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Review article

Green-hydrogen research: What have we achieved, and where are we going? Bibliometrics analysis

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A B S T R A C T

In response to the global challenge of climate change, 136 countries accounting for 90% of global GDP and 85% of the population have now set net-zero targets. A transition to net-zero will require the decarbonization of all sectors of the economy. Green-hydrogen produced from renewable energy sources poses little to no threat to the environment and increasing its production will support net-zero targets Our study examined the evolution of green-hydrogen research themes since the UN Sustainable Development Goals were adopted in 2015 by utilizing bibliographic couplings, keyword co-occurrence, and keyphrase analysis of 642 articles from 2016 to 2021 in the Scopus database. We studied bibliometrics indicators and temporal evolution of publications and citations, patterns of open access, the effect of author collaboration, influential publications, and top contributing countries. We also consider new indicators like publication views, keyphrases, topics with prominence and field weighted citation impact, and Altmetrics to understand the research direction further. We find four major thematic distributions of green-hydrogen research based on keyword co-occurrence networks: hydrogen storage, hydrogen production, electrolysis, and the hydrogen economy. We also find networks of four research clusters that provide new information on the journal's contributions to green-hydrogen research. These are materials chemistry, hydrogen energy and cleaner production, applied energy, and fuel cells. Most green-hydrogen research aligns with Affordable and Clean Energy (SDG 7) and Climate Action (SDG 13). The outcomes of policy decisions in the United States, Europe, India, and China will profoundly impact green-hydrogen production and storage over the next five years. If these policies are implemented, these countries will account for two-thirds of this growth. Asia will account for the most significant part and become the second-largest producer globally.

Contents

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1. Introduction

The critical role greenhouse gas emissions play in the unprecedented climate crisis has led nations worldwide to agree that urgent attention and immediate solutions are required. The 2015 Paris Climate Accord was the first step in this direction. The unprecedented climate change resulting from the emissions of greenhouse gases is a problem that all nations of the world unanimously agree needs urgent attention and immediate solutions, as is manifest in the 2015 Paris Climate Accord. The Paris Agreement strengthens the United Nations Sustainable Development Goals to create a better and more equitable world. To achieve this goal, it is essential to know how to harness natural resources without presenting the danger of further depletion or endangering the survival of future generations (Ueckerdt et al., 2021). Sustainable and scalable energy sources that provide high energy density are urgently needed as alternatives to secure the energy supply and lessen the environmental impact of the current state-of-the-art non-renewable energy sources (Li et al., 2017).

Fossil fuels remain the primary source of greenhouse gas emissions across different sectors of the economy, from electricity production to transportation. In 1950 the world emitted 6 billion tonnes of CO2 from fossil fuels. By 1990 this had almost quadrupled, reaching more than 22 billion tonnes. It is important to note that industrialization in the 19th and 20th centuries was responsible for unprecedented economic and political growth and increased civilization and technological advancements. However, it was also responsible for significant levels of environmental degradation and mass interference with nature and natural resources (Martinez-Burgos et al., 2019). Emissions have continued to grow rapidly, and we now emit over 34 billion tonnes each year (Ritchie et al., 2020). Today, the world is entirely reliant on energy and electricity. The means of generating it quite often threaten the planet's sustainability.

Reducing and eventually eliminating anthropogenic emissions of greenhouse gases will require a shift to alternative forms of energy production and new energy carriers, replacing petroleum-based energy systems (Armaroli and Barbieri, 2021). With that in mind, the United Nations created the UN Sustainable Development Goals (SDG) 2030, a set of goals that would guide the world to increased sustainable existence while continuing to drive technological and engineering innovations that have made life and work easier for humanity (Falcone et al., 2021). In addition to hydroelectric power, solar photovoltaics, nuclear fission, and wind energy, contemporary scientists are leading calls for research on hydrogen energy as the next step toward eliminating petroleum-based energy sources such as oil. Political leaders are increasingly supportive of such ideas, as COP26 held in November 2021 proves. The increasing ambition of climate targets creates a significant role for hydrogen, especially in achieving carbon-neutrality in sectors presently difficult to decarbonize (Ayodele and Munda, 2019). Hydrogen as an energy vector is likely to replace fossils due to the political, financial, and environmental factors associated with the latter. (Gondal et al., 2018). The available technical potential for producing green electricity from wind, solar and hydro is easily sufficient to cover all current electricity consumption as well as this additional demand for green hydrogen (Kakoulaki et al., 2021)

While the transition to a low carbon economy is urgently needed for environmental sustainability, the UN SDGs are framed broadly to include equity, well-being, and justice considerations. Consequently, issues such as affordability and access are essential for achieving a "just" transition. Green-hydrogen is a potential path to the achievement of such goals. The first reference to the term green or renewable hydrogen was mentioned by (NREL, 1995). They used the term renewable hydrogen (hydrogen produced from renewables) as a synonym for green. Renewable hydrogen (or green hydrogen) is produced through electrolysis using renewable energy sources (RES), and it is a near-zero carbon production route (IRENA, 2019). Realizing green-hydrogen satisfies SDG 7 (Affordable and Clean Energy), advocating for responsible production and consumption. Its implementation allows humanity to enjoy the benefits of energy and electricity without posing a threat to the environment, which is the definition of responsible consumption (Armaroli and Barbieri, 2021). The abundance of natural Hydrogen in the world's atmosphere makes the realization of green-hydrogen a viable solution to the energy crisis. Furthermore, it satisfies SDG 13 (Climate Action), which advocates for climate action by regulating carbon energy emissions and implementing renewable energy forms.

In the future, hydrogen will not be the most significant player in the global energy infrastructure instead green-hydrogen economy is foreseen in which hydrogen will fill a secondary role as the keystone that is necessary to enable a 100% renewable energy society (de Oliveira et al., 2022). Green hydrogen energy is a natural substitute for fuel-based energy, and it increases a country's long-term energy safety (Chien et al., 2021). The international nature of global warming concerns has led to multiple countries interested in investing in research on alternative means of green energy generation, including Hydrogen, addressing the need for climate action. Consequently, funding has intensified over the last six years, with founder parties to the Paris Climate Agreement committing to a $ 100 billion funding for climate action. However, as per COP26, there were inadequacies in the total amount, and most countries were yet to fulfill their commitment Consequently, through its president, the USA committed to providing $ 24 billion in funds by 2024 (PricewaterhouseCoopers, 2019). Other countries that have followed suit in making funding commitments include the United Kingdom and Australia. The COP26 summit showed that the last two years had contributed tremendously to research on green-hydrogen with viable breakthroughs in storing hydrogen fuels effectively and affordably to reduce the cost of hydrogen energy (Ogden et al., 2018).

