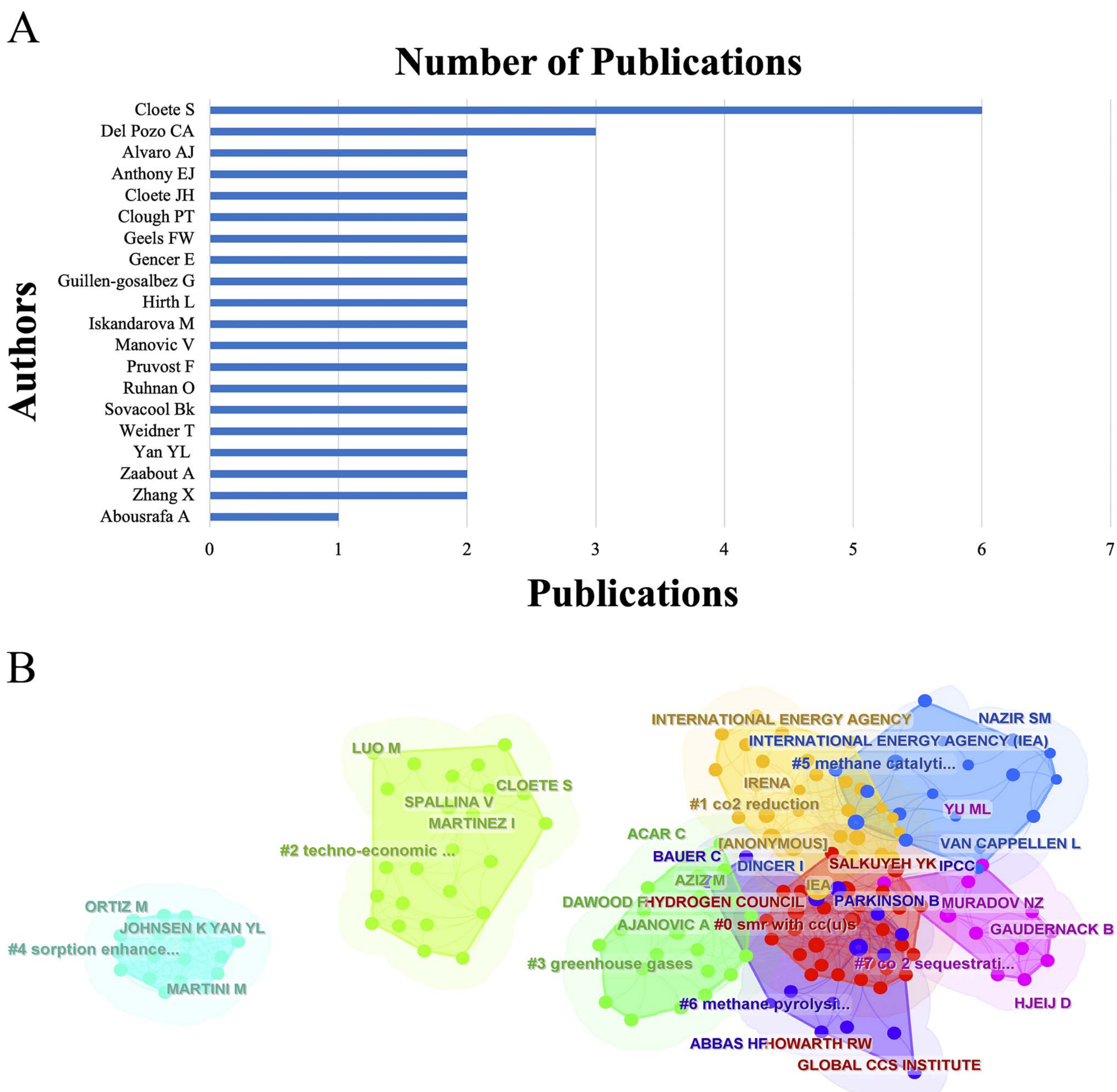

Fig. 6 (A) Top 20 most productive authors based on the number of publications. (B) Co-citation analysis depicting authors involved in blue hydrogen research, showing clusters connected by thematic links in different colours.

Table 3 Top 10 journals in blue hydrogen research ranked by publication number

Rank	Journal title	Country	Count	Percentage (%)	IF (2021)	Quartile in category (2021)	H-index
1	*International Journal of Hydrogen Energy*	England	13	14.94	7.139	Q2	7
2	*Energies*	Switzerland	9	10.34	3.252	Q3	3
3	*Energy Conversion and Management*	England	9	10.34	11.533	Q1	5
4	*Journal of Cleaner Production*	USA	6	6.90	11.072	Q1	3
5	*Energy*	England	4	4.60	8.857	Q1	3
6	*Renewable Sustainable Energy Reviews*	USA	4	4.60	16.799	Q1	3
7	*ACS Sustainable Chemistry Engineering*	USA	2	2.30	9.224	Q1	1
8	*Applied Energy*	England	2	2.30	11.446	Q1	2
9	*Applied Sciences Basel*	Switzerland	2	2.30	2.838	Q2	2
10	*Energy Policy*	England	2	2.30	7.576	Q1	1

focused on hydrogen production and carbon capture but in a limited number. However, starting in 2022, there was a significant increase in work in this area, as evidenced by the growth in the co-occurrence of keywords such as "hydrogen economy" (AAY = 2022.71), "liquid hydrogen" (AAY = 2022.67), "hydrogen storage" (AAY = 2022.67), and "renewable energy" (AAY = 2022.67), visualized by using VOSviewer overlay visualization. Thus, it is implied that these keywords are likely to be among the hotspots in blue hydrogen research in the coming years.

4. Advanced analysis

Advanced bibliometric analysis helps understand and obtain parameters that integrate the current research scenario within a specific field, differentiating itself from the usual bibliographic reviews. Through this analysis, it becomes possible to capture future trends in a domain of interest and present the patterns of research development in that area. Thus, network maps constructed with the assistance of VOSviewer and CiteSpace software reveal the structural relationships of emerging research fields in hydrogen production based on bibliometric data, providing insights into the growth of scientific output in the studied field. Therefore, by visualizing the analyses presented in this study, it was possible to identify and examine the contributions of countries and institutions in recent years and the essential authors, the relevance of their works, significant publications, and the funding agencies involved. This offers a metric, qualitative, and objective visualization of the research patterns in blue hydrogen and provides insights into the prospects for this field in the coming years.

Initially, our research focused on the period from 2012 to 2023. However, it was observed that publications related explicitly to blue hydrogen only emerged starting in 2020. The bibliometric data analysis revealed that until May 2023, only 87 articles were published, considering they met the research criteria outlined in Fig. 1. The Web of Science platform found 1138 citations, with 629 occurring in 2022. Although research in

