Trend of Research on Green Hydrogen Production Based on Scopus Database: A Bibliometric Analysis

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Abstract- Green hydrogen has emerged as an innovative solution to deal with challenges: dependence regarding the utilization of fossil fuels and the incorporation of renewable energy sources. Presently, a significant obstacle in green hydrogen production lies in the cost-effectiveness and efficiency. In this context, research plays a crucial role in striving for more economical and efficient hydrogen production. To explore the latest developments and trends in research on green hydrogen production, bibliometric analysis is a valuable tool. In this analysis, VOS viewer enables the use of co-occurrence, bibliographic coupling, and co-authorship methods. Scopus serves as the database for collecting articles. From the search results, 356 scientific journal articles published between 2018 and 2022 were found. China emerges as the leading contributor, with a total of 81 articles. Notably, the International Journal of Hydrogen Energy emerges as the top journal contributor, boasting 62 articles. Within the realm of scientific disciplines, the field of energy science demonstrates the strongest influence and correlation, comprising 28.7%. The co-occurrence analysis reveals that research can be categorized into three clusters: Cluster I focusing on green hydrogen as a future renewable energy source, Cluster II centering on chemical applications of green hydrogen, and Cluster III dedicated to green hydrogen production. When evaluating the average year of publication and average normalized citation values, it becomes evident that research themes in Cluster I and "solar-electrolysis" fall into the "trending" category, while Cluster III falls under the "middle trending" category.

Keywords Green hydrogen, bibliometrics, co-occurrence, vosviewer, scopus.

1. Introduction

The Paris Agreement stands as a milestone in the global crusade against climate change. This universal accord has garnered ratification from a majority of nations worldwide and is designed to curb the rise in global temperatures, with the objective of maintaining a temperature increase of less than 2 degrees Celsius above pre-industrial levels [1][2]. The Paris Agreement focuses on tackling the crucial issue of reducing greenhouse gas emissions, which are the main cause of global warming [3]. Within this framework, renewable energy sources, represent clean and sustainable alternatives capable of significantly mitigating greenhouse gas emissions [4][5]. However, gaining increasing attention in recent times is the burgeoning potential of green hydrogen. Utilizing sustainable energy sources, green hydrogen, which is generated through environmentally friendly methods, shows great potential as a clean energy source for the future [6][7].

The significance of green hydrogen in the journey toward achieving Net Zero Emissions (NZE) target by 2050 is vital in the global shift towards a sustainable society [8][9]. In this context, green hydrogen serves as a catalyst for positive change, enabling a shift towards cleaner and more sustainable energy systems. First, green hydrogen serves as an efficient means of storing renewable energy [10][11].

Moreover, green hydrogen holds great promise in the realm of transportation as an alternative fuel for fuel cell-powered vehicles [12][13]. In the industrial sector, green hydrogen plays a pivotal role in the decarbonization of processes that rely heavily on heat and chemicals, such as steel and chemical production [14][15].

The current landscape of green hydrogen production remains quite limited, constituting a minuscule portion of the worldwide hydrogen supply. According to a study by the IEA, At now, 76% of hydrogen is obtained from natural gas., 22% from coal, and merely 2% from water electrolysis [7][16]. In fact, to attain the NZE target by 2050, it is projected that two-thirds of the total hydrogen demand in that year must be met by green hydrogen [17]. Despite increased investments and research endeavors in the field of green hydrogen, the notable expansion in production continues to encounter obstacles, including exorbitant production expenses, inadequate infrastructure, and the requirement for reliable renewable energy sources [18][19]. Nevertheless, in light of worldwide obligations to decrease greenhouse gas emissions and advocate for sustainable energy alternatives, there exists substantial potential for rapid expansion producing green hydrogen.

The significance of conducting research on green hydrogen is becoming increasingly evident within the context of sustainable energy. Numerous countries have now adopted national hydrogen strategies and are actively supporting various research initiatives related to green hydrogen. Such a decision reflects an increasing recognition of the vast capabilities of green hydrogen in mitigating the release of greenhouse gases and advancing cleaner energy solutions [20]. The role of research becomes paramount in the pursuit of more cost-effective hydrogen production. Rigorous research efforts have found new technologies, more efficient production processes, and more affordable methods for storage and distribution [21]. Consequently, research on green hydrogen bringing us closer to a future.

Bibliometric analysis is a powerful tool for assessing the intellectual landscape and research trends in specific domains, and it can play a pivotal role in understanding the developments related to green hydrogen production. By systematically examining and quantifying scientific publications, citations, and research networks, bibliometric analysis offers valuable analyse the development, advancement, and influence of research in this particular area [22]. It also allows for the identification of key researchers, influential works, emerging topics, and collaborative efforts that shape the trajectory of green hydrogen research. In essence, this bibliometric analysis provides an extensive examination of the progress and possibilities in the field of green hydrogen production.

In the existing literature, several studies have been conducted on hydrogen-related topics. These studies encompass areas such as hydrogen production and storage [23], green hydrogen research [24], the hydrogen economy [25], analysis and evaluation of hydrogen energy [26], hydrogen electrolyzer [27], and global trends in hydrogen production [28]. However, this paper specifically focused on the subject of green hydrogen production, utilizing VOSviewer software to perform co-occurrence, co-author, and bibliographic coupling analyses. Additionally, it assessed the subtopic “solar-electrolysis” through keyword analysis to determine whether it would represent a trending research area.

2. Methodology

2.1. Bibliometrics Analysis with Vosviewer

Research topic mapping is a comprehensive process that involves identifying, analyzing, and presenting information related to a specific topic within a particular field of study. One of the primary objectives of topic mapping is to determine whether the chosen research topic is currently trending or not [29]. It is worth noting that mapping research topics is an integral part of the broader literature review process [30]. Beyond assessing the trending status of a research topic, topic mapping can also unveil the latest trends in a research field. This information can then serve as a valuable reference for researchers when making decisions regarding their research topics [31].

Bibliometric analysis is a commonly employed method for mapping research topics [32]. Through bibliometric, scientific publication data related to a specific topic can be statistically analyzed and visually represented [33][34]. It is a method that involves analyzing research topics using metadata obtained from scientific literature databases [24][35]. Various software tools are available to assist in mapping research topics, VOS viewer is one of the most commonly used software tools for bibliometric analysis [36][37]. In the context of this research, bibliometric analysis will be conducted using VOSviewer 1.6.18 software. The search strategy employed for Table 1, provides an overview of the Scopus scientific literature database.

Table 1. Search strategies in scientific literature database

Component	Description
Data Source	Scopus
Keywords	"*Green hydrogen production*"
Publication Time	2018-2022
Publication types	Journal
Language	English

Table 1 shows that the literature database used in this search came from Scopus and the string used was:

TITLE-ABS-KEY search query: "green hydrogen production" AND (LIMIT-TO (PUBYEAR, 2022) OR LIMIT-TO (PUBYEAR, 2021) OR LIMIT-TO (PUBYEAR, 2020) OR LIMIT-TO (PUBYEAR, 2019) OR LIMIT-TO (PUBYEAR, 2018)) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (SRCTYPE, "j"))

The selection of Scopus as the database for bibliometric analysis research was based on various strong justifications [24][38]. Firstly, its rigorous indexing process is well-regarded, ensuring the inclusion of high-quality publications [39]. Secondly, Scopus offers extensive multidisciplinary coverage, encompassing various scientific fields and research

topics [40]. Thirdly, it provides comprehensive citation data [41]. Fourthly, Scopus includes publications from around the world, facilitating global analyses. The last, Scopus offers flexible and customizable search and data extraction tools [42]. Given these advantages, Scopus stands as the primary choice for collecting datasets. Following the search, a total of 356 literature pieces were identified that met the supplied search criteria.