The other significance of investigating green-hydrogen lies in its potential role in achieving Net-zero by 2050. Net-zero is defined as 'reducing net CO2 emissions from energy and industrial processes to zero, after accounting for carbon capture and sequestration (Rogelj et al., 2015). It is a term that defines the achievement of balance between the number of greenhouses added into the atmosphere and the ones removed from the same (Sridhar et al., 2021). Net-zero manifests when the amount of greenhouse gases added into the atmosphere is not more than the amount removed (PricewaterhouseCoopers, 2019). According to climate experts and authorities concerned, the world must reach net-zero by 2050 to realize the UN SDG goal of increasing temperatures below 2 °C by 2100. Global CO2 emissions must be cut by 45% in 2030 to reach the net-zero emission by 2050 globally to avoid catastrophic climate impacts (Bhagwat and Olczak, 2020). Research estimates show that failure to reach the present figure could see the earth experience adverse and extreme effects of global warming and reach unsustainable or even unhabitable climate levels. The recent success of electric cars and hydropower are more significant reasons for increased interest in green-hydrogen. Success in both cases is proof that with added research, there is hope that cheaper and more affordable means of energy production that are friendly to the earth and safer for consumption could be realized. With that hope comes the motivation to intensify research on the production and use of green-hydrogen.

Even without the threat of global warming and increased attention on sustainability, interest in alternative methods of generating energy has always been of interest in energy production (Chanchetti et al., 2020). Hydroelectric power and wind energy, for instance, have always been available as an alternative means of generating energy and electricity. To some extent, even nuclear energy has been an alternative energy source. Nuclear energy has recorded multiple disaster incidents, making it an unsafe alternative for electricity generation. Wind and hydropower have become unreliable and unable to adequately produce sufficient power to drive the modern world without the support of petroleum-based energy sources. Recent developments on existing alternatives for energy generation have provoked the scientific community into additional research on the potential of green-hydrogen (Nikolaidis and Poullikkas, 2017).

Currently, green-hydrogen accounts for just 0.1% of the total energy production in the world (IEA, 2019), which is an underutilization of one of the best technological innovations to tackle climate change for which petroleum energy, to a large extent, is responsible. Specialized tools accountable for enhancing the production of green-hydrogen include electrolysis which also allows for industrial application of Hydrogen. A recent PwC report on the corporate demand and opportunities for hydrogen energy maintains that pre-2030, the market will keep a steady pace (PricewaterhouseCoopers, 2019). After 2035 however, the world will see an increased demand for green-hydrogen. Post-2050, however, there could be a demand for between 150-500 million tonnes per year for the same period.

The reasons for hydrogen-energy production are numerous, and current world trends show that stakeholders are more than eager to increase production. There are different methods for producing hydrogen-based fuels, i.e., electrical, thermal, biochemical, photonic, electro-thermal, photo-thermal, photo-electric, photo-biochemical, and thermal-biochemical (Dincer, 2012). Green-hydrogen production using renewables-powered, low-temperature water electrolysers is crucial for rapidly decarbonizing the industrial sector and many chemical transformation processes (Lagadec and Grimaud, 2020). However, there are concerns about its implementation.

It must be noted that bibliometrics is a vital indicator to contextualize the increasing relevance, importance, and scholarship in clean and renewable energy. The pioneering work of Garfield (1955), in the 1950s, on citation index introduced the research on published works in this field of bibliometrics (Hood and Wilson, 2001). Analysis of bibliographic data using quantitative tools is called Bibliometrics (Broadus, 1987). It is used to investigate the performance of various research themes (Ramos-Rodríguez and Ruíz-Navarro, 2004), to map the interrelation among research themes (Cobo et al., 2011), and to study the development and thematic structure of a research field through various citation statistics and bibliometric indicators (Valtakoski, 2020). Bibliometrics can be divided into two categories, i.e., performance analysis and science mapping analysis (Noyons et al., 1999). The use of publications and citation data to evaluate various scientific factors such as countries, and institutions form performance analysis (Narin and Hamilton, 1996) and assess the cognitive and social structure of the research field constitutes science mapping analysis (Small, 1999).

The US, Japan, and China are some of the leading countries in terms of research on the production, storage, and use of Hydrogen as a fuel, with a particular focus on hydrogen fuel storage (He et al., 2019). The volatility of hydrogen fuel and its high reactivity with other compounds makes it complicated to store. For that reason, various research attempts as documented by the bibliometric analysis of hydrogen storage (He et al., 2019). According to the publication's contents, the systematic review of storage methods and levels for existing systems defines future trends based on predictive analysis. In addition, the article contends that research on hydrogen storage though existing since the 90 s, was limited to about 300 publications a year. With time, however, interest in this topic exponentially increased, and by 2018, the number of publications on the topic per year averaged 1500 (Liu et al., 2020). According to Tan et al. (2021), research on hydrogen energy is most prevalent in the United States, Japan, China, Germany, and South Korea. In addition to the research on the topic, these countries contribute to literary works on the topic, and other 15 countries have contributed a total of 14,000 plus publications since 2005. Since 2004 however, attributes such as CO2 emissions, green energy, and greenhouse associations have improved clarity on green-hydrogen implementation (Tsay, 2008).

The literature review revealed that previous authors had conducted bibliometric studies in the related areas like Hydrogen Energy (Tsay, 2008), Green Economy (D'Amato et al., 2017; Loiseau et al., 2016), Blockchain, and Energy (Ante et al., 2021), Hydrogen Production and Storage, etc. (Liu et al., 2020), Emergy (Xu and Feng, 2021) and sustainable development (Raman et al., 2022a,b). However, no studies have been found which discusses and analyzes the research trends and potential of green-hydrogen by bringing in a new perspective and analysis based on keyphrases, the contribution of open access, prominence percentile, altmetrics, and alignment to UN SDG, which our study addresses.

2. Study methodology

The study methodology is discussed in the following sections.