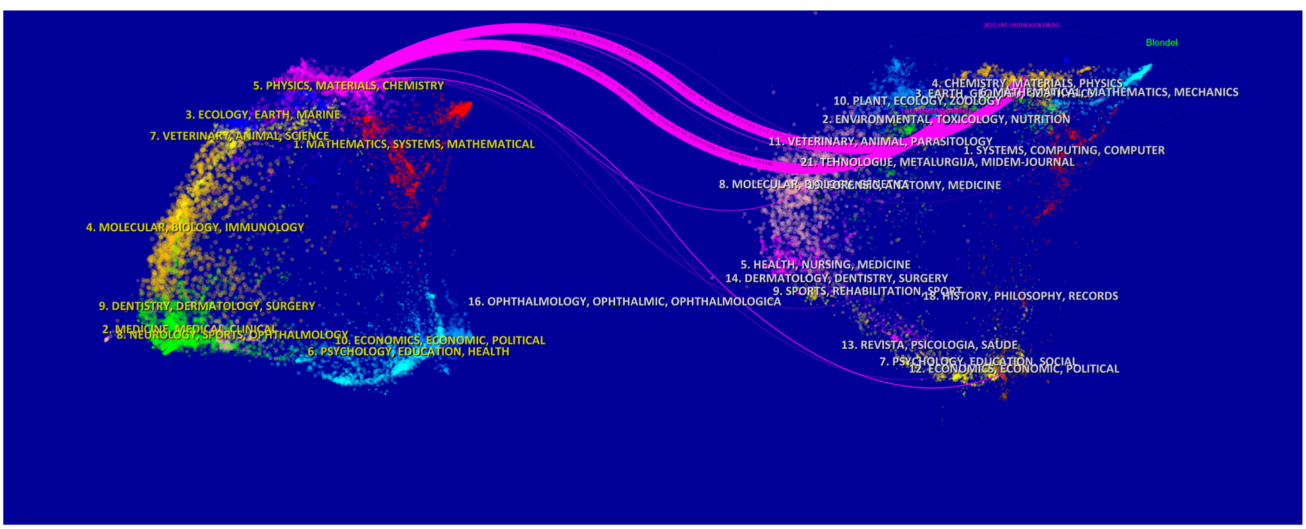

Fig. 7 Dual-map overlay illustrating journals in blue hydrogen research generated by CiteSpace. The labels denote diverse research facets within the field. Citing journals are positioned on the left side, while the right side represents the cited journals. Various coloured lines trace distinct reference paths, originating from the citing map and terminating at the mentioned map. Path widths are proportionally scaled based on the frequency of z-score-scaled citations.

Table 4 Top 10 blue hydrogen papers with the most citations

Rank	Title	Journal	First Author	Year	Citations
1	How green is blue hydrogen?	*Energy Science & Engineering*	Howarth, Robert W.	2021	165
2	Insights into low-carbon hydrogen production methods: green, blue and aqua hydrogen	*International Journal of Hydrogen Energy*	Yu, Minli	2021	113
3	Low-carbon production of iron and steel: technology options, economic assessment, and policy	*Joule*	Fan, Zhiyuan	2021	79
4	A framework for assessing economics of blue hydrogen production from steam methane reforming using carbon capture storage & utilisation	*International Journal of Hydrogen Energy*	Khan, Muhammad H. A.	2021	55
5	The role of carbon capture and storage in the energy transition	*Energy & Fuels*	Lau, Hon Chung	2021	54
6	On the climate impacts of blue hydrogen production	*Sustainable Energy & Fuels*	Bauer, Christian	2021	51
7	Process simulations of blue hydrogen production by upgraded sorption enhanced steam methane reforming (SE-SMR) processes	*Energy Conversion and Management*	Yan, Yongliang	2020	49
8	Hydrogen and hydrogen-derived fuels through methane decomposition of natural gas – GHG emissions and costs	*Energy Conversion and Management: X*	Timmerberg, Sebastian	2020	49
9	Comparative assessment of blue hydrogen from steam methane reforming, autothermal reforming, and natural gas decomposition technologies for natural gas-producing regions	*Energy Conversion and Management*	Oni, A. O.	2022	43
10	The economics and the environmental benignity of different colors of hydrogen	*International Journal of Hydrogen Energy*	Ajanovic, A.	2022	42

this field is still in its early stages, 37 countries have contributed to developing blue hydrogen research. Among these contributing countries, the United States showed the highest productivity in this research field, with 16 published articles, closely followed by England, with 13 publications. However, even though the United States leads the ranking in terms of scientific productivity, its first studies in this area were only published in 2021, indicating the current growth trajectory of this field. It can be considered that the rise of these studies is directly driven by the country's increasing interest in clean fuels, particularly in the transportation sector and hydrogen production for fuel cells.[71] Therefore, it is expected that the number of contributions will continue to grow in the academic landscape, given the significant number of countries that have dedicated themselves to scientific production in this field over the past two years.

In order to classify the main contribution vectors in the academic research sector, the total number of citations and the H-index of significant countries were considered. Thus, it was found that the United States takes a prominent position in the world both in quantitative terms of citations as in the H-index, closely followed by England, which has a similar H-index, considering that this parameter is essential to indicate the most expressive collaborators in a given field of study and the impact of their publications. In addition, it is worth mentioning that Canada and China also played a prominent role in the central regions where these studies were concentrated. Furthermore, when considering the top 10 institutions involved in the scientific production of research for the hydrogen category addressed, the United Kingdom leads with 4 institutions, thus adding the highest number of collaborations among the analyzed ranking. Therefore, the progress of academic interest and the growth of the approach to this topic in the United Kingdom is notorious, a fact evidenced by the significant participation of these institutions in the production of these studies. However, even if this is considerable progress for studying the blue hydrogen category in this region, it is essential to note that England had a substantially lower number of citations than the United States. In addition, Scotland has a lower number than England both in citations and when compared to its respective H-index, revealing that in addition to the significant participation among the most relevant institutions, it is still necessary to guarantee the quality of these works in the scientific scope of search. With this, it should be highlighted that the financial subsidy for research associated with the participation and encouragement of human resources is essential for the growth of production and quality of works related to the category of hydrogen analyzed in this study. Thus, knowing the relevant role that financial incentives play in supporting the development of new scientific productions, among the top 10 funding agencies, South Korea comprises 8.046% of participation in economic incentives for research groups and institutions. This proves consistent because South Korea has acted as a world reference with an economy based on hydrogen.[72]