After conducting a search of scientific publication data from Scopus, the subsequent steps involve conducting several types of analyses, including co-occurrence analysis, bibliographic coupling, and co-authorship analysis. For these purposes, VOSviewer software proves to be a valuable and specialized tool. It is specifically designed to create and visualize bibliometric maps, making it an invaluable resource for researchers as it simplifies the generation of effective maps that depict the research landscape's structural and dynamic features. [43]. VOSviewer facilitates the exploration of relationships among various entities, including authors, keywords, or publications, enabling researchers to gain a comprehensive understanding of patterns and connections within their datasets [25] [44]. In this study, co-occurrence and bibliographic coupling analyses were conducted using VOSviewer software, while co-authorship analysis was performed through manual calculations using Scopus online analysis tools and Microsoft Excel.

Bibliographic coupling analysis, facilitated by VOSviewer software, allows researchers to detect and visually represent connections across scientific documents by examining shared references referenced in these publications. The parameters for bibliographic analysis can be configured within the VOSviewer software. Once the parameters are set, VOSviewer processes the data and generates a network visualization that illustrates bibliographic coupling connections between documents. In this network, each document is represented as a node, and edges connecting these nodes indicate that the documents share the same references [45]. The resulting network visualization can be interpreted to identify clusters of documents closely related through shared references. It aids researchers in comprehending the research landscape's structure, recognizing research trends, and understanding how scientific works interrelate within a research context [46].

Co-occurrence analysis in VOSviewer is a bibliometric technique used to reveal relationships between words or phrases that frequently appear together in scientific publications [47]. In this type of network map, each term is also depicted as a node, and the edges between nodes signify that the terms co-occur frequently in the same publications. Utilizing this analysis facilitates researchers' understanding of the principal topics within a research field and the interplay among these topics. The output of this analysis includes keyword network visualizations, overlay visualizations (indicating the time of appearance of keywords in scientific publications), and density visualizations (showing the frequency of keyword appearance in scientific publications) [48].

2.2. Literature Review Protocol

The methodology utilized in this investigation is derived from the Scientific Procedures and Rationales for Systematic Literature Reviews (SPAR-4-SLR) protocol, which was created by Paul et al. (2021) [49] and has been adapted for use in bibliometric research aimed at analyzing trends in green hydrogen production. The protocol steps are outlined in Figure 1.

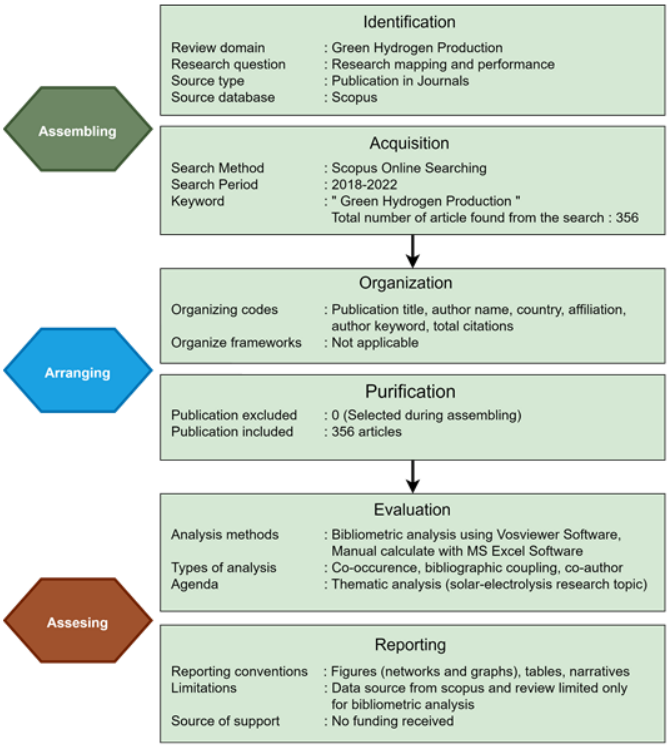


Fig. 1. Research design protocol.

The first stage of the process is "Assembling," which entails identifying and collecting the publications to be reviewed (acquisition). The Scopus database was utilised as the primary data source for this research., with the search keyword "green hydrogen production" applied to the abstract, title, and keywords. A total of 356 articles meeting the specified criteria were identified. The next stage is "Arranging," involves the arrangement of materials and the filtering of publications through inclusion and exclusion criteria. Publication search data was coded using factors such as journal title, publication title, author names, keywords, country of affiliation, funding organization, total citations (TC), and total publications (TP). throughout the data organization stage, no articles were excluded throughout the screening phase. The final stage is "Assessment," which comprises the examination and reporting of findings. The evaluation portion of the article examines the analytical methods and constraints applied in this investigation. The key tools utilized for trend evaluation and analysis include VOS viewer and MS Excel.

3. Results and Discussion

3.1. Bibliographic Analysis Research Performance and Temporal Evolution

Based on the search results, a total of 356 literature pieces were identified, spanning the years 2018 to 2022, as illustrated in Figure 2, provides an overview of the publication trends, citations, and authors related to the research topic "green hydrogen production". The selection of the time frame (2018-2022) for the inclusion of articles in our bibliometric analysis was a carefully considered decision based on several factors aimed at capturing the most relevant and recent developments in the field of green hydrogen production. Based on the historical data from the Scopus database, the period from 2018 to 2022 showed the most significant increase in the number of articles compared to other periods.

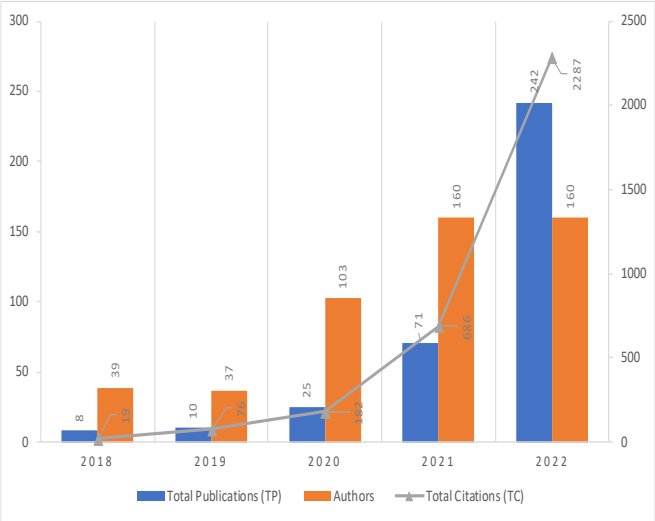


Fig. 2. Publication trends, citations, and authors focused on the subject of green hydrogen production.

Figure 2 demonstrates a notable surge in publications and citations in 2021 and 2022, with both metrics tripling. This analysis indicates a significant increase in research output concerning green hydrogen production during these years. However, it is important to note that the number of researchers actively engaged in this field remains limited. The overall growth in publications, citations, and authors over the past five years underscores the substantial interest in this research topic, likely driven by the increasing need for sustainable energy options, particularly through the utilization of green hydrogen.