2.1. Bibliometrics analysis

The Scopus database was used for retrieving the bibliographic data for this study as it not only meets the stringent quality criteria for indexation (Donthu et al., 2021; Paul et al., 2021) but also because the journals indexed in the Scopus database are more inclusive. Scopus data covers a wide range of subjects, and it is the most significant citation and abstract database and it is the most commonly used search database (Amrutha and Geetha, 2020). VOSviewer, Scival, and Altmetrics were used for bibliometric analysis and the network visualizations (Butt et al., 2021; Farooq et al., 2021; Raman et al., 2022a,b). VOSviewer (Van Eck and Waltman, 2010) is software designed to construct and visualize bibliometric maps. Such maps illustrate scientific research's structural and dynamic aspects (Cobo et al., 2011). Scival's Field-Weighted Citation Impact (FWCI) is used in this study which is an article-level metric that considers the differences in research behavior across disciplines (Colledge and Verlinde, 2014; Raman et al., 2022a,b). FWCI takes the form of a simple ratio: actual citations to a given publication divided by the expected rate for publications of similar age, subject, and type. The study uses bibliographic couplings to examine the temporal evolution of themes published in green-hydrogen. VOSviewer has been used for Keyword co-occurrence analyses. Bibliographic coupling (Kessler, 1963; Small, 1973) occurs when two documents cite the same third document, and this technique is used to understand patterns of intellectual content shared between the documents. Author co-citation analysis (ACA) provides insight into how authors connect ideas between published works (Chen, 2017). To determine the central theme of each cluster, we separate the publications into several clusters and analyze the publications within each cluster. Each article is a node in the cluster, and the links connecting the nodes represent the strength of links between the nodes.

The thematic development of the research topic co-occurrence of keywords analysis is used for science mapping. (Strozzi et al., 2017). Both author and index keywords are extracted in this paper and clustered based on their thematic similarities (Cancino et al., 2017; Martínez-López et al., 2018) to investigate the evolution of topics published about green-hydrogen between 2016 and 2021. This article studied the most productive authors, institutions, and countries of journal publications. Co-authorship analysis has been used to map the authors, their institutions, and countries visually and to explore the collaborative structure of article authors. For analyzing the recognition and the influence of green-hydrogen publications, we identified the top-cited green-hydrogen publications and the journals that most frequently cite those publications. Keyphrase-based analysis (Rehn and Kronman, 2014) using SciVal has been performed to study the focus of a particular research domain. Top keyphrases are extracted through text mining in publications by SciVal.

We investigated a new indicator called topic prominence, which is very useful in identifying emerging research topics with the potential to attract research funding (Klavans and Boyack, 2017; Muñoz-Écija et al., 2019). Given the low count of research publications about green-hydrogen, we used Altmetrics, an alternative and extension of traditional bibliometric indicators such as Journal Impact Factor or h-index. Altmetrics, articulated by Priem et al. (2010) and a group of scientists, uses data from the social web to track and quantify interactions and is proposed as complementary to citation-based metrics. Studies in the past have investigated the use of Altmetrics, and it is noted to be a very useful tool for informing scholarship (Bornmann, 2014, 2015). Altmetrics Attention Score (AAS) used in the study is defined as the weighted count of all the online attention found for individual research output.

Finally, a unique contribution from our study is about how green-hydrogen research is aligned with UN SDG with a specific focus on Affordable and Clean Energy (SDG 7) and Climate Action (SDG 13). Here we explore the relationships between the SDG index of a country and its share of renewable energy in the total primary energy supply (Sachs et al., 2021) and the country's research output regarding green-hydrogen. We do not have reliable data on R&D spending on green-hydrogen, so looking at research output as a proxy is an exciting alternative.

We have organized our study, starting with describing the protocol used for the systematic literature review. This is followed by the results section, which discusses the overall research performance and temporal evolution of publications and citations, patterns of open access, the effect of collaboration, prolific authors, top journal sources, influential publications, top contributing countries, top subject areas, major funders, and their country affiliations. Then we describe the knowledge structure of green-hydrogen research based on keywords, research topics with prominence, related research topics, and keyphrase analysis. In the following section, we study the alignment of green-hydrogen research with UN SDG, and the last section discusses the study's conclusions, highlighting the limitations.

2.2. SPAR-4-SLR protocol

Scientific Procedures and Rationales for Systematic Literature Reviews (SPAR-4-SLR) protocol developed by Paul et al. (2021) is adopted in this bibliometric study on green-hydrogen. The approach in each stage of the protocol which guides the assembling, arranging, and assessing tasks is highlighted in Fig. 1:

Assembling

Assembling is the first stage that involves identifying and acquiring publications for review. For this study, the Scopus database was used. The search was conducted in the week of January 15, 2022, using the search phrase green-hydrogen in abstracts, titles, and keywords. A total of 642 publications were returned for the period 2016 to 2021.

Arranging

The next stage of arranging involves the organization and purification of the publications through inclusion and exclusions. The search data of publications were coded using the journal title, publication title, author name, keywords, country of affiliation, funding organizations, total citations (TC), total publications (TP), FWCI, and altmetrics attention score for arranging the data. No publications were excluded as part of purification.

Assessing

The final stage is assessing, which involves evaluation and reporting. The evaluation part of the article discusses the analysis method and limitations used in the study. VOSviewer and MS Excel are the primary tools used for evaluation and trend analysis.

Since the review is based on secondary data that can be accessed by anyone who has access to Scopus, ethics clearance was not required.