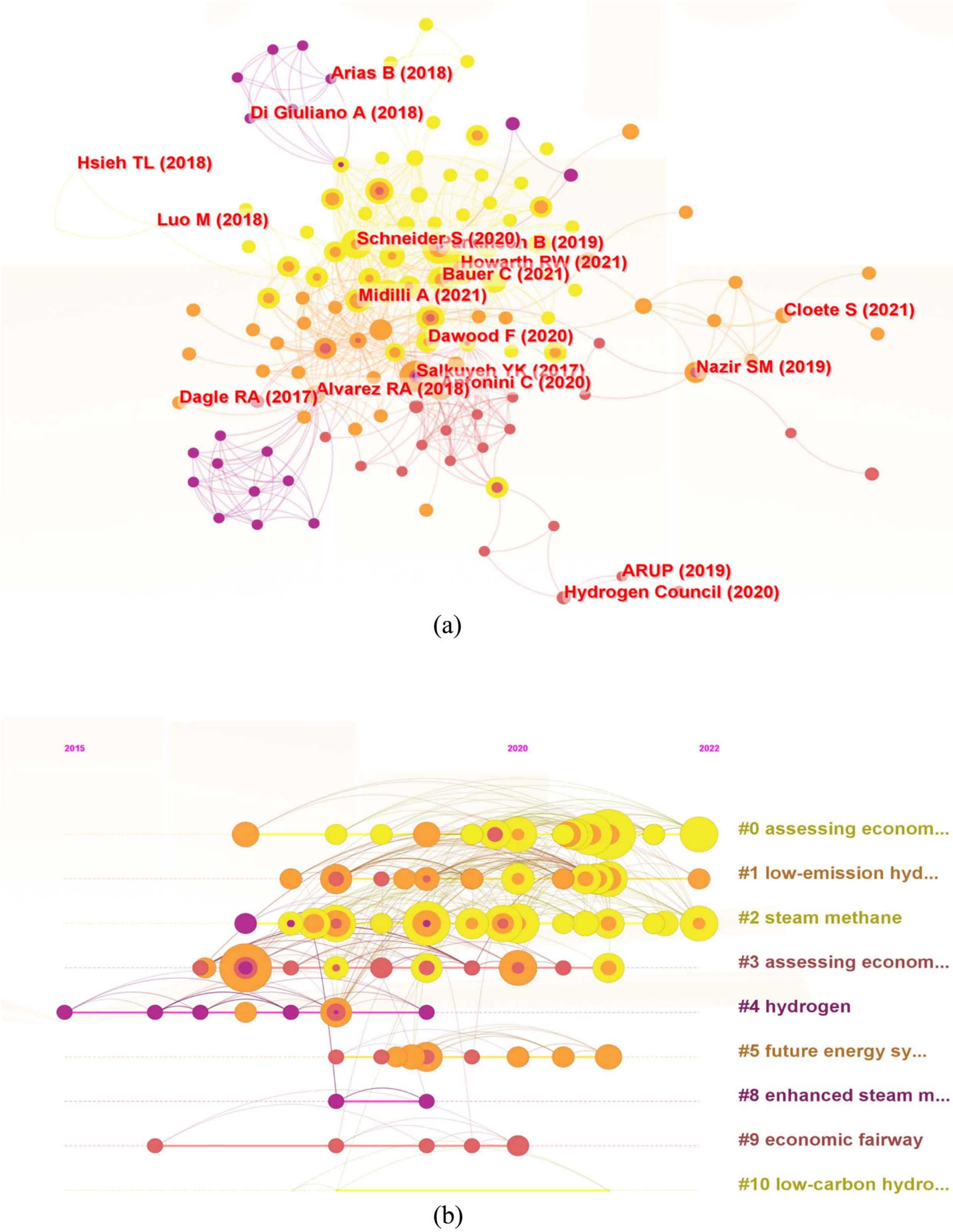

Fig. 8 (A) Cluster view of co-citation references. (B) The clusters are arranged in a vertical hierarchy, descending in order of size. The temporal evolution is delineated by differently coloured lines, where nodes along the lines denote cited references and links represent co-cited references. The varying node density at distinct temporal intervals indicates the dynamic alterations within the corresponding clusters along the temporal axis.

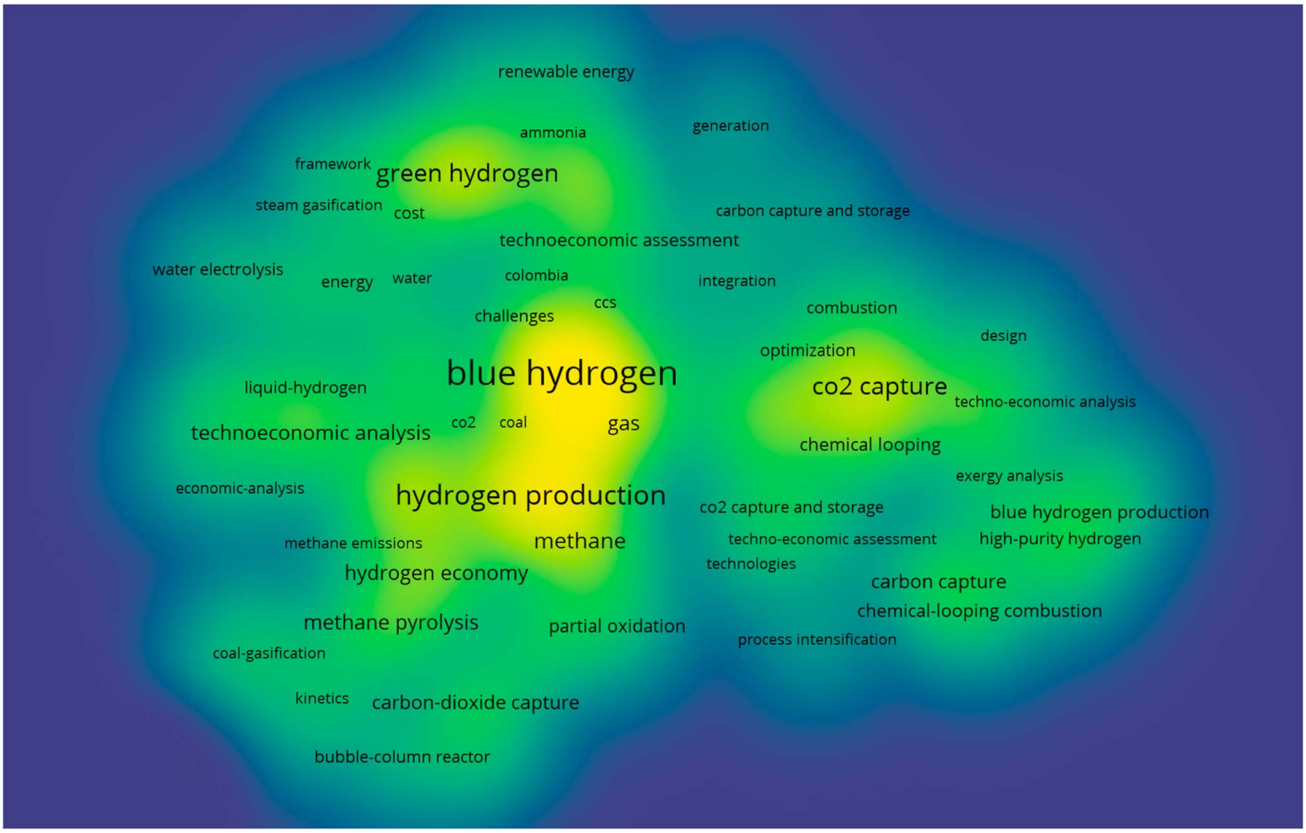

Fig. 9 Density map of keywords generated by the VOSviewer showing the hotspot on blue hydrogen research.

Regarding the prominent journals in the field covered, the three most productive, within the top 10, are the *International Journal of Hydrogen Energy* (IF = 7.139, Q2), *Energies* (IF = 3.252, Q3), and *Energy Conversion and Management* (IF = 11 533, Q1). However, even considering that the scientific journal *Energy Conversion and Management* is in third place in the total number of publications, its IF value and classification as Q1 indicate its relevance for the academic scope based on the number of citations this journal received. However, it is noteworthy that even though the ranking presented having the number of publications of each of the newspapers as a starting point, the newspaper *Renewable Sustainable Energy Reviews* is more prominent in terms of impact factor, thus showing the quality of its publications and their relevance for the scientific community involved with this research topic, since it is essential for researchers that scientific journals have high visibility and reach so that more significant numbers of submissions of papers for publication are encouraged. A dual-map overlay was employed to analyze the flow of information between journals, revealing scientific portfolio trends comprehensively. This approach proved to be a valuable resource for understanding knowledge dynamics. The results indicated that the published studies focused mainly on journals in the following areas:

Table 5 Top 20 keywords in terms of frequency[a]

Rank	Keyword	Occurrences	TLS	Rank	Keyword	Occurrences	TLS
1	Blue hydrogen	18	43	11	Hydrogen economy	7	18
2	Hydrogen production	12	42	12	Steam methane reforming	7	18
3	Life cycle assessment	10	41	13	Techno-economic analysis	6	21
4	CO_2 capture	10	26	14	Methane pyrolysis	6	14
5	Green hydrogen	10	23	15	Carbon-dioxide capture	5	18
6	Natural gas	9	32	16	Power-to-gas	5	17
7	Hydrogen	8	27	17	Storage	5	17
8	Methane	8	25	18	Decarbonization	5	13
9	Electrolysis	7	22	19	H-2 production	5	13

[a] TLS: total link strength.