Figure 3 provides data on Open Access (OA) publications, Total Publications (TP), and the percentage of OA publications relative to total publications (%OA) over the last 5 years. In 2018, there were 5 OA publications out of a total of 8 publications, resulting in an OA percentage of 62.5%. In 2019, there were 3 OA publications out of a total of 10 publications, resulting in an OA percentage of 30%. In 2020, there were 15 OA publications out of a total of 25 publications, resulting in an OA percentage of 60%. In 2021, there were 33 OA publications out of a total of 71 publications, resulting in an OA percentage of 46.48%. Finally, in 2022, there were 77 OA publications out of a total of 242 publications, resulting in an OA percentage of 31.82%.

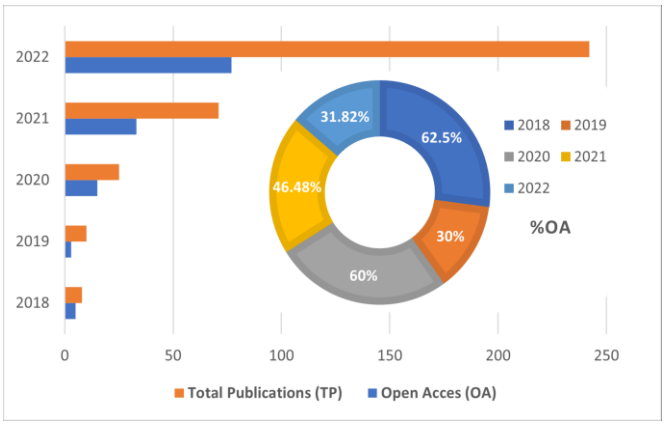


Fig. 3. Open access publications trends.

The trend of OA publications in Figure 3 reveals that the percentage of OA publications in green hydrogen research has varied significantly from year to year, with a notable increase in 2020, followed by a decrease in 2021 and 2022. Nevertheless, the contribution of OA publications remains important in expanding access to research in this domain. The substantial presence of open-access scientific articles in the field of green hydrogen production has several implications for the accessibility and dissemination of research findings, including contributing to more widespread dissemination of knowledge and ensuring that research findings are accessible to a broader audience, including researchers, policymakers, and the general public. This accessibility can foster collaboration, innovation, and the implementation of sustainable practices in the field. While open access promotes broader dissemination, its correlation with citation rates can vary. Open-access articles often receive higher citation rates due to increased visibility, but factors such as journal reputation, article quality, and the specific field of study also influence citation impact. The observed trend towards open access suggests a commitment to sharing knowledge, potentially accelerating advancements and solutions in green hydrogen production.The top five publications in the Open Access category are presented in Table 2.

Table 2 highlights that publications published between 2018 and 2022 achieved varying TC/Y values, ranging from 13.6 to 98. This diversity indicates the substantial impact of such research in a relatively short period of 3 years. Table 3. provides information about the top ten contributors of research in terms of total publications and total citations.

Table 2. The most popular publications in open access

Paper Title	Journal	Year	TC	TC/Y
Bifunctional Heterostructured Transition Metal Phosphides for Efficient Electrochemical Water Splitting	Advanced Functional Materials	2020	242	80.67
Water electrolysers with closed and open electrochemical systems	Nature Materials	2020	137	45.67
Principles of Water Electrolysis and Recent Progress in Cobalt-, Nickel-, and Iron-Based Oxides for the Oxygen Evolution Reaction	Angewandte Chemie International Edition	2022	98	98
Techno-economic Analysis of Hydrogen Electrolysis from Off-Grid Stand-Alone Photovoltaics Incorporating Uncertainty Analysis	Cell Reports Physical Science	2020	69	23
Bimetallic catalysts for green methanol production via CO2 and renewable hydrogen: A mini-review and prospects	Catalysis Science and Technology	2018	68	13.6

Table 3. The highest authors of publications and citations

Ranked by TP			Ranked by TC		
Name	Country	TP	Name	Country	TC
Dincer, I.	Canada	7	Dincer, I.	Canada	105
Javani, N.	Turkey	5	Javani, N.	Turkey	41
Karayel, G.K.	Turkey	5	Karayel, G.K.	Turkey	41
Kim, N.H.	South Korea	5	Liu, L.	Portugal	35
Lee, J.H.	South Korea	5	Kim, N.H.	South Korea	25
Tran, D.T.	South Korea	5	Lee, J.H.	South Korea	25
Lim, H.	South Korea	4	Tran, D.T.	South Korea	25
Liu, L.	Portugal	4	Barhoumi, E.M.	Oman	15
Nguyen, T.H.	South Korea	4	Nguyen, T.H.	South Korea	11
Barhoumi, E.M.	Oman	3	Lim, H.	South Korea	9

According to Table 3, based on the Total Publications (TP) parameter, the top 3 authors are Dincer, I. Javani, N. Karayel, G.K. with total publications of 7, 5, and 5, respectively. Interestingly, these top three authors also have the highest Total Citation (TC) scores, namely 105, 41, and 41. However, it is worth noting that authors like Liu, L. (TP 4) and Barhoumi, E.M. (TP 3), who have fewer publications, actually have higher Total Citation (TC) values than several other authors. This suggests that their work has had a significant impact on the field despite their lower publication count. Additionally, it is noteworthy that many of the prolific authors in this field come from Asian countries, particularly South Korea, which may indicate a strong emphasis on green hydrogen research in these regions.

In Figure 4, information regarding the top 10 journals is presented, along with figures representing the overall number of papers and citations in the field of producing green hydrogen. Research on this subject has been published in 133 journals in total.

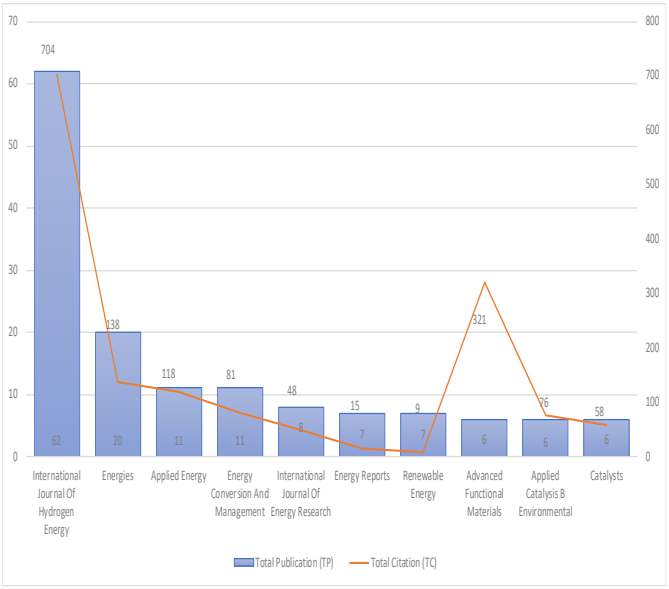


Fig. 4. Top 10 journals focused on the subject of green hydrogen production.

Within Figure 4, the list of the 10 most productive journals is displayed, ordered by the number of publications released. These top 10 journals collectively account for 40.45% of the total publications spanning from 2018 to 2022. Notably, the most widely read journal in this topic is the International Journal of Hydrogen Energy. Furthermore, using VOSviewer software and applying a minimum publication threshold of 4 articles, it was possible to identify 22 journals that met the criteria for clustering based on bibliographic coupling analysis. The results of this clustering analysis are depicted in Figure 5.