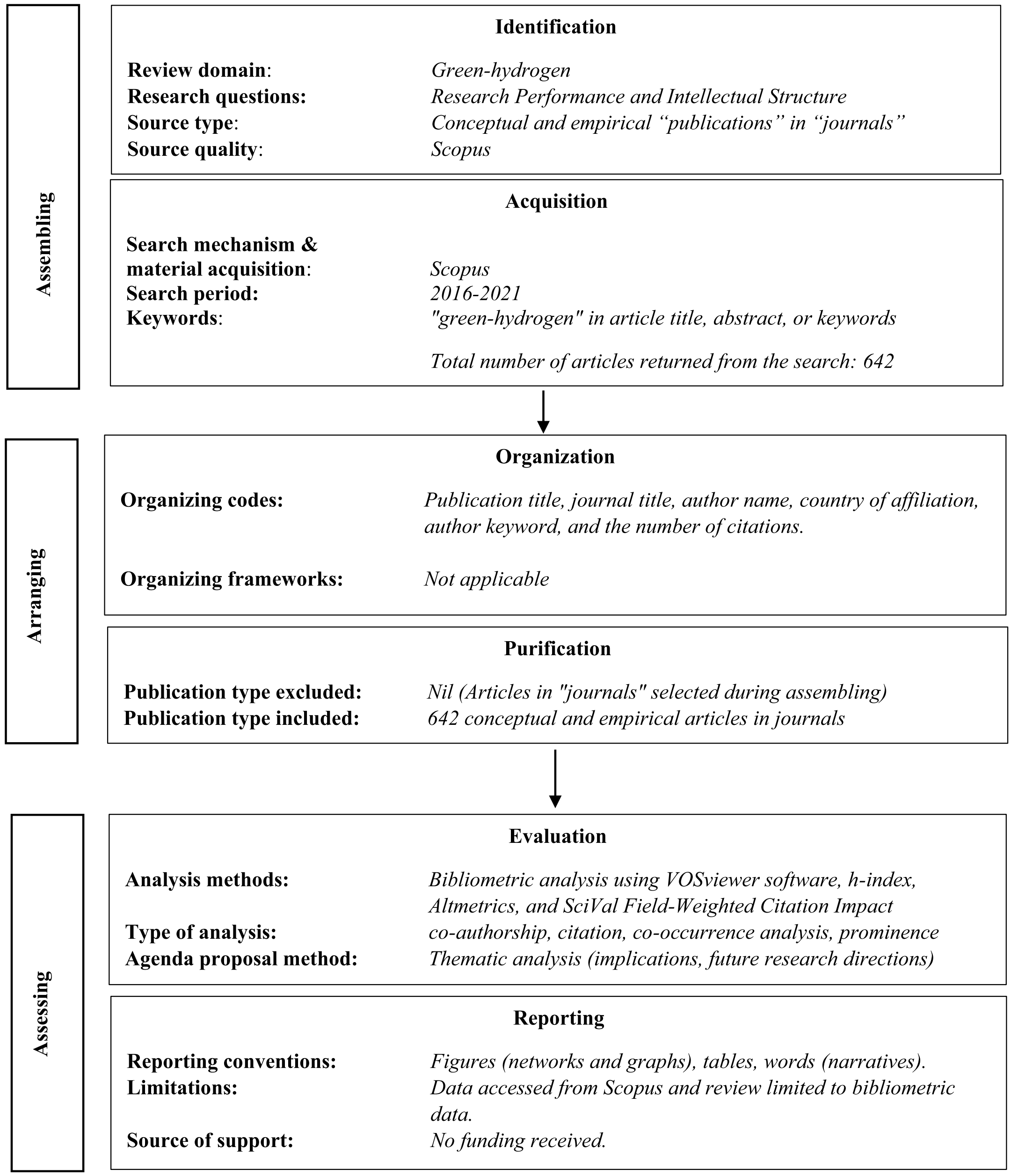

Fig. 1. Research design follows the SPAR-4-SLR protocol.

3. Results and discussion

3.1. Bibliometrics performance

3.1.1. Research performance and temporal evolution

For this study, 642 publications published between 2016 and 2021 were analyzed. Though the first publication indexed in Scopus can be seen as early in 1997, publications in this area were in the single digits for the next twenty years. From 2010 we observed yearly publications were in double digits. But following UN SDG adoption in 2015, annual publications increased to over 50 but are still low, possibly due to less research investment in this topic.

Table 1 shows the growing trend of green-hydrogen publications and citations, especially in the two most recent years where the publication growth has been multifold. This increase in publications and the number of authors', from 92 in 2016 to 1,686 in 2021, reflects increased research infield. More remarkably, publications in the Top 10% journal percentiles, based on the CiteScore percentile, show a healthy average of 50% per year. An average of 29.9% of publications per year have international co-authors. Noteworthily are the outputs in the top 10% citation percentiles in a short time reflecting the research influence of green-hydrogen research. Research studies also show that literature on the hydrogen economy has been recently increasing, particularly from 2016 to 2020 (Kar et al., 2022), highlighting the interest in one of the most promising possibilities for meeting future energy demands (Hosseini et al., 2015).

3.1.2. Open access and its temporal evolution

The growth of the Open Access (OA) publishing model has been the subject of bibliometric research over the years (Archambault et al., 2014; Laakso and Björk, 2012; Piwowar et al., 2018). Consistent with these studies, the trend for green-hydrogen research under OA shows a healthy trend, as shown in Table 2 and has grown from a single publication in 2016 to 47% in 2021. About

Table 1
Research performance and temporal evolution.

Indicators	2016	2017	2018	2019	2020	2021
Total Publications (TP)	25	25	33	58	111	390
Total Citations (TC)	8	110	301	725	1,564	3,578
FWCI	0.64	1.78	3.03	1.63	2.11	1.75
TC/TP	0.32	4.4	9.12	12.5	14.09	9.17
% Outputs in Top 10% Citation Percentiles	4	28	27.3	22.4	27.1	19.2
% Publications in Top 10% Journal Percentiles (by CiteScore percentile)	38.9	55.6	40.7	54	47.5	47.6
International Collaboration (%)	34.8	20	24.2	24.6	28.2	29.7
Authors	92	121	149	265	493	1,686

Table 2
Open access publications trends.

Publications	2016	2017	2018	2019	2020	2021
OA	1	6	15	14	60	189
TP	25	25	33	58	111	390
% OA	4%	24%	45%	24%	54%	48%

44% of the total publications (TP) are in open access for 2016 to 2021.

The top 5 papers under OA are further analyzed, as seen in Table 3. Remarkably, the publications in 2018 and 2020 have achieved a high TC/Y ranging from 39 to 120 in a short span of 3 years.

3.1.3. Effect of collaboration

A research topic's publications are collaborative to the extent that international, national, or institutional co-authorship is incorporated into their publications. Each publication is assigned to mutually exclusive collaboration types based on its affiliation information. In the affiliation information for a publication, international, national, and institutional collaboration may all appear. However, only one collaboration type is assigned to ensure that a publication across all four categories equals 100% of the publications with the necessary affiliation information.