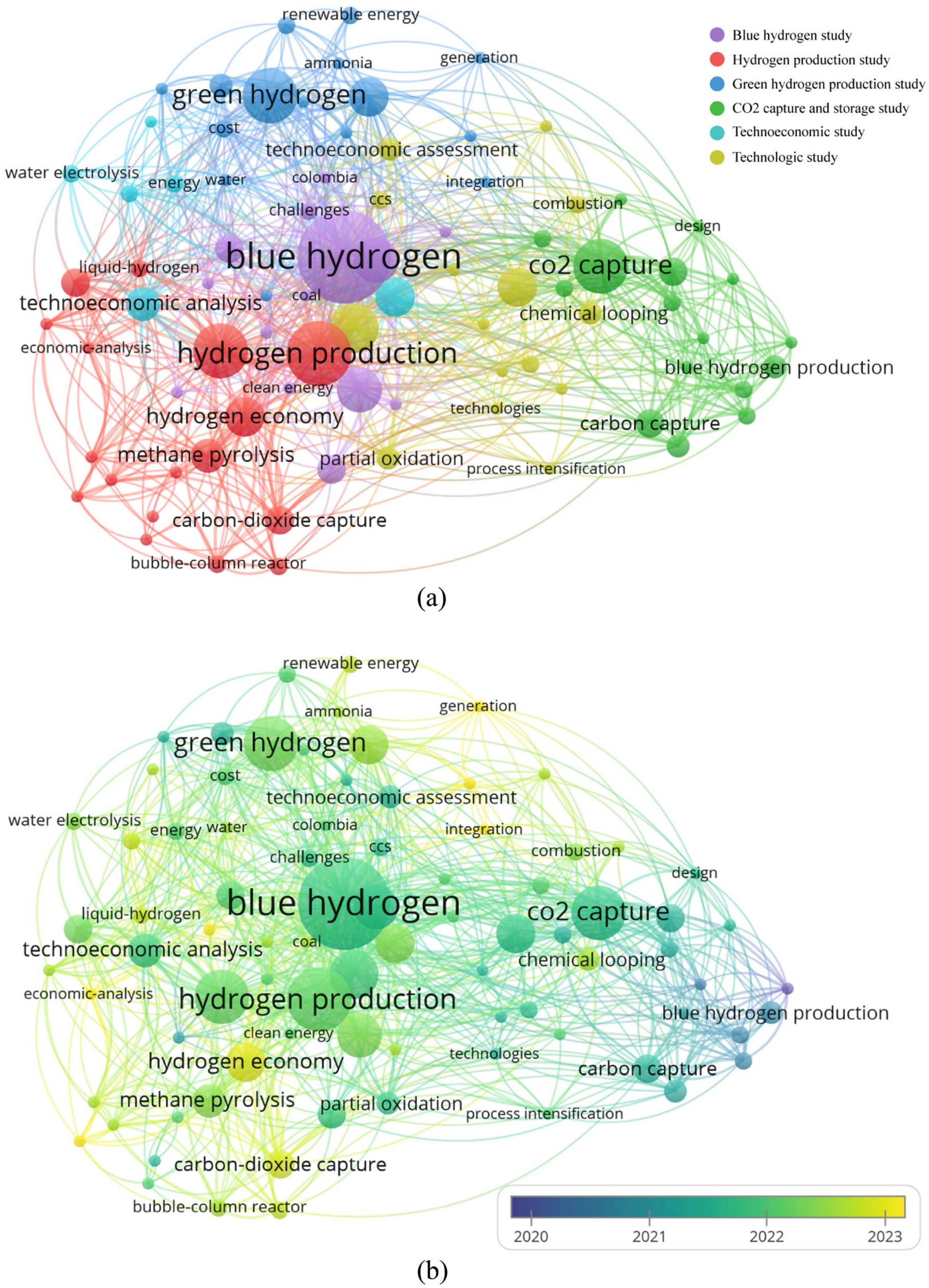

Fig. 10 (A) Keyword co-occurrence analysis in VOSviewer for blue hydrogen research. The image highlights a central cluster of closely related keywords, indicating strong thematic connections, while other keywords at a distance suggest broader, less direct associations. (B) Overlay visualization of the co-occurrence analysis.

physics, materials, and chemistry. In addition, all analyzed journals cited other journals in the same areas.

This study's co-authorship analysis was crucial in defining the cooperation connections between different authors, institutions, and countries. This assessment is based on understanding the relationship between the items through the number of co-authored documents. To obtain how this cooperation occurred in terms of proximity between the works, the TLS indicator played an essential role in supporting the discussions. The higher the TLS value, the more frequent the cooperation between authors, institutions, and countries. Therefore, based on recent data, it was possible to assess that the United States established considerable collaborations with England and Canada as notable research centres. Such information infers a perceptible sharing of collaboration between these countries regarding academic productivity, which is directed toward developing hydrogen production. This exchange of information between researchers is an essential factor for the advancement and visibility of research in any sector. Thus, according to the results analyzed, it is consistent to state that there is cooperation among the academic agents involved in this field, suggesting that such collaborations reaffirm the relevance of these countries as currently more productive in the topic of blue hydrogen, where they can play essential roles in the field. Creating new innovations and solutions specifically tailored for this industry segment, working together to ensure the ongoing positive impacts they bring to their respective productions. When performing the co-authorship analysis between institutions, the network map produced revealed, for example, close collaborations with the University of Calgary, Canada, with the Swiss Federal Institutes of Technology Domain, Switzerland, Universidad Politécnica de Madrid, Spain, and SINTEF, from Norway. These data prove the active participation of these institutions in developing new research projects through mutual collaboration, driving advancements, and paving the way for significant contributions. With an author co-authorship analysis, it was possible to verify that Cloete S, from Norway, had the highest number of publications related to blue hydrogen. It is possible to assess the prominence of his participation in this field based on these discoveries, as they show how this author cooperated with the academic community with many works, enriching the literature with his approaches. Del Pozo CA, Alvaro AJ, and Anthony EJ were other authors with relevant published works. Based on the retrieved information (WoS), it was found that the authors who stood out in the number of publications are affiliated with institutions that also hold a prominent position in the area, institutions that have already been presented in this study. Thus, the integration of human resources and opportunities provided by specialized research institutions boost the progress and visibility of their contributions to the scientific community. The results analyzed in this study reinforce the importance of these authors and the institutions in which they are affiliated, pointing to the significant impact they can have on the research sector, cooperating for the growth and development of new techniques and improvement of production routes to blue hydrogen.

The results of the co-citation analysis were obtained based on the measurement of the relationship between documents. In the case of co-citation analysis between authors, the prominence of each author is determined by the number of times their articles are cited by the same work. This approach is commonly used in order to assess the relevance of an author, as well as their impact and influence in the academic field. Thus, our results show that Howarth R. W. stands out as the most cited author, and it can be stated that his works significantly impact the research sector. Howarth R. W. has an H-index of 76, which shows this researcher's degree of productivity and influence. In addition, his last work in blue hydrogen was published in 2022. Fig. 6B divides the authors into eight clusters, where these represent the main research areas, such as "SMR with CCUS" (#0), "CO_2 reduction" (#1), "techno-economic" (#2), and "greenhouse gases" (#3). When considering these fields, it is possible to observe where the focus of researchers has been concentrated in recent years, given the dynamic character of the research sector, which seeks to promote discussions aimed at solving challenges and developing new approaches. Thus, given the analysis of the visualization map, the hydrogen production routes and concerns arising from the emission of pollutants into the atmosphere have recently received notable attention among researchers. Thus, studies aimed at assessing the efficiency and profitability of these means of production have provided an environment for discussion that seeks to ensure the sustainable implementation of blue hydrogen as an energy vector, optimizing the processes already used and ensuring future improvements. However, the authors noted additional challenges. These include, for the most part, the need for adequate infrastructure to capture and store carbon dioxide from production processes. It is also worth highlighting the obstacles involved in making projects for the safe transportation and distribution of the hydrogen that has been produced feasibly. Therefore, the increase in studies in this area corroborates the improvement of these processes, making blue hydrogen increasingly commercially attractive.

The most cited studies in blue hydrogen occurred between 2020 and 2022, as evidenced by the top 10 presented in Table 4, revealing the still-recent nature of this field of research. The fact that Howarth R. W. wrote the most cited work indicates the significant effect and relevance of this research in particular because, when considering the number of productions obtained from the database, this author stood out among the others as evidenced by the impact of his work on the academic community. When observing the still recent period of the beginning of the publications, it is essential to highlight that the production of blue hydrogen is a relatively new approach compared to other hydrogen production routes. Therefore, scientific knowledge constantly expands as more researchers explore its potential. Fig. 8B offers a chronological representation of the co-citation clusters of references, providing exciting insights into dynamic changes and development trends over different periods. Notably, the largest cluster identified is that of "assessing economy" (#0) (Howarth *et al.*, 2021; Bauer *et al.*, 2022),[15,22] closely followed by the cluster of "low-emission hydrogen" (#1) (Noussan *et al.*, 2020; Antzaras *et al.*, 2022)[11,14] and "steam methane" (#2) (Longden *et al.*, 2022).[73] It can be said that clusters 4 (hydrogen) and 9 (economy fairway) occurred earlier than the others. However, they remained relevant over time, being themes addressed until recently.