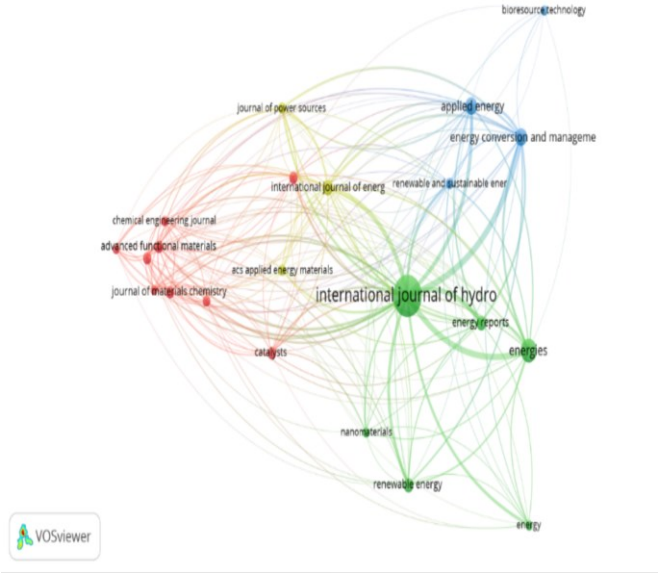


Fig. 5. Network visualization from journal sources.

The clustering results, as illustrated in Figure 5, provide a visual representation of the map structure generated by VOSviewer, utilizing parameters such as link value (L) and total link strength (TLS). The analysis identified a total of 4 clusters. The largest cluster, highlighted in red, encompasses 9 journals and falls under the category of materials chemistry. The member journals of this cluster include Advanced Functional Materials (L:18, TLS:216), Applied Catalysis B: Environmental (L:19, TLS:169), Catalysts (L:19, TLS:124), Chemical Engineering Journal (L:17, TLS:86), Electrochemical Acta (L:17, TLS:95), Green Chemistry (L:16, TLS:80), Journal of Colloid and Interface Science (L:14, TLS:75), Journal of Materials Chemistry A (L:17, TLS:122), and Sustainable Energy and Fuels (L:20, TLS:116).

The second cluster, represented in green, focuses on hydrogen energy and cleaner production and consists of 6 journals: Energies (L:21, TLS:501), Energy (L:12, TLS:129), Energy Reports (L:17, TLS: 420), International Journal of Hydrogen Energy (L:21, TLS:1733), Nanomaterials (L:15, TLS:85), and Renewable Energy (L:18, TLS:230). The third cluster, indicated in blue, belongs to the applied energy group and comprises 4 journals: Applied Energy (L:20, TLS:378), Bioresource Technology (L:7, TLS:13), Energy Conversion and Management (L:20, TLS :674), and Renewable and Sustainable Energy Reviews (L:19, TLS:167). Lastly, the fourth cluster, denoted in yellow, is centered around applied energy materials and includes 3 journals: ACS Applied Energy Materials (L:18, TLS:108), International Journal of Energy Research (L:21, TLS:481), and Journal of Power Sources (L :18, TLS:221). Table 4 presents data on the ten most cited articles in the field of green hydrogen production from 2018 to 2022.

Table 4. Most influential publications, according to citations

Title	TC	Year	TC/Y	Ref.
Bifunctional Heterostructured Transition Metal Phosphides for Efficient Electrochemical Water Splitting	242	2020	80.67	[50]
Water electrolysers with closed and open electrochemical systems	137	2020	45.67	[51]
Nanoporous Zn-doped Co_3O_4 sheets with single-unit-cell-wide lateral surfaces for efficient oxygen evolution and water splitting	116	2018	23.2	[52]
Principles of Water Electrolysis and Recent Progress in Cobalt-, Nickel-, and Iron-Based Oxides for the Oxygen Evolution Reaction	98	2022	98	[53]
Green hydrogen production potential for developing a hydrogen economy in Pakistan	92	2018	18.4	[54]
Potential and economic viability of green hydrogen production by water electrolysis using wind energy resources in South Africa	90	2019	22.5	[55]
Dynamic planning, conversion, and management strategy of different renewable energy sources: A Sustainable Solution for Severe Energy Crises in Emerging Economies	80	2021	40	[56]
Renewable hydrogen implementations for combined energy storage, transportation and stationary applications	79	2020	26.33	[57]
Techno-economic Analysis of Hydrogen Electrolysis from Off-Grid Stand-Alone Photovoltaics Incorporating Uncertainty Analysis	69	2020	23	[58]
Bimetallic catalysts for green methanol production via CO_2 and renewable hydrogen: A mini-review and prospects	68	2018	13.6	[59]

The most cited article is “Bifunctional Hetero-structured Transition Metal Phosphides for Efficient Electrochemical Water Splitting,” which has reached a total of 242 citations. This study investigates the use of transition metal phosphides (TMP) as durable bifunctional electrocatalysts for the water splitting process's hydrogen evolution reaction (HER) and oxygen evolution reaction (OER). The article with the second-highest TC value is titled “Water Electrolyzers with Closed and Open Electrochemical Systems.” It discusses the challenges associated with scaling up and utilizing water electrolyzers to produce green hydrogen with energy from renewable sources, low-temperature water electrolyzers. Taking the third spot in terms of TC value is “Nanoporous Zn-doped Co3O4 Sheets with Single-Unit-Cell-Wide Lateral Surfaces for Efficient Oxygen Evolution and Water

Splitting," which has garnered 116 citations. This article explores the progress in creating electrocatalysts, notably focusing on nanoporous Zn-doped Co_3O_4 sheets that have lateral surfaces only one unit cell wide, demonstrating their ultrahigh activity and durability for oxygen evolution and water splitting. This unique structure and composition make these sheets promising for practical and sustainable green hydrogen production.

The International Journal of Hydrogen Energy emerged as the top contributor, featuring 62 articles. The research topics in the articles with the highest citations in the journal International Journal of Hydrogen Energy focus on sustainable energy solutions, green hydrogen production, and the economic viability of green hydrogen through various renewable energy sources. These topics align with the growing interest in addressing energy challenges, particularly in emerging economies, and highlight the potential of green hydrogen as a sustainable energy carrier. Table 5 presents information about the top 10 institutions in terms of total publications, total citations, and authors involved in research on green hydrogen production.

Table 5. List of institutions on the green hydrogen production research topic

Institution	Country	TP	TC	TC/TP	Authors
UNSW Sydney	Australia	7	80	11.4	48
Nanyang Technological University	Singapore	5	57	11.4	39
Ministry of Education China	China	6	33	5.50	37
Technical University of Denmark	Denmark	6	26	4.33	35
Deutsches Zentrum für Luft- und Raumfahrt DLR	Germany	5	66	13.2	29
Aalborg University	Denmark	5	35	7	29
Jeonbuk National University	South Korea	7	22	3.14	25
Universidade do Porto	Portugal	5	56	11.2	23
Ontario Tech University	Canada	7	90	12.9	6
Yildiz Technical University	Turkey	6	55	9.17	4

The institutions with the highest total number of authors are UNSW Sydney, Nanyang Technological University, and the Ministry of Education China. Notably, 5 of the top 10 productive institutions are from European countries, while the remaining 3 are from Asian countries. In terms of sectors, 8 of these institutions are from the academic sector, while the remaining 2 are from the government sector. UNSW Sydney has the largest number of authors and total publications, the institution with the highest TC/TP (total citations per total publications) value is the Deutsches Zentrum für Luft- und Raumfahrt DLR. This indicates that TC/TP can be independent of the number of authors. Additionally, there appears to be no correlation between the TC value and the number of authors based on the data in Table 5. The data regarding the top 10 countries that have made noteworthy contributions to research on green hydrogen production is displayed in Figure 6.