As seen in Table 4, while the share of international and national collaborated papers are nearly equal, the number of citations, citations per publication, and FWCI are higher for internationally co-authored papers. This confirms that research on green-hydrogen is consistent with studies that state international collaboration leads to higher citations (Kato and Ando, 2013; Wang et al., 2015)

3.1.4. Most prolific authors

A total of 2809 authors contributed 642 green-hydrogen publications increasing from 92 authors in 2016 to 1686 authors in 2021. Table 5 ranks the most prolific authors based on their publications (TP), citations (TC), and Field Weighted Citation Impact (FWCI). Based on TC, the top three authors are Poullikkas, Qiao, and Ran, with TC of 817, 500, and 500, respectively. Author Quadi has the lowest TC of 1, possibly illustrating depreciated attention to detail. Additionally, this author has a low FWCI of 0.2. Hence, the performance of authors is linked to factors such as TP, TC, and FWCI. If we look at FWCI, the top author is Yu followed by Qiao and Ran with FWCI of 18.2, 12.7, and 12.7, respectively. FWCI demonstrates how the number of citations received by a publication compares to the average. It is the ratio of the actual number of citations received by an output to date and the total citations that would be expected based on the average of the subject field. Hence, it is seen that though authors like Yu (TP:2) and Poullikkas (TP:1) have fewer publications, their publications are well-cited, especially that of Poullikkas, but authors like Kim, who has a higher number of publications (TP:5) have low citations (TC:24). Interestingly, the most prolific authors are from Asian countries of the Republic of Korea and China, a possible indication of those governments' priority accorded to green-hydrogen research.

3.1.5. Top journal sources

A total of 160 journals have published 642 green-hydrogen related publications. Table 6 lists the twenty most productive journals ranked based on three separate indicators: TP, TC, and AAS, accounting for 41% of total publications. The top journals, with TP of 92, 38, and 21, are the International Journal of Hydrogen Energy, Energies, and ECS Meeting Abstracts. In contrast, the best journals based on TC of 1562, 1024, and 482 are the International Journal of Hydrogen Energy, Renewable and Sustainable Energy Reviews, and Advanced Materials.

Due to the recentness of the green-hydrogen topic and a possible lag effect of citations, we also ranked journals based on Altmetrics, which looks at research dissemination in social media platforms like Tweets, blogs, Facebook likes, etc. The top 3 journals based on Altmetric Attention Score (AAS) were Scientific American, Nature Chemistry, and Solar RRL, with AAS of 159, 122, and 114. But these top journals based on AAS have low values of TP and TC. However, the journals of the AAS section are different from the other sections in terms of the order of top journals and composition.

Using VOSviewer, we arrive at a network of four journal clusters, as shown in Fig. 2, which gives new information on the contributions of journals to green-hydrogen research. The clusters-structured resulting maps are sized based on the links (L) and the total link strength (TLS) the Links and Total link strength attributes indicate, respectively, the number of links of an item with other items and the total strength of the links of an item with other items.

The largest cluster (red) with ten journals is the materials chemistry cluster, consisting of journals such as Journal of Materials Chemistry A (L:20, TLS:280), Chemical Engineering Journal (L:15, TLS:107), Catalysts (L:18, TLS:96), Applied Catalysis B: Environmental (L:20, TLS:118) and International Journal of Energy Research (L:26, TLS:369). The next largest cluster is the hydrogen energy and cleaner production cluster (green), consisting of 8 journals i.e. the International Journal of Hydrogen Energy (L:27, TLS:2897), Energy Conversion and Management (L:23, TLS:740), Renewable and Sustainable Energy Reviews (L:24, TLS:471), Journal of Cleaner Production and Energy (L:22, TLS:277). Next follows the applied energy cluster (blue), consisting of 6 journals such as Applied Energy (L:25, TLS:709), Energy Procedia (L:7, TLS:15), Journal of Power Sources (L:20, TLS:292), ECS transactions (L:16, TLS:99), and Chemie-Ingenieur-Technik (L:17, TLS:277). Finally, the fuel cells cluster (yellow) consists of 5 journals: Energies (L:25, TLS:1398), Fuel Cells Bulletin (L:1, TLS:2), Sustainability (Switzerland) (L:23, TLS:439), ACS Sustainable Chemistry and Engineering (L:23, TLS:423), and Frontiers in Energy Research (L:19, TLS:124). The journal with the greatest number of links and total link strength is the International Journal of Hydrogen Energy in Cluster 2 followed by Energies in Cluster 4.

The total publications (TP) of the largest cluster, i.e., the materials chemistry cluster, is 74, with total citations (TC) of 850. This cluster's top-cited (TC:78) article is "Defective and ultrathin NiFe LDH nanosheets decorated on V-doped Ni3S2 nanorod arrays: A 3D core–shell electrocatalyst for efficient water oxidation"

Table 3
Top publications under Open Access.

Title	Journal	Year	TC	TC/Y
Metal-Free 2D/2D Phosphorene/g-C3N4 Van der Waals Heterojunction for Highly Enhanced Visible-Light Photocatalytic H2 Production	Advanced Materials	2018	480	120.0
Bifunctional Heterostructured Transition Metal Phosphides for Efficient Electrochemical Water Splitting	Advanced Functional Materials	2020	116	58.0
Green-hydrogen from anion exchange membrane water electrolysis: a review of recent developments in critical materials and operating conditions	Sustainable Energy & Fuels	2020	78	39.0
Enhanced performance and durability of low catalyst loading PEM water electrolyzer based on a short-side chain perfluorosulfonic ionomer	Applied Energy	2017	77	15.4
Templated dewetting: designing entirely self-organized platforms for photocatalysis	Chemical Science	2016	70	11.6

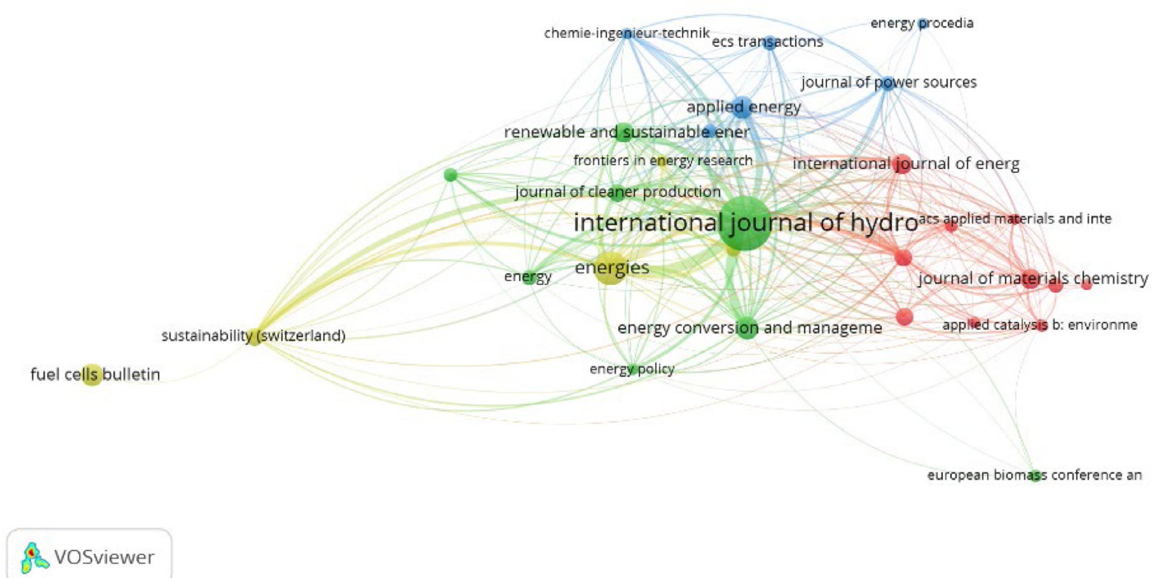

Fig. 2. Network of Journal sources.