On the other hand, clusters 0 (assessing economy) and 1 (low-emission hydrogen) are currently highlighted in the area, revealing their possible participation in future research. Thus, from the data observed in each map, it is possible to assess how the trends for this field are moving towards applying blue hydrogen in a sustainable economy, considering the evolution of publications in the context of the growing demand for clean energy sources. The initial groupings indicate the established baseline for further studies, while the current groupings reflect this sector's most recent challenges and opportunities. This diversity of areas of interest demonstrates the dynamism of research in this hydrogen category since, by analyzing the co-citation of references, one can understand how the different themes are connected and their distribution over time. This provides the foundation for future research, collaborations, and advancements in blue hydrogen production.

In the field of bibliometrics, the analysis of frequently mentioned keywords plays an essential role in identifying highlighted categories, in addition to helping to monitor the development of a particular research theme. By using the VOSviewer to perform a keyword co-occurrence analysis, it was possible to identify 6 distinct clusters based on the keywords present in the WoSCC database: "blue hydrogen study", "hydrogen production study", "green hydrogen production study", "CO_2 capture and storage study", "techno-economic study" and "technological study". These clusters indicate the areas of most significant interest and investigation within the field of hydrogen, ranging from the study of blue hydrogen to the evaluation of different technologies and economic aspects related to the production and use of hydrogen. In addition, the CO_2 capture and storage study reflects the concern with sustainability and the environmental impact of producing this fuel. These results suggest that this field of research is constantly expanding, addressing aspects ranging from efficiency and economic viability to reducing carbon emissions.

Regarding the analysis of the co-occurrence of keywords carried out in this study, it was possible to obtain an overview of the main topics addressed, identify future directions for these studies, and provide an evaluation consistent with the current scenario. This information is crucial for directing research efforts and promoting significant advancements in the large-scale application of blue hydrogen. By identifying the research clusters, such as the "blue hydrogen study" and "green hydrogen production study", it is possible to perceive that the search for a sustainable energy matrix has had undeniable growth, even though both areas of study deal with technologies that are still new in the hydrogen tracking. The fact that there is a significant number of studies, considering a short period since the beginning of publications, indicates an increase in interest and awareness of new approaches to hydrogen production by processes that emit less and fewer pollutants. This can be attributed to global concerns about climate change and the need to find sustainably competent solutions.

It is important to emphasize that the presence of the "techno-economic study" cluster suggests a focus on assessing the viability of blue hydrogen to contribute to the potential that this fuel can offer to the economy, an aspect essential for its adoption on a large scale. Effectively integrating this technology into current energy systems in a commercially viable manner. However, although the production of blue hydrogen is in its initial stages, the data shows that the development takes place to meet the energy demand. However, even if the number of works published in this field has not yet reached expressive levels, the focus observed from the analysis of production routes to the evaluation of the viability of new projects reflects the need to understand and improve the different aspects of this technology by some of the researchers to incorporate blue hydrogen in a decisive way in the economy and the energy sector.

The data obtained indicate that the keywords "hydrogen economy", "liquid hydrogen", "hydrogen storage," and "renewable energy" are the main hotspots for future research, which highlights the concerns and current themes addressed among the academics concerning energy production having blue hydrogen as a vector.

(i) *Hydrogen economy*. The presence of this keyword indicates the growing approach to this theme since there is a significant interest in building a conscious economy in the quest to reduce the emission of pollutants, as well as the need to implement a source of energy in the global energy system of power that meets social and market demands. However, for the production of blue hydrogen, it is necessary to have government incentives and the development of specialized infrastructure focused on the safety and maintenance of this fuel within the energy matrix. Thus, given the data obtained, it is clear that the insertion of hydrogen as an energy vector is a growing agenda in the academic sector, which continuously helps in the development of technologies and provides the emergence of new prospects for the global energy market, improving the techniques already implemented in the hydrogen production chain and cooperating for significant and dynamic growth of this segment.

(ii) *Liquid hydrogen and hydrogen storage*. The fact that these terms appear together within the research environment reinforces the relevance of the theme of safe hydrogen storage concerning the other topics considered. Hydrogen, in its liquid form, has high energy efficiency. However, there are several challenges regarding its storage and transport.[70,74,75] Liquid hydrogen requires low temperatures and adiabatic conditions for transport through pipelines. However, the costs arising from the initial processes of implementing an infrastructure that serves this distribution are still the limiting factor for the widespread use of this system. In addition, an advanced refrigeration system is also necessary to guarantee the required conditions for storage. Tanks or containers with certain pressure conditions can be used. However, this method is indicated for short distances. Whether in its liquid or gaseous form, hydrogen storage is an element that must be considered in any project implementation study in this field, as ensuring the safety and efficiency of the production chain is essential for introducing hydrogen into the energy system. Thus, the need to develop research aimed at understanding such factors is necessary for the viable and economical application of this fuel, considering that there is a need for means to store hydrogen in large volumes to supply the growing demand.

(iii) *Renewable energy*. Faced with the emergence of new prospects for reducing energy production by conventional routes, which are based on the use of fossil fuels, the growth in the number of studies, as well as the development of new technologies for energy production by sustainable means, are indicative of the transition of the global energy system to new heights. Integrating clean energy sources already widely used, such as solar and wind, with other forms of energy, such as hydrogen, is fundamental for achieving social and economic advancements. The presence of "renewable energy" as one of the potential hotspots for the scientific field shows the connection between emerging topics in the field of blue hydrogen. In this way, it is clear that in the current scenario of the research sector, the productions directed to this type of hydrogen have grown substantially. However, the number of projects for implementing this energy vector globally is still in its initial stages. Therefore, the continuous production of research in these areas helps to improve existing technologies and explore new horizons for application in the energy market, seeking new solutions for the current challenges.

5. Strengths and limitations

Given the strengths that can be referred to in this study, it can be said that it mainly carried out a systematic analysis of how the academic production in terms of research related to the production of blue hydrogen took place between 2012 and 2023, presenting parameters that indicate the main trends in the energy market, thus providing a comprehensive view of the participation of institutions, authors and emerging countries in this field of research. Another point to be considered is that this bibliometric analysis provides an overview of the principal published studies, the hotspots in evidence, and the future directions of these works. Data processing and the construction of visualization maps were obtained using specialized software in compiling bibliometric data and elaborating visual means to subsidize the analysis dynamically and precisely. The initial data were taken from a database widely used for performing advanced bibliometric analyses (WoS), where, once processed, they could provide an understanding of research on blue hydrogen.

However, some limitations were identified and are relevant to mention. The first was that the database obtained by WoS contained a small number of articles to be analyzed, making it difficult to build more accurate visualization maps in the software used for observing data more complexly and understanding the interconnections between works. Another limitation found is that the data obtained in this study may differ from the current WoS information due to the constant updates that the platform performs as new works are published.

6. Opportunities and future prospects

The implementation of blue hydrogen as a way to provide the decarbonization of essential socioeconomic sectors still needs improvement. The characteristics that configure it as a clean fuel need to be explored. The growing demand for environmentally friendly fuels points to expanding production technologies, focusing on making them economically viable in the long term. Thus, establishing the current limitations of the production chain for this hydrogen category will help prospect for innovations and how these will act as means of accessing improvements, thus contributing to large-scale applications.