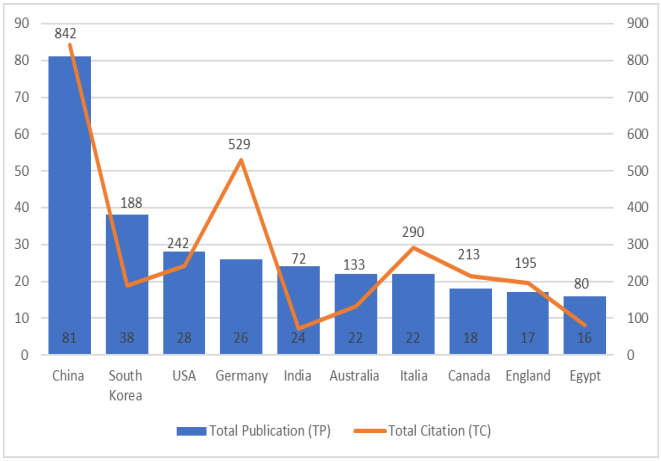


Fig. 6. List of countries with total publications and total citations.

China is the foremost country in terms of total publications, with a grand total of 81 articles. This is consistent with China's significant endeavors and investments in the manufacture of environmentally friendly hydrogen, which encompasses proposals for the establishment of extensive units for green hydrogen production.. Additionally, many of the top 10 countries in Figure 6 have already developed national green hydrogen roadmaps, aligning their research with strategic plans for green hydrogen production. Figure 7 presents data illustrating the visualization of a bibliographic network, specifically emphasizing the leading countries that contribute to the issue of green hydrogen.

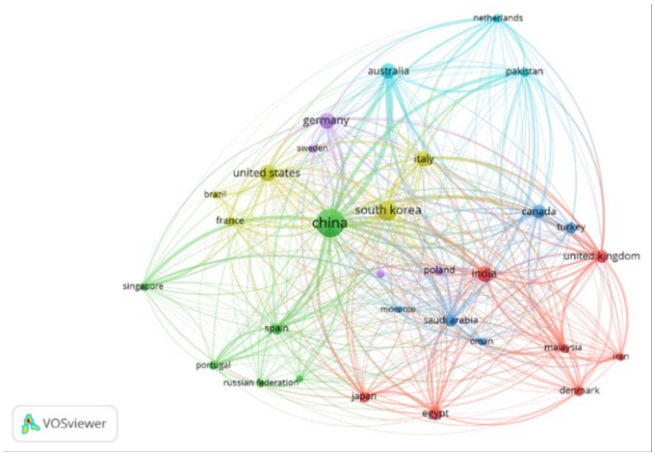


Fig. 7. Visualization of the bibliographic network showcasing the nations that make the highest contributions.

Figure 7 presents the results of cluster analysis for 30 countries, each of which has contributed at least 5 publications to the research topic "green hydrogen production" out of a total of 70 contributing countries. VOSviewer grouped these 30 countries into 6 clusters, manifesting the cooperative networks and shared research interests among these countries in the realm of green hydrogen generation.

- Cluster 1 (red): Denmark, Egypt, India, Iran, Japan, Malaysia, and the UK
- Cluster 2 (green): China, Portugal, Russia, Singapore, South Africa, and Spain
- Cluster 3 (blue): Canada, Morocco, Oman, Saudi Arabia, and Turkey
- Cluster 4 (yellow): Brazil, France, Italy, South Korea, and America
- Cluster 5 (purple): Germany, Poland, Sweden, and United Arab Emirates
- Cluster 6 (light blue): Australia, Netherlands, and Pakistan

The results of the cluster analysis, as shown in Figure 7, provide a visualization of the map structure created by VOSviewer. This visualization is generated using parameters such as L and TLS in the context of bibliographic coupling at the country level. The clustering likely reflects factors such as geographical proximity and collaborative networks among researchers or institutions from different countries in the realm of scientific articles pertaining to the creation of green hydrogen. Table 6. provides information on the top funders contributing to research on green hydrogen production, organized by to country and ordered based on the quantity of publications financed.

Table 6. Main funders with the highest contribution based on published works

Country	Funders Institution	TP	TC
China	National Natural Science Foundation of China	55	559
	China Scholarship Council	10	91
	Fundamental Research Funds for the Central Universities	8	21
	National Key Research and Development Program of China	8	39
South Korea	National Research Foundation of Korea	29	141
	Ministry of Science, ICT and Future Planning	21	98
Europe	Horizon 2020 Framework Programme	11	178
	European Regional Development Fund	8	69
Germany	Bundesministerium für Bildung und Forschung	9	314
Australia	Australian Research Council	8	77

Funding for research can originate from various government institutions within a country, and when multiple institutions within a country are involved in funding research regarding the generation of green hydrogen, it may indicate that green hydrogen is a national priority for that country. Table 3.5 highlights those Asian countries, particularly China and South Korea, have the highest number of institutions funding research in this field. China, with 81 publications funded, has a total of 750 citations, followed by South Korea with 50 publications and 239 citations. The data regarding the top 10 countries classified by regions that focused on green hydrogen research is displayed in Figure 8.

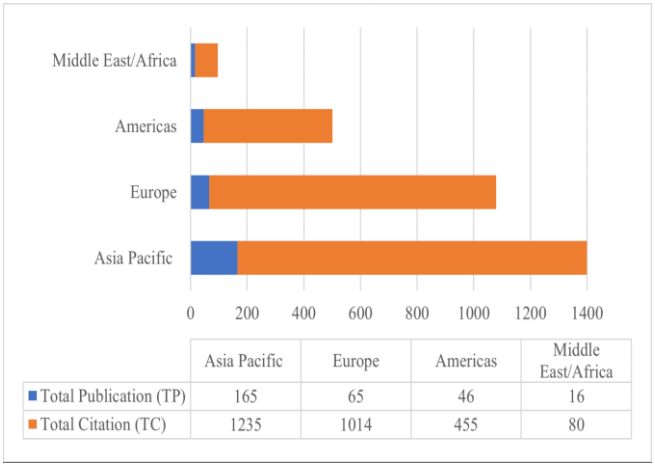


Fig. 8. List of regions with total publication and total citation.

Based on Figure 8, the Asia Pacific region has the highest research output and demonstrates the highest research impact, as reflected in the total citations. The result indicates that the research from this region is not only prolific but also influential. The top countries focused on green hydrogen research in the Asia-Pacific region include China, South Korea, India, and Australia. Germany, Italy, and England are the top European countries focused on green hydrogen research. The top countries focused on green hydrogen research in the Americas region consist of the USA and Canada. Egypt is the top country focused on green hydrogen research in the Middle East/Africa region.

The top five subject areas that are most closely related to green hydrogen production research are energy, chemistry, materials science, physics, and astronomy. Energy is the most influential scientific field, with the highest correlation percentage at 28.7%, followed by chemistry at 12%, and engineering at 11.3%. Table 7 offers details on the quantity of published works, citations, and authors in each scientific field that correlates with green hydrogen production research.