Table 4
Effect of collaboration.

Type of collaboration	% Share	TP	TC	TC/TP	FWCI
International	29.9%	204	2,644	12.96	2.21
Only national	28.6%	195	1,665	8.54	1.4
Only institutional	33.7%	230	2,184	9.50	1.33
Single authorship	7.9%	54	175	3.24	0.95

authored by Zhou et al. (2019). In the hydrogen energy and cleaner production cluster, the TP and TC are 132 and 2215, respectively.' A comparative overview of hydrogen production processes'' authored by Nikolaidis and Poullikkas (2017) with TC (829) is the most cited publication in this cluster. The next cluster, i.e., the applied energy cluster, has total publications (TP:31) with total citations (TC:416). ''Enhanced performance and durability of low catalyst loading PEM water electrolyzer based on a short-side chain perfluorosulfonic ionomer'' with total citations (TC:77) by (Siracusano et al., 2017) is the topmost publication in this cluster. Fuel cells are the last cluster with total publications (TP:67) and total citations (TC:289). The role of green and blue Hydrogen in the energy transition — a technological and geopolitical perspective authored by Noussan et al. (2021) is the top publication in this cluster with TC:49.

3.1.6. Influential publications

Citation is considered an essential metric for measuring the impact of an article or a journal (Svensson, 2010; Tsay, 2009). Table 7 illustrates the most influential publications based on TC from 2016 to 2021. The topmost cited publication is titled ''A comparative overview of hydrogen production processes'' has an impressive TC of 823 and is seen discussing hydrogen production, water splitting and pyrolysis, gasification, and impact on climate change. The second most influential article (TC:480) titled ''Metal-Free 2D/2D Phosphorene/g-C3N4 Van der Waals Heterojunction for Highly Enhanced Visible-Light Photocatalytic H2 Production'' focuses on Environmental impact. This work not only discusses a new metal-free phosphorene/g-C_3N_4 photocatalyst but also sheds light on the design and fabrication of 2D/2D VDW heterojunction for applications in catalysis, electronics, and optoelectronics. ''Toward practical solar hydrogen production, an artificial photosynthetic leaf-to-farm challenge'' with TC of 284 is the third most influential publication which discusses devices and systems for solar-to-hydrogen production including a comparison of the above solar water splitting systems and the fourth most influential publication is ''Energiepark Mainz: Technical and economic analysis of the worldwide largest Power-to-Gas plant with PEM electrolysis'' with TC of 111. This publication analyzes the three options: electricity purchase at the European power exchange, excess electricity from a direct marketing company, and control reserve participation.

3.1.7. Highly productive institutions

Table 8 indicates the most productive institutions researching green-hydrogen. According to the number of publications, 20 institutions globally have been ranked in descending order. The

Table 5
Most prolific authors based on publications and citations.

Ranked by TP					Ranked by TC			
Name	Country	TP	TC	FWCI	Name	TC	TP	FWCI
Tran, D.T.	Republic of Korea	5	24	2.8	Poullikkas, Andreas	817	1	9.9
Kim, N.H	Republic of Korea	5	24	2.6	Qiao, Shizhang	500	3	12.7
Lee, J.H	Republic of Korea	5	24	2.5	Ran, Jingrun	500	3	12.7
Tahir, M Bilal	Pakistan	4	146	3.2	Yu, Jiaguo	477	2	18.2
Stolten, Detlef	Germany	4	114	4.6	Tahir, M Bilal	146	4	3.2
Yang, Siyuan	China	4	101	7.3	Rafique, Muhammad	141	3	3.7
Zhang, Shengsen	China	4	101	3.1	Nabi, Ghulam	127	2	4.9
Leo Mena, T. J.	Spain	4	58	7.4	Kopp, M.	122	2	4.1
Xue, Huaqing	China	4	32	7.4	Coleman, D.	122	2	4.1
Pan, Songqi	China	4	32	1.8	Scheppat, Birgit	122	2	4.1
Xiong, Bo	China	4	32	0.3	Desideri, Umberto	121	2	5.5
Thanh, Tran Duy	South Korea	4	12	0.9	Stolten, Detlef	114	4	4.6
Ould, Belkacem	France	4	11	0.2	Wehrspohn, Ralf B.	106	1	5.7
Dincer, Ibrahim	Canada	4	10	0.2	Schweizer, Stefan L.	106	1	5.7
Ouadi, Miloud	UK	4	1	0.2	Yang, Siyuan	101	4	7.3

top three institutions are the Chinese Academy of Sciences, CNRS, and the Ministry of Education China, with 73, 50, and 40 authors. Two of the top institutions come from China, while one comes from France. The Table shows that most of the top institutions are from Europe and Asia. Out of the 20 institutions, seven are from the government sector, while the academic sector dominates with 13 institutions. However, the highest TC/TP is for the University of Adelaide. This illustrates that TC/TP is not dependent on the number of authors. Some institutions with the highest TC/TP have fewer authors than others with lower TC/TP. Moreover, the citation impact (CI) ranking is also not dependent on the number of authors. Regardless, the FWCI ranking is proportional to TC/TP since the University of Adelaide has the largest FWCI of 7.17. On the other hand, the University of Porto does not have the least TC/TP and FWCI, which are 2.2 and 0.76, despite being at the bottom of the table. The University of Birmingham has the least TC/TP and FWCI, which are 0.6 and 0.33. Based on the number of authors and TP, Australia, Norway, and Portugal are the best three countries.