6.1 Technical and economic feasibility aspects

Although there is a specific plurality in hydrogen applications, it still does not represent a majority share in several sectors, such as transport and power generation. Even though the production of blue hydrogen is becoming an emerging topic for researchers in the area, developing new technologies and improving existing processes will collaborate with the comprehensive consolidation of this fuel in the international market. Some valid aspects to be considered include the implications directly involved with the production of blue hydrogen since, like grey hydrogen, it has carbon dioxide (CO_2) as a by-product. The emission of such a by-product acts as the threshold to determine the environmental impacts of both fuels and, therefore, defines which technologies will be applied to reduce this pollutant. Thus, for hydrogen to be classified as "blue", it is necessary that there is the most significant possible reduction in the release of carbon dioxide into the atmosphere. Although grey hydrogen is relevant and its production is already implemented and economically accessible, the large amount of CO_2 released intrinsic to its production process encourages the development of new ventures that can sustainably supply the demand for hydrogen. Much of the hydrogen produced has natural gas as raw material, where the most used production route is steam reforming of methane (SMR), the basic process for obtaining grey hydrogen. However, when carbon capture and storage technology (CCUS) is added to this process, the product is blue-category hydrogen with a low emission rate of pollutants. However, integrating this additional process can compromise the project's economic viability for separating CO_2 from hydrogen. It is necessary to use equipment and operational resources to reduce this by-product of the process. However, considering that the production of blue hydrogen globally is still in its early stages, it is worth mentioning that the CCUS process for the projects already installed has a carbon dioxide capture rate of between 60 and 65%.[76] Even if there are currently ways to increase this rate, it would not be possible to carry them out without affecting the economic conditions of the enterprise. For countries where natural gas prices are not attractive, coal as a raw material for hydrogen is an alternative, with brown category hydrogen as a product. However, like grey hydrogen, it has high rates of greenhouse gas emissions since the production route used is coal gasification. Even so, it is possible to integrate the CCUS system into the base process so that blue hydrogen is also obtained and, in this way, contributes to the decarbonization of the production chain using an alternative route. Thus, ensuring the availability of raw materials, storage infrastructure, and technological readiness is essential for the iconic blue hydrogen and environmental sustainability of blue hydrogen.

Monitoring the progress of the global energy transition is necessary for synchronicity and economic returns to occur, as among the financial risks facing the development of the hydrogen economy is the making of considerable investments in infrastructure and uncertain market acceptance. In this sense, studies are developed that aim at application and economic forecasts. Lee *et al.* (2023) carried out a technical and financial analysis of the production of blue hydrogen against grey hydrogen. They listed the operational costs in six cases, confirming the high cost for development, application and maintenance.[77]

6.2 Economic analysis of blue hydrogen production: feasibility and challenges

Blue hydrogen production represents an alternative promise for reducing carbon emissions, although the costs associated with this process are a point of specific economic analysis. The costs of producing blue hydrogen vary considerably, with estimates showing a wide range. On average, studies indicate an approximate cost of US$1.80 to US$4.70 per kilogram of hydrogen produced. Comparatively, grey hydrogen, not considering the prices of carbon emissions, has an average production cost of around US$0.98 to US$2.93 per kilogram, while green hydrogen, depending on the region and market conditions, can vary between US$4.5 and US$12.00 per kilogram.[82] Considering its current position in the energy market, analyzing the economic viability of blue hydrogen is challenging. Despite having higher initial costs than grey hydrogen, obtaining government subsidies and carbon credits can make blue hydrogen more competitive. In locations with stricter environmental policies, the incentive to produce blue hydrogen may be greater due to its lower carbon footprint than grey hydrogen. Scalability plays a crucial role in reducing blue hydrogen production costs. With increased production and investments in research and development, costs can decrease significantly. Designing future scenarios for blue hydrogen involves considering technological advancements and government policies. Cost reduction is one of the main challenges currently faced, along with the continued dependence on fossil resources and the need to improve carbon capture and storage infrastructure.

In summary, although the initial cost of blue hydrogen is higher than some alternatives, its potential for cost savings and lower environmental impact make it an attractive option. Implementing enabling policies and continued development of technologies can boost their economic viability and significantly contribute to the global transition to a low-carbon economy. These values are indicative and may vary depending on the region, specific production methods and market conditions.

6.3 Opportunities and future applications of blue hydrogen

Through the bibliometric analysis applied in this study, it was possible to place aspects of blue hydrogen in the global scenario, presenting the technologies involved in its production and the processes already implemented by the industry. In this way, the panorama presented here can offer strategies around the future prospects of the production of this fuel, as well as collaboration in terms of incentives in the development of new research. With the growing interest in an economy based on environmentally friendly energy sources, research focused on “blue” hydrogen production can suggest several alternatives for integrating this source into countrie's energy systems. Hydrogen is considered a versatile fuel, as its use can be observed in industrial food processes, ammonia and methanol production, metal treatment, petroleum refining, and glass production.[78] According to the International Energy Agency (IEA), the estimated world demand for hydrogen was 73.9 Mt H_2 per year in 2018, where the countries with the highest demand for the fuel were China, the United States, the European Union, India, Japan and South Korea.[79] In this way, noting that research for the production of blue hydrogen is still recent but is expanding, it is possible to estimate a promising future for this production route in the hydrogen market since, with the technological advancements observed in the most diverse areas, having an energy source that presents the desirable energy potential and guarantees a reduction in the levels of pollutants emitted each year will be decisive for the integration of blue hydrogen in the world energy system with a diversity of applications, considering that the growing number of discussions in and around this agenda nurtures interest in the development and improvement of new technologies to make this fuel viable on a large scale, to meet the demand that grows every year.

7. Blue hydrogen patents

Notably, the literature on blue hydrogen production has increased significantly, reaching its peak in 2022. However, it is essential to emphasize that the year 2023 promises to surpass the number of publications of the previous year. Topics such as new production approaches, reduction of environmental impacts, and economic viability have gained prominence along with the production of blue hydrogen. At the academic level, research in this field is having a significant impact on renewable energy. Simultaneously, industrial research has recognized the valuable potential of blue hydrogen production routes for systemic applications in industrial facilities. When searching for research platforms or robust patent databases, such as the United States Patent and Trademark Office (USPTO)[80] and the European Patent Office (EPO),[81] it found a total of 26 international patents related to blue hydrogen in the period from 1997 to May 2023.

There has been significant growth in the volume of patents granted or deposited in recent years, with industries and universities playing a vital role in this increase. Industries account for more than 46% of patents deposited or granted, while academic institutions hold about 54%. This increase can be attributed to the development of engineering and computational tools that allow for deeper analyses and applications of routes related to the production of blue hydrogen. Fig. 11 presents a graph that shows this growth in the volume of patents over the last few years.

It is also important to highlight that some countries stand out regarding the number of patents deposited. China, the

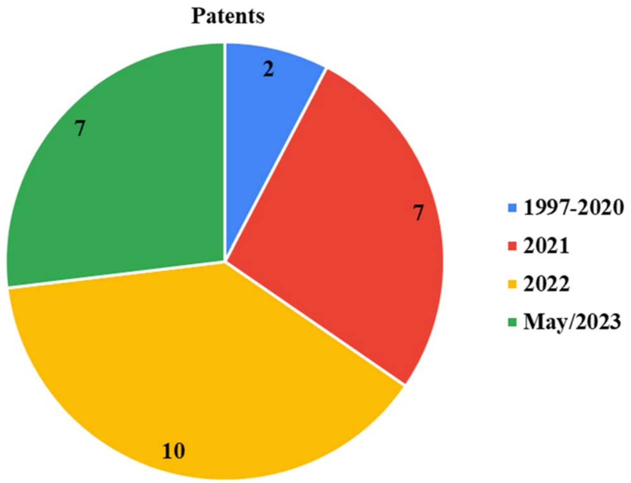

Fig. 11 Graph showing the number of patents per year.

United States, and South Korea occupy the 1st, 2nd, and 3rd places in the ranking, respectively. The Chinese are responsible for about 54% of the patents granted, while the North Americans and the South Koreans hold 19% each. It is worth mentioning that the predominant language in the scientific writing of these patents is English. In summary, the patent scenario for the production of blue hydrogen is promising. It has been gaining prominence in research, seeking various applications for these production routes and this product, which is vital for global energy development.

8. Conclusion

The present study presented an overview of the scientific production focused on the blue hydrogen category, showing current and future trends in developing new research in this segment. Productivity in this field has only recently begun. However, it already has many publications that consolidate it as an emerging field of study. The United States is the country that leads both in the number of publications and in the sum of citations, presenting itself as one of the leading centres of research in this area today. In this way, the prospects of the growth of new research projects addressing this theme are promising. However, cooperation between research groups and institutions should be encouraged and strengthened to increase the visibility of future productions. Considering that works related to "hydrogen economy", "liquid hydrogen", "hydrogen storage," and "renewable energy" will be the most apparent hotspots, it is possible to state that the commitment to the development of new studies with well-defined purposes and proposals that help technological advancements will pave the way for the integration of new researchers and funding agencies, collaborating with the massive insertion of blue hydrogen in the energy market.