Table 7. TP, TC and authors from each scientific field

Sciencetific Field	TP	TC	Authors	TC/TP
Energy	229	1941	160	8.48
Chemistry	96	1121	160	11.68
Engineering	90	905	160	10.06
Physics and Astronomy	86	1328	160	15.44
Chemical Engineering	84	746	160	8.88
Materials Science	80	889	160	11.11
Environmental Science	65	442	160	6.80
Mathematics	24	204	92	8.50
Computer Science	10	94	36	9.40
Biochemistry	9	82	65	9.11

According to Table 7, energy, chemistry, engineering, physics and astronomy, chemical engineering, materials science, and environmental science are the scientific fields with the highest number of authors, each having 160 authors. On the other hand, the three scientific fields with the highest total citations are energy, physics and astronomy, and chemistry, with citation counts of 1941, 1328, and 1121, respectively. However, when considering TC/TP, physics and astronomy, chemistry, and materials science stand out. This demonstrates that the ranking can vary when using TC/TP as a parameter, compared to using individual parameters like TP, TC, and the number of authors.

3.2. Keywords Analysis

Co-occurrence analysis in VOSviewer is a valuable technique in bibliometric analysis as it helps identify relationships between words or phrases that frequently appear together in scientific publications [47]. This analysis enables researchers to gain insights into the primary topics within a research field and how these topics are interconnected. The output of co-occurrence analysis includes keyword network visualizations, overlay visualizations indicating the timing of keyword appearances in publications, and density visualizations depict the frequency of keyword occurrences. The results of co-occurrence analysis for the research topic "green hydrogen production" are presented in Figure 9.

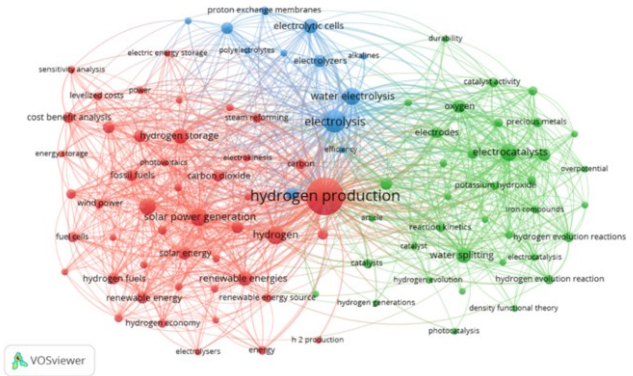


Fig. 9. Network visualization of analysis results with co-occurrence of keywords.

Using a minimum keyword occurrence criterion of 10, the analysis identified 96 keywords out of a total of 3.216 keywords related to green hydrogen production research. These 96 keywords are subsequently grouped into clusters, representing research sub-topics that can serve as references for defining research directions and specific areas of study. The depiction of term co-occurrence is shown using unique colors in a network analysis. The first cluster (red) contains a total of 47 keyword items, the second cluster (green) has 37, and the third cluster (blue) comprises 12.

Cluster I emphasize the broader context of green hydrogen as a future renewable energy source. Topics include various hydrogen production methods with various resources, like wind and solar power generation, storage, and the economic aspects of integrating green hydrogen into renewable energy systems. Cluster II is centered around the chemical processes involved in green hydrogen production. The emphasis is on developing efficient and cost-effective chemical methods for green hydrogen production. Cluster III focused on specific technologies and methods related to green hydrogen production. This cluster highlights the optimization and efficiency aspects of these production methods. Table 8 details the main keywords in each cluster and represents the research themes.

Table 8. Research themes and main keywords in green hydrogen production research

Cluster	Research Topic	Main Keywords
I (Red)	Green hydrogen as future renewable energy	Hydrogen production, hydrogen, solar power generation, green hydrogen, hydrogen storage, renewable energies, costs, solar energy, renewable energy, renewable energy resources, economic analysis, hydrogen fuels, etc.
II (Green)	Green hydrogen chemical process	Electrolcatalysts, water splitting, oxygen, oxygen evolution reaction, cost effectiveness, electrodes, hydrogen evolution reactions, catalyst activity, catalysts, electrolytes, hydrogen evolution reaction, precious metals, etc.
III (Blue)	Green hydrogen production	Alkaline water electrolysis, alkalines, efficiency, electrolysis, electrolytic cells, electrolyzers, green hydrogen production, optimization, polyelectrolytes, proton exchange membrane fuel cells (PEMFC), proton exchange membranes, water electrolysis.

However, the focus of this analysis is on the first and third cluster, as the second cluster is disregarded due to its limited relevance to "solar electrolysis". Table 9 presents information about the 47 keywords in the first cluster, which represents the research theme "Green hydrogen as future renewable energy." This cluster is expected to encompass keywords and themes that are strongly associated with the

wider study on green hydrogen production and its potential as a sustainable energy resource.

Table 9. Characteristics of cluster I keywords correlate with solar-electrolysis research topics

Keywords	Occurrence	Total Link Strength	Avg. Pub. Year	Avg. Norm. Citation
Hydrogen production	304	2059	2021.47	1.08
Solar power generation	63	491	2021.63	1.28
Solar energy	33	249	2021.7	1.28
Renewable energy	32	240	2021.53	2.01
Economic analysis	31	225	2021.35	1.6
Energy efficiency	23	186	2021.3	0.96
Hydrogen economy	19	138	2021.42	2.66
Levelized costs	15	132	2021.93	1.71
Photovoltaics	13	109	2021.69	1.02
Electrolysers	10	84	2021.9	1.67
Hydrogen production costs	10	85	2021	1.8

Table 10 presents information about the 12 characteristics of the third cluster keywords are presented with their respective occurrence, total link strength, average publication year, and average normalized citation.

Table 10. Characteristics of cluster III keywords correlate with solar-electrolysis research topics

Keywords	Occurrence	Total Link Strength	Avg. Pub. Year	Avg. Norm. Citation
Electrolysis	113	934	2021.61	1.13
Water electrolysis	66	569	2021.52	1.52
Electrolyzers	35	276	2021.71	0.92
Green hydrogen production	30	175	2021.40	0.99
Proton exchange membranes	15	123	2021.73	2.28
Alkalines	12	102	2021.92	0.73
Efficiency	12	64	2021.25	0.54
Alkaline water electrolysis	11	95	2021.64	1.05
Optimization	11	69	2021.55	0.72
Polyelectrolytes	11	94	2021.73	0.67

The focus of the analysis in the next section will be on the first cluster (red), which is associated with the research topic "Green hydrogen as future renewable energy," and the third cluster (blue), related to the research theme "Green hydrogen production." These clusters are closely aligned with the research topic to be discussed. In the first cluster, there are 11 keywords with relevance to the upcoming discussion, with 4 of them being the most frequently occurring. In the third cluster, there are 9 relevant keywords, with 4 of them having the highest occurrence values. This indicates a strong foundation for the research topic to be explored, which is firmly rooted in the main topic "green hydrogen production systems".