3.1.8. Top contributing countries

Table 9 illustrates the ranking of the most prolific countries according to research productivity (TP) and research influence (TC) along with total views (TV) and FWCI. The highest-ranked countries based on TC are China (1,858), Cyprus (806), Germany (761), and Italy (686). In contrast, the top countries based on TP are China (145), Germany (94), Italy (58), and the US (57). China, Germany, and Italy are in the top four spots. The Table has countries from multiple regions such as Asia, Europe, Australia, and North America validating the importance and urgency of research about green-hydrogen. Four countries are from Asia in the right column while Europe takes the lead with the most significant number of countries, totaling 8. North America has two representatives, which are the US and Canada. TC and TP are slightly different in ranking. Total Publication Views (TV) may be an early indicator of future impact on a document. With a growing emphasis on responsible metrics, TV is a valuable indicator to combine with other metrics. Many readers are possibly interested in viewing publications with a high ranking from a reputable country and journal while their research is still not ready to cite them. Italy has the highest TV of 3901, followed by Germany and China, which have 3661 and 3565.

The top countries with the highest-ranking FWCI are Cyprus, Pakistan, and Switzerland, with 4.96, 4.14, and 3.32, respectively, indicating the mean citation impact. The right and left column of Table 9 shows a slight difference in country positioning. Countries such as Poland, Belgium, and Switzerland are in one column each. The top countries come from different areas globally, which is a sign of the diversification of research scholars. The topic of green-hydrogen is taken seriously by all countries and not just the big economies that are more responsible for the rise in Green House Gas emissions.

Fig. 3 shows the bibliographic network of countries, which has 4 clusters. The node size of the country is determined by the number of articles (TP) published by the country. More the number of articles will be the node size. The links between the countries indicate the number of co-authored papers between the connected countries, and the thickness of the line indicates the level of collaboration between the two countries. In Cluster 1 (red) Germany (TP:94) with France (TP:32) has the most number of publications. The other countries in this cluster are Canada, Poland, Russia, Turkey, Portugal, Sweden, Austria, Brazil, Chile, and Ireland. In the second cluster (green) there are eight countries with China (TP:145) with the United States (TP:57) having the most number of publications. The other countries in this cluster are Korea, India, Australia, Japan, Norway, and Singapore. In the blue cluster, Saudi Arabia (TP:18) leads with the most publications followed by Malaysia, Egypt, Pakistan, Denmark, Iran, and United Arab Emirates. The yellow cluster with five countries is led by Italy (TP:58) and the countries in the cluster are the United Kingdom, Spain, Netherlands, Belgium, and Switzerland.

The closer two countries are located to each other, the stronger their relatedness. We can observe strong relatedness between Germany and Sweden, the United States with Norway, China with South Korea, Italy with Spain, and Malaysia with Saudi Arabia.

3.1.9. Major funders and their country affiliations

The practice of acknowledging funding sources by authors is increasing though the percentage of publications with funding sources is low (Costas and van Leeuwen, 2012; Cronin et al., 2003; Shapira and Wang, 2010). We try to understand the importance of an emerging topic like green-hydrogen by national and international agencies by analyzing funding patterns. From those publications which have acknowledged funders, the top 15 funders of green-hydrogen research, grouped by country and ranked by publications, are shown in Table 10. The funding sources are from different government agencies, indicating green-hydrogen is a national priority. Equally interesting is that funding is spread across different regions of the world. Led by Chinese agencies, the National Natural Science Foundation, Ministry of Science and Technology of the People's Republic of China, Chinese Academy of Sciences, and China Scholarship Council, they have funded 134 publications contributing to 1461 citations. The second highest is the European Commission funding 45 publications resulting in 694 citations. We also see government agencies in developing nations like India and Portugal funding green-hydrogen related research.

Table 6
Top journal sources based on publications, citations, and altmetrics.

Ranked by TP				Ranked by TC				Ranked by AAS			
Journal	TP	TC	AAS	Journal	TC	TP	AAS	Journal	AAS	TP	TC
International Journal of Hydrogen Energy	92	1562	11.3	International Journal of Hydrogen Energy	1562	92	11.3	Scientific American	159.0	1	0
Energies	38	162	6.3	Renewable and Sustainable Energy Reviews	1024	10	29.8	Nature Chemistry	122.0	1	24
ECS Meeting Abstracts	21	0	–	Advanced Materials	482	2	1.0	Solar RRL	114.0	4	17
Focus on Catalysts	20	2	–	Journal of Materials Chemistry A	444	14	1.8	Industrial & Engineering Chemistry Research	74.0	3	89
Journal of Materials Chemistry A	14	444	1.8	Materials Science for Energy Technologies	330	1	38.0	Journal of Renewable and Sustainable Energy	48.0	3	22
Applied Energy	13	243	38.3	Chemical Society Reviews	316	1	4.0	Science Advances	46.0	1	60
International Journal of Energy Research	13	106	2.0	Applied Energy	243	13	38.3	Applied Energy	38.3	13	243
Sustainable Energy & Fuels	11	121	20.2	Energies	162	38	6.3	Materials Science for Energy Technologies	38.0	1	330
Journal of Cleaner Production	11	33	2.5	Energy Policy	161	4	10.3	Joule	38.0	1	1
Renewable and Sustainable Energy Reviews	10	1024	29.8	Advanced Functional Materials	154	5	1.3	Clean Technologies and Environmental Policy	33.5	3	23
Membrane Technology	10	0	–	Journal of Power Sources	143	8	2.5	Cell Reports Physical Science	31.7	3	28
Energy Conversion and Management	9	120	22.0	Sustainable Energy & Fuels	121	11	20.2	Renewable and Sustainable Energy Reviews	29.8	10	##
Catalysts	9	38	2.0	Energy Conversion and Management	120	9	22.0	Energy and Climate Change	25.0	1	1
Sustainability	9	25	1.0	International Journal of Energy Research	106	13	2.0	Energy Conversion and Management	22.0	9	120
Journal of Power Sources	8	143	2.5	Applied Catalysis B Environmental	102	4	2.0	Energy & Environmental Science	21.3	3	4
Chemie Ingenieur Technik	8	15	2.0	Nano Energy	102	2	–	Sustainable Energy & Fuels	20.2	11	121
E3S Web of Conferences	8	5	–	Metabolic Engineering	98	2	–	ACS Energy Letters	19.0	1	3
C&EN Global Enterprise	8	1	–	Ceramics International	95	1	–	Vakuum in Forschung und Praxis	16.0	1	0
Chemical Engineering Journal	7	34	–	ChemSusChem	92	2	4.0	Frontiers in Sustainability	15.0	1	7
ACS Sustainable Chemistry & Engineering	7	17	–	Industrial & Engineering Chemistry Research	89	3	74.0	The Innovation	15.0	1	1

3.1.10. Top subject areas

Table 11 highlights the ranking of the top fourteen subject areas of the green-hydrogen study based on the ASJC (All Science Journal Classification) scheme in Scopus. The highest achieving subject areas are Energy, Engineering, Chemistry, and Physics and Astronomy with TP of 386, 183, 153, and 144. These subject areas also lead in the number of authors, 1555, 838, 809, and 656, respectively. Furthermore, Energy, Chemistry, and Engineering have a high TC of 3846, 1764, and 1608. Comparatively, Business, Economics, and Biochemistry have the lowest ranks due to TP of 20, 11, and 10. Material science, Chemistry, and Energy have the most significant TC/TP, which conform to 15.7, 11.5, and 10. This shows that even though TC/TP differs slightly from the individual ranking of TC and TP, their overall relevance is retained. However, the order in terms of CI is different. The top subject areas for FWCI are Earth and Planetary Sciences, Physics and Astronomy, and Materials Science, with CI of 2.7, 1.97, and 1.93. Also, the top subject areas are the field of Science and Mathematics

3.2. Knowledge structure: major themes, prominence topics, and keyphrases

3.2.1. Keywords analysis

The main contents of existing studies depicting the topics that have been focused on within a given domain are called keywords (Su and Lee, 2010). Co-occurrence Analysis with VOSviewer was used in this study to examine the network of keywords to display their relationships and intellectual organization of research themes (Van Eck and Waltman, 2014). Keyword co-occurrence analysis reflects the presence of green-hydrogen research, and this is shown as different clusters (Donthu et al., 2021).

Keyword co-occurrence network analysis demonstrates four clusters of green-hydrogen research, as seen in Fig. 4, which

Table 7
Most influential publications, according to citations.

TC	Title	Year	TC/Y
823	A comparative overview of hydrogen production processes	2017	164.6
480	Metal-Free 2D/2D Phosphorene/g-C3N4 Van der Waals Heterojunction for Highly Enhanced Visible-Light Photocatalytic H2 Production	2018	120.0
284	Toward practical solar Hydrogen production-an artificial photosynthetic leaf-to-farm challenge	2019	94.7
116	Bifunctional Heterostructured Transition Metal Phosphides for Efficient Electrochemical Water Splitting	2020	58.0
111	Energiepark Mainz: Technical and economic analysis of the worldwide largest Power-to-Gas plant with PEM electrolysis	2017	22.2
98	Nanoporous Zn-doped Co3O4 sheets with single-unit-cell-wide lateral surfaces for efficient oxygen evolution and water splitting	2018	24.5
85	Role of MoSe2 on nanostructures WO3-CNT performance for photocatalytic hydrogen evolution	2018	21.3
78	Green-hydrogen from anion exchange membrane water electrolysis: A review of recent developments in critical materials and operating conditions	2020	39.0
78	Defective and ultrathin NiFe LDH nanosheets decorated on V-doped Ni3S2 nanorod arrays: A 3D core–shell electrocatalyst for efficient water oxidation	2019	26.0
77	Enhanced performance and durability of low catalyst loading PEM water electrolyzer based on a short-side chain perfluorosulfonic ionomer	2017	15.4

Table 8
Most productive institutions.

Institution	Sector	Country	TP	TC	Authors	TC/TP	FWCI
Chinese Academy of Sciences	Government	China	24	269	73	11.2	1.69
CNRS	Government	France	18	187	50	10.4	1.77
Ministry of Education, China	Government	China	13	215	40	16.5	2.01
University of Chinese Academy of Sciences	Academic	China	10	99	28	9.9	1.27
German Aerospace Center	Government	Germany	10	60	30	6.1	1.39
RWTH Aachen University	Academic	Germany	9	131	15	14.6	2.62
Korea Institute of Energy Research	Government	South Korea	8	30	16	3.8	2.14
Julich Research Centre	Government	Germany	8	123	23	15.4	3.07
National Research Council of Italy	Government	Italy	8	216	15	27.0	2.67
Polytechnic University of Milan	Academic	Italy	8	108	18	13.5	1.22
Zhejiang University	Academic	China	7	26	27	3.7	1.03
Karlsruhe Institute of Technology	Academic	Germany	7	56	16	8.0	1.18
University of Birmingham	Academic	United Kingdom	7	4	10	0.6	0.33
University of Adelaide	Academic	Australia	6	506	9	84.3	7.17
CAS — Dalian Institute of Chemical Physics	Academic	China	6	77	25	12.8	1.74
Technical University of Madrid	Academic	Spain	6	66	8	11.0	1.43
University College London	Academic	United Kingdom	6	61	19	10.2	2.01
University of Bologna	Academic	Italy	6	10	11	1.7	0.36
Norwegian University of Science and Technology	Academic	Norway	6	42	6	7.0	1.43
University of Porto	Academic	Portugal	6	13	9	2.2	0.76

Table 9
Top contributing countries based on citations and publications.

Ranked by citations					Ranked by publications				
Country	TC	TP	TV	FWCI	Country	TP	TC	TV	FWCI
China	1,858	145	3,565	2.23	China	145	1,858	3,565	2.23
Cyprus	806	2	1,156	4.96	Germany	94	761	3,661	1.13
Germany	761	94	3,661	1.13	Italy	58	686	3,901	2.88
Italy	686	58	3,901	2.88	United States	57	376	1,677	1.36
Australia	674	31	696	2.09	United Kingdom	49	381	1,909	0.95
South Korea	424	45	1,011	1.82	South Korea	45	424	1,011	1.82
United Kingdom	381	49	1,909	0.95	Spain	37	270	1,485	0.79
United States	376	57	1,677	1.36	France	32	316	1,541	1.73
France	316	32	1,541	1.73	Australia	31	674	696	2.09
Pakistan	291	13	487	4.14	India	29	137	441	0.83
Spain	270	37	1,485	0.79	Netherlands	21	164	1,061	2.93
Saudi Arabia	198	18	518	2.63	Canada	19	127	492	2.57
Netherlands	164	21	1,061	2.93	Saudi Arabia	18	198	518	2.63
India	137	29	441	0.83	Poland