Data availability

Data will be made available on request.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

1 R. Bartali, in *Proceedings of the ISES EuroSun 2020 Conference – 13th International Conference on Solar Energy for Buildings and Industry*, International Solar Energy Society, Freiburg, Germany, 2020, pp. 1–13.
2 M. Merten, F. Rücker, I. Schoeneberger and D. U. Sauer, *Appl. Energy*, 2020, **268**, 114978.
3 X. J. Li, J. D. Allen, J. A. Stager and A. Y. Ku, *Clean Energy*, 2020, **4**, 26–47.
4 A. Kovač, M. Paranos and D. Marciuš, *Int. J. Hydrogen Energy*, 2021, **46**, 10016–10035.
5 G. Mancò, E. Guelpa, A. Colangelo, A. Virtuani, T. Morbiato and V. Verda, *Sustainability*, 2021, **13**, 1938.
6 C. Acar and I. Dincer, *J. Cleaner Prod.*, 2019, **218**, 835–849.
7 A. da Silva César, T. da Silva Veras, T. S. Mozer, D. da Costa Rubim Messeder dos Santos and M. A. Conejero, *J. Cleaner Prod.*, 2019, **207**, 751–763.
8 W. Cheng and S. Lee, *Sustainability*, 2022, **14**, 1930.
9 B. Shadidi, G. Najafi and T. Yusaf, *Energies*, 2021, **14**, 6209.
10 F. Fatigati, A. Di Giuliano, R. Carapellucci, K. Gallucci and R. Cipollone, *Processes*, 2021, **9**, 1440.
11 M. Noussan, P. P. Raimondi, R. Scita and M. Hafner, *Sustainability*, 2020, **13**, 298.
12 M. Yu, K. Wang and H. Vredenburg, *Int. J. Hydrogen Energy*, 2021, **46**, 21261–21273.
13 J.-L. Fan, P. Yu, K. Li, M. Xu and X. Zhang, *Energy*, 2022, **242**, 123003.
14 A. N. Antzaras and A. A. Lemonidou, *Renewable Sustainable Energy Rev.*, 2022, **155**, 111917.
15 R. W. Howarth and M. Z. Jacobson, *Energy Sci. Eng.*, 2021, **9**, 1676–1687.
16 D. Khatiwada, R. A. Vasudevan and B. H. Santos, *Renewable Sustainable Energy Rev.*, 2022, **168**, 112775.

17 S. D. C. Walsh, L. Easton, Z. Weng, C. Wang, J. Moloney and A. Feitz, *Int. J. Hydrogen Energy*, 2021, **46**, 35985–35996.
18 Z. Navas-Anguita, D. García-Gusano, J. Dufour and D. Iribarren, *Sci. Total Environ.*, 2021, **771**, 145432.
19 V. Epurescu, *Proc. Int. Conf. Bus. Excell.*, 2021, **15**, 415–424.
20 Y. Yang, L. Tong, S. Yin, Y. Liu, L. Wang, Y. Qiu and Y. Ding, *J. Cleaner Prod.*, 2022, **376**, 134347.
21 O. Massarweh, M. Al-khuzaei, M. Al-Shafi, Y. Bicer and A. S. Abushaikha, *J. CO2 Util.*, 2023, **70**, 102438.
22 C. Bauer, K. Treyer, C. Antonini, J. Bergerson, M. Gazzani, E. Gencer, J. Gibbins, M. Mazzotti, S. T. McCoy, R. McKenna, R. Pietzcker, A. P. Ravikumar, M. C. Romano, F. Ueckerdt, J. Vente and M. van der Spek, *Sustainable Energy Fuels*, 2022, **6**, 66–75.
23 S. Atilhan, S. Park, M. M. El-Halwagi, M. Atilhan, M. Moore and R. B. Nielsen, *Curr. Opin. Chem. Eng.*, 2021, **31**, 100668.
24 A. K. Tiwari, S. Nasreen and M. A. Anwar, *J. Cleaner Prod.*, 2022, **334**, 130244.
25 F. S. AlHumaidan, M. Absi Halabi, M. S. Rana and M. Vinoba, *Energy Convers. Manage.*, 2023, **283**, 116840.
26 J. F. George, V. P. Müller, J. Winkler and M. Ragwitz, *Energy Policy*, 2022, **167**, 113072.
27 S. Cloete, C. Arnaiz del Pozo and Á. J. Álvaro, *Energy*, 2022, **259**, 124954.
28 S. Cloete, O. Ruhnau and L. Hirth, *Int. J. Hydrogen Energy*, 2021, **46**, 169–188.
29 Y. Ma, X. R. Wang, T. Li, J. Zhang, J. Gao and Z. Y. Sun, *Int. J. Hydrogen Energy*, 2021, **46**, 27330–27348.
30 R. R. Esily, Y. Chi, D. M. Ibrahiem and Y. Chen, *Int. J. Hydrogen Energy*, 2022, **47**, 18629–18647.
31 M. Luberti, A. Brown, M. Balsamo and M. Capocelli, *Energies*, 2022, **15**, 1091.
32 H. C. Lau, S. Ramakrishna, K. Zhang and A. V. Radhamani, *Energy Fuels*, 2021, **35**, 7364–7386.
33 S. Moon, Y. Lee, D. Seo, S. Lee, S. Hong, Y.-H. Ahn and Y. Park, *Renewable Sustainable Energy Rev.*, 2021, **141**, 110789.
34 C. Saccani, M. Pellegrini and A. Guzzini, *Energies*, 2020, **13**, 4835.
35 T. Talan, *Int. J. Technol. Educ.*, 2021, 428–442.
36 F. S. Neto, M. M. Fernandes de Melo Neta, M. B. Sales, F. A. Silva de Oliveira, V. de Castro Bizerra, A. A. Sanders Lopes, M. A. de Sousa Rios and J. C. S. dos Santos, *Polym.*, 2023, **15**, 2057.
37 R. C. Nogueira, F. S. Neto, P. G. de S. Junior, R. B. R. Valério, J. de F. Serpa, A. M. da S. Lima, M. C. M. de Souza, R. K. C. de Lima, A. A. S. Lopes, A. P. Guimarães, R. L. F. Melo, M. A. de S. Rios and J. C. S. dos Santos, *Energy Nexus*, 2023, **10**, 100199.
38 K. Castañeda, O. Sánchez, R. F. Herrera and G. Mejía, *Sustainability*, 2022, **14**, 5544.
39 A. F. S. Rodrigues, A. F. da Silva, F. L. B. da Silva, K. M. dos Santos, M. P. de Oliveira, M. M. R. Nobre, B. D. Catumba, M. B. Sales, A. R. M. Silva, A. K. S. Braz, A. L. G. Cavalcante, J. Y. N. H. Alexandre, P. G. S. Junior, R. B. R. Valério, V. de Castro Bizerra and J. C. S. dos Santos, *Process Biochem.*, 2023, **126**, 272–291.
40 M. B. Sales, J. G. L. Neto, A. K. De Sousa Braz, P. G. De Sousa Junior, R. L. F. Melo, R. B. R. Valério, J. de F. Serpa, A. M. Da Silva Lima, R. K. C. De Lima, A. P. Guimarães, M. C. M. de Souza, A. A. S. Lopes, M. A. de S. Rios, L. F. Serafim and J. C. S. dos Santos, *Electrochem*, 2023, **4**, 181–211.
41 V. C. Ferreira, L. C. Ampese, W. G. Sganzerla, L. M. S. Colpini and T. Forster-Carneiro, *Sustainable Chem. Pharm.*, 2023, **33**, 101070.
42 A. Knapczyk, S. Francik, J. Fraczek and Z. Slipek, *Engineering for Rural Development*, 2019, **22**, 1503–1509.
43 R. Khatun, H. Xiang, Y. Yang, J. Wang and G. Yildiz, *J. Cleaner Prod.*, 2021, **317**, 128373.
44 A. D. Akinwekomi and F. Akhtar, *Entropy*, 2022, **24**, 329.
45 A. F. S. Rodrigues, A. F. da Silva, F. L. B. da Silva, K. M. dos Santos, M. P. de Oliveira, M. M. R. Nobre, B. D. Catumba, M. B. Sales, A. R. M. Silva, A. K. S. Braz, A. L. G. Cavalcante, J. Y. N. H. Alexandre, P. G. S. Junior, R. B. R. Valério, V. de Castro Bizerra and J. C. S. dos Santos, *Process Biochem.*, 2023, **126**, 272–291.
46 M. B. Sales, P. T. Borges, M. N. Ribeiro Filho, L. R. Miranda da Silva, A. P. Castro, A. A. Sanders Lopes, R. K. Chaves de Lima, M. A. de Sousa Rios and J. C. S. dos Santos, *Bioengineering*, 2022, **9**, 539.
47 G. Ferreira Mota, I. Germano de Sousa, A. Luiz Barros de Oliveira, A. Luthierre Gama Cavalcante, K. da Silva Moreira, F. Thálysson Tavares Cavalcante, J. Erick da Silva Souza, Í. Rafael de Aguiar Falcão, T. Guimarães Rocha, R. Bussons Rodrigues Valério, S. Cristina Freitas de Carvalho, F. Simão Neto, J. de França Serpa, R. Karolinny Chaves de Lima, M. Cristiane Martins de Souza and J. C. S. dos Santos, *Algal Res.*, 2022, **62**, 102616.
48 P. T. Borges, M. B. Sales, C. E. César Guimarães, J. de França Serpa, R. K. C. de Lima, A. A. Sanders Lopes, M. A. de Sousa Rios, A. S. Desai, A. M. da Silva Lima, E. E. S. Lora and J. C. S. dos Santos, *Int. J. Hydrogen Energy*, 2024, **49**, 433–458.
49 V. K. Singh, P. Singh, M. Karmakar, J. Leta and P. Mayr, *Scientometrics*, 2021, **126**, 5113–5142.
50 F. Guo, F. Li, W. Lv, L. Liu and V. G. Duffy, *Int. J. Hum.-Comput. Interact.*, 2020, **36**, 801–814.
51 B. D. Catumba, M. B. Sales, P. T. Borges, M. N. Ribeiro Filho, A. A. S. Lopes, M. A. de Sousa Rios, A. S. Desai, M. Bilal and J. C. S. dos Santos, *Int. J. Hydrogen Energy*, 2023, **48**, 7975–7992.
52 R. L. F. Melo, M. B. Sales, V. de Castro Bizerra, P. G. de Sousa Junior, A. L. G. Cavalcante, T. M. Freire, F. S. Neto, M. Bilal, T. Jesionowski, J. M. Soares, P. B. A. Fechine and J. C. S. dos Santos, *Int. J. Biol. Macromol.*, 2023, **253**, 126709.
53 C. E. C. Guimarães, F. S. Neto, V. de Castro Bizerra, J. G. A. do Nascimento, R. B. R. Valério, P. G. de Sousa Junior, A. K. de Sousa Braz, R. L. F. Melo, J. de França Serpa, R. K. C. de Lima, A. P. Guimarães, M. C. M. de Souza, A. A. S. Lopes, M. A. de Sousa Rios, A. S. Desai, M. Bilal, W. Smułek, T. Jesionowski and J. C. S. dos Santos, *Bioresour. Technol. Rep.*, 2023, **23**, 101543.
54 J. L. da Silva, M. B. Sales, V. de Castro Bizerra, M. M. R. Nobre, A. K. de Sousa Braz, P. da Silva Sousa, A. L. G. Cavalcante, R. L. F. Melo, P. Gonçalves De Sousa