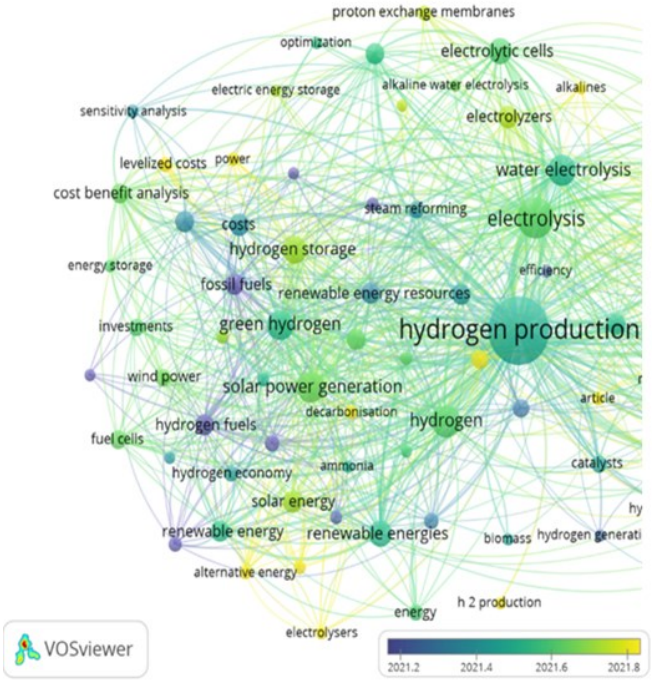


Fig. 10. Overlay visualization of average year of publication analysis results with co-occurrence of keywords for clusters I and III.

Figure 10 indicates that the average year of publication for keywords in clusters I and III, analyzed using co-occurrence of keywords analysis, tends to be in the range of 2021. This suggests that the keywords associated with these clusters are relatively new in the scientific literature, highlighting their current relevance. This novelty reflects the ongoing development of knowledge in these areas, underscoring their importance in the current research landscape. Figure 11 presents the visualization of the average normalized citation values obtained from the co-occurrence of keywords analysis. This visualization allows us to identify keywords with varying levels of impact and influence within the field of research on green hydrogen [60].

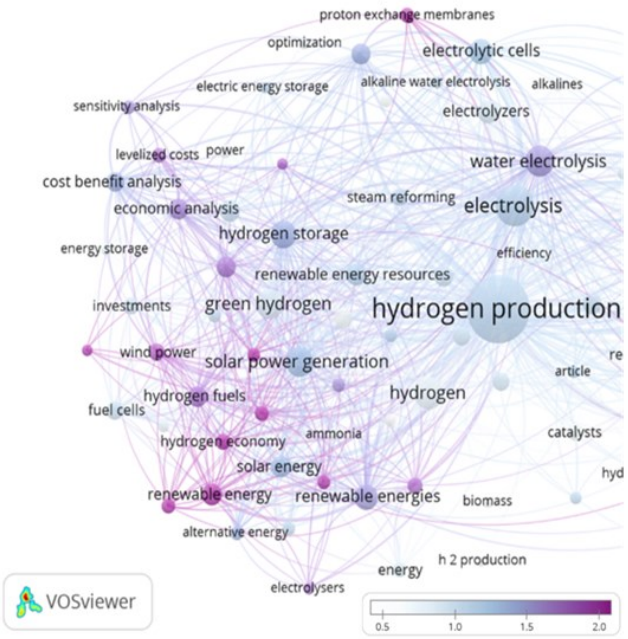


Fig. 11. Overlay visualization of average normalized citation analysis results with co-occurrence of keywords for clusters I and III.

Based on Figure 11, it is evident that the average normalized citation values for keywords in clusters I and III show considerable variability. Some keywords, such as "energy utilization" (0.35), "efficiency" (0.54), and "H_2 production" (0.56), have relatively low normalized citation values. This suggests that certain concepts or topics related to these keywords may not receive a large number of citations or significant attention in the scientific literatures. The diversity in normalized citation values provides valuable insights into the level of influence and popularity of different subtopics within the broader field of green hydrogen research. Researchers can use this information to gauge the research areas that are currently receiving greater attention and recognition in the academic community.

Using data from Tables 9 and 10, along with overlay visualizations from the co-occurrence of keywords analysis found in Figure 10 and 11, the trending status of the solar-electrolysis research topic can be ascertained. Formulas, considering both the average year of publication and the average normalized citation, are employed for this purpose. When the average publications year (avg. pub. year) and average normalized citations (avg. norm. citations) exceed their respective median values, the research area is classified as trending; otherwise, it is categorized as "old." These evaluation thresholds are derived from the statistical data presented in Figure 10 and 11. The median value for avg. pub. year is 2021,5, denoting topics above this threshold as "novel" and those below as "old." In the context of avg. norms. citations, the median citation value is 1.25, segregating topics above this median as "High Impact" and those below as "Low Impact." The outcomes of this classification are presented in Table 11.

Table 11. Remark formula from combination results of average year of publication and average normalized citation category values

		Average year of publication category	
		Novel (Value ≥ 2021.5)	Old (Value < 2021.5)
Average normalized citation Category	High Impact (Value ≥ 1.25)	Novel + High Impact (Trending)	Old + High Impact (Middle Trending)
	Low Impact (Value < 1.25)	Novel + Low Impact (Middle Trending)	Old + Low Impact (Not Trending)

Table 11 are presented the results of the evaluation of value scores and categories regarding research positions based on the parameters average publication year and average normalized citation.

Table 12. Categorization of research topics (keywords) using average publication year and average normalized citation parameters

Cluster	Avg. Pub. Year		Avg. Norm. Citation		Result
	Value	Category	Value	Category	
I	2021.51	Novel	1.30	High	Trending
III	2021.61	Novel	1.09	Low	Middle-Trending
"Solar electro lysis "	2021.57	Novel	1.32	High	Trending

The analysis presented in Table 12 reveals that research in cluster 1 is currently a trending topic, while cluster 3 falls into the middle-trending category. This is primarily due to the low average normalized citation value of 1.09 (Low) in cluster 3. Nevertheless, it is important to acknowledge that this could be ascribed to a restricted researchers focusing on topics within this field, resulting in fewer keywords being used and cited. When considering the average publication year value, cluster III is classified as "novel" with an average year of publication of 2021.61, indicating that research in this area is relatively new and has yet to gain significant impact or influence. Additionally, in the analysis of the research subtopic "solar-electrolysis," the results indicate that this topic is indeed a trending area of study. Therefore, based on the outcomes of the bibliometric analysis, it can be concluded that the subtopic "solar-electrolysis" represents a research theme that is both worthwhile and exhibits a positive research trend. It is based on the latest advancements in this sector.

The identified trends in green hydrogen production research have practical implications for policymakers, researchers, and industry professionals. Policymakers can leverage insights to formulate supportive policies for renewable energy integration and green hydrogen development. Researchers should focus on interdisciplinary collaborations, exploring areas like advanced materials and catalysis for improved efficiency. Industry professionals can strategically invest in technologies related to electrolysis and storage. Specific areas warranting further investigation include the socio-economic impacts of green hydrogen production, advanced materials for electrolysis efficiency, and the integration of solar energy. Overall, aligning research efforts, policies, and investments with these trends can accelerate the transition toward sustainable and efficient green hydrogen production.

The study's scope is constrained by the data available up to 2022 and may not capture recent developments. Additionally, the reliance on bibliometric analysis poses challenges, such as potential biases in keyword selection. Future research should explore real-time data integration, consider a broader range of databases, and delve into specific regional dynamics. Promising avenues include in-depth life cycle assessments, techno-economic analyses, and interdisciplinary investigations to enhance the sustainability and economic viability of green hydrogen production methods.

3.3. Regulation current status and reccomendation for development green hydrogen as clean energy

Table 13 present information about simplified outlining general regulatory considerations for hydrogen in ten countries that have the highest level of research contribution in the Scopus database.

Table 13. Regulatory considerations for green hydrogen in ten countries

Country	Regulatory Considerations	Ref.
China	Developing safety standards for hydrogen production and use	[61]
South Korea	Emphasizing safety guidelines for hydrogen handling	[62]
India	Early stages of formulating comprehensive hydrogen regulations	[63]
Australia	Developing safety regulations and standards for hydrogen	[64]
Germany	Established safety standards and regulations for hydrogen	[65]
Italy	Developing regulatory frameworks, including safety standards.	[66]
England	Comprehensive safety regulations aligning with the Hydrogen Strategy	[67]
USA	Federal and state-level safety regulations for hydrogen.	[68]
Canada	Developing safety regulations and guidelines for hydrogen use	[69]
Egypt	Early stages of developing regulatory frameworks for hydrogen	[70]

The global regulatory approach to hydrogen development demonstrates a unified commitment to safety and sustainability. Prioritizing safety standards, countries like China, South Korea, Germany, Italy, England, USA, and Canada are actively shaping guidelines for hydrogen across production, storage, and utilization. Notably, aligning with national hydrogen strategies, these regulations emphasize the seamless integration of green hydrogen into diverse energy landscapes. This versatile and comprehensive regulatory stance, covering applications from industry to transportation, underscores a collective dedication to addressing the multifaceted aspects of hydrogen utilization. As hydrogen gains prominence in global energy transitions, these regulations signify a shared commitment to harmonizing best practices and ensuring the secure deployment of hydrogen technologies on a worldwide scale.

Global policies toward green hydrogen underscore a collective commitment to a sustainable, low-carbon energy future. Leading by established nations have enacted comprehensive strategies, integrating green hydrogen into broader energy transitions for carbon neutrality. These initiatives emphasize economic and environmental benefits, driving the growth of green hydrogen industries. In contrast, India and Egypt are at early policy stages, recognizing the crucial role of green hydrogen in their energy futures. Overall, the global focus on green hydrogen policies reflects a united effort to leverage its potential for decarbonization, economic advancement, and international cooperation. Recommendations for future research are crucial to guide governments and stakeholders in navigating the energy transition toward renewable sources, particularly green hydrogen. Here are some potential recommendations:

- Techno-Economic Analyses: Conduct in-depth techno-economic assessments to evaluate the cost-effectiveness and feasibility of large-scale green hydrogen production. Identify key factors influencing the economic viability, such as advancements in electrolysis technologies, renewable energy integration, and potential scale economies.
- Life Cycle Assessments (LCA): Perform comprehensive life cycle assessments of green hydrogen production methods to understand the environmental impact throughout the entire value chain. This includes assessing emissions, resource use, and energy efficiency and providing insights into the overall sustainability of green hydrogen.
- Integration with Existing Infrastructure: Investigate strategies for the seamless integration of green hydrogen into existing energy infrastructure. This includes exploring opportunities for repurposing existing facilities, adapting natural gas infrastructure, and optimizing hydrogen transportation and storage systems.
- Policy Frameworks and Incentives: Analyze the effectiveness of existing policy frameworks and incentives supporting green hydrogen adoption. Propose innovative policy measures that could further incentivize investment, research, and development in the sector, ensuring a conducive regulatory environment.

- Cross-Sectoral Applications: Explore diverse applications of green hydrogen across sectors, including industrial processes, transportation, and energy storage. Identify specific use cases where green hydrogen can provide optimal benefits and contribute to sectoral decarbonization.
- International Collaboration: Emphasize the importance of international collaboration to share best practices, research findings, and technological advancements in green hydrogen. Encourage joint research projects, knowledge exchange, and the establishment of global standards to accelerate the development of a cohesive green hydrogen market.
- Hydrogen Storage and Distribution: Investigate innovative storage solutions for green hydrogen, considering various methods such as underground storage, chemical carriers, and advanced materials. Explore efficient distribution networks that can support the widespread adoption of green hydrogen as an energy carrier.
- Community Engagement and Education: Highlight the significance of community engagement and education programs to raise awareness about the benefits of green hydrogen. Develop strategies to address public concerns, promote acceptance, and build a positive perception of hydrogen technologies.
- Cross-Border Energy Trading: Explore opportunities for cross-border energy trading using green hydrogen. Investigate the development of international hydrogen pipelines or shipping routes, facilitating the global exchange of renewable energy resources.
- Emerging Technologies: Invest in research on emerging technologies, such as advanced catalysts, materials, and innovative electrolysis methods, to enhance the efficiency and scalability of green hydrogen production.

These recommendations aim to guide researchers, governments, and stakeholders in focusing their efforts on critical areas that can accelerate the transition from traditional fuels to renewable energy, with a specific emphasis on the pivotal role of green hydrogen.

4. Conclusion

This paper addresses the advancements in research on "green hydrogen production," a process that utilize renewable energy sources. Green hydrogen plays a significant role in transitioning from environmentally detrimental fossil fuels to cleaner, sustainable energy sources. Green hydrogen serves as a versatile alternative fuel, finding applications in fuel cell-powered vehicles, heavy industries, and as energy storage in renewable energy-based power plants. Consequently, investigating green hydrogen production is essential for harnessing its capacity to reduce greenhouse gas emissions and promote energy sustainability.

Through an analysis of 356 scientific journal articles sourced from the Scopus database spanning 2018-2022, it is evident that approximately 70 countries have actively engaged in green hydrogen production research, with around 30 countries contributing a minimum of 5 publications. This underscores the global research interest in green hydrogen, and this interest continues to rise, as evidenced by the growing trend in publications and citations. Notably, there is a substantial presence of open-access scientific articles, with a trajectory that points to 62.5% by 2022. China stands out as the leading contributor to green hydrogen production research, boasting 81 articles, funded by four key institutions. In terms of journals, there are 133 that have published research on this topic, with the International Journal of Hydrogen Energy emerging as the top contributor, featuring 62 articles. Within the realm of scientific fields, energy science exerts the most significant influence, constituting 28.7% of the overall composition and being closely intertwined with the research domain of green hydrogen production.

Co-occurrence analysis conducted in VOSviewer, with a minimum keyword occurrence threshold of 10, identified 96 keywords among the 3.216 keywords associated with research on green hydrogen production. These keywords were organized into three clusters: Cluster I centering on "Green hydrogen as future renewable energy," emphasizing the application of green hydrogen as a prospective sustainable energy resource, Cluster II pertaining to "Green hydrogen chemical process," encompassing the chemical processes involved in green hydrogen production, including material research and chemical reactions, and Cluster III revolving around "Green hydrogen production," concentrating on electrolyzer efficiency and application in green hydrogen production.

Moreover, the evaluation results, derived from a formula combining average publication year and average normalized citation values, revealed that Cluster I fall into the "trending" category, Cluster III is categorized as "middle trending," while the subtopic "Solar-Electrolysis" emerges as "trending." These findings underscore the significance of "Solar-Electrolysis" and "Green hydrogen as future renewable energy" as research themes worthy of exploration, highlighting their positive research trajectories and their robust affiliations with the latest advancements in green hydrogen production. The identified trends in green hydrogen production underscore the need for collaborative efforts among policymakers, researchers, and industry professionals. Policymakers can shape supportive regulations, researchers should focus on interdisciplinary studies, and industry professionals can strategically invest in key technologies. Areas requiring further attention include the socio-economic impacts of green hydrogen, advancements in electrolysis efficiency, and the integration of solar energy. Addressing these trends collectively will drive the transition towards sustainable green hydrogen production.

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