Junior, F. S. Neto, A. M. da Fonseca and J. C. S. dos Santos, *Fermentation*, 2023, **9**, 581.
55 R. W. Cooksey, *Illustrating Statistical Procedures: Finding Meaning in Quantitative Data*, 2020, pp. 61–139.
56 P. Mishra, C. M. Pandey, U. Singh, A. Gupta, C. Sahu and A. Keshri, *Ann. Card. Anaesth.*, 2019, **22**, 67.
57 A. Sezgin, K. Orbay and M. Orbay, *SAGE Open*, 2022, **12**, 215824402211416.
58 C. Lunny, T. Neelakant, A. Chen, G. Shinger, A. Stevens, S. Tasnim, S. Sadeghipouya, S. Adams, Y. W. Zheng, L. Lin, P. H. Yang, M. Dosanjh, P. Ngsee, U. Ellis, B. J. Shea, E. K. Reid and J. M. Wright, *Res. Synth. Methods*, 2022, **13**, 109–120.
59 K. Orbay, R. Miranda and M. Orbay, *Particip. Educ. Res.*, 2020, **7**, 1–13.
60 V. Koltun and D. Hafner, *PLoS One*, 2021, **16**, e0253397.
61 W. E. Schreiber and D. M. Giustini, *Am. J. Clin. Pathol.*, 2019, **151**, 286–291.
62 M. Bevilacqua, F. E. Ciarapica and G. Marcucci, *IFAC-Pap.*, 2019, **52**, 2821–2826.
63 J. L. Aldridge and F. Diekmann, *J. Agric. Food Inf.*, 2019, **20**, 98–128.
64 S. Zhu, W. Jin and C. He, *Eur. Plan. Stud.*, 2019, **27**, 639–660.
65 T. Balz, *Remote Sens.*, 2022, **14**, 4285.
66 H. Sikandar, Y. Vaicondam, N. Khan, M. I. Qureshi and A. Ullah, *J. Interact. Mob. Technol.*, 2021, **15**, 129.
67 J. Jiang, Z. Huang, W. Qian, Y. Zhang and Y. Liu, *IEEE Access*, 2019, **7**, 53566–53584.
68 X. Li and H. Li, *IEEE Access*, 2018, **6**, 63243–63257.
69 R. Zhao, D. Wu and S. Patti, *Energies*, 2020, **13**, 4233.
70 Z. Fan and S. J. Friedmann, *Joule*, 2021, **5**, 829–862.
71 H. Cai, M. Prussi, L. Ou, M. Wang, M. Yugo, L. Lonza and N. Scarlat, *Sustainable Energy Fuels*, 2022, **6**, 4398–4417.
72 J.-E. Shin, *Energies*, 2022, **15**, 8983.
73 T. Longden, F. J. Beck, F. Jotzo, R. Andrews and M. Prasad, *Appl. Energy*, 2022, **306**, 118145.
74 D. Zivar, S. Kumar and J. Foroozesh, *Int. J. Hydrogen Energy*, 2021, **46**, 23436–23462.
75 E. Rivard, M. Trudeau and K. Zaghib, *Materials*, 2019, **12**, 1973.
76 *Resources for the Future*, https://www.rff.org/publications/reports/decarbonizing-hydrogen-us-power-and-industrial-sectors/, accessed May 2023.
77 J. Lee, H. Cho and J. Kim, *J. Environ. Chem. Eng.*, 2023, **11**, 109549.
78 N. Rambhujun, M. S. Salman, T. Wang, C. Pratthana, P. Sapkota, M. Costalin, Q. Lai and K.-F. Aguey-Zinsou, *MRS Energy Sustain.*, 2020, **7**, 33.
79 IEA, *The Future of Hydrogen: Seizing today's opportunities*, OECD, Paris Cedex 16, 2019, DOI: 10.1787/1e0514c4-en.
80 World Intellectual Property Organization, *WIPO Intellectual Property Handbook: Policy, Law and Use*, 2004, vol. 489.
81 European Patent Office, https://www.epo.org/en, accessed April 2023.
82 *Bloomberg the Company & Its Products*, https://about.bnef.com/blog/green-hydrogen-to-undercut-gray-sibling-by-end-of-decade/, accessed August 2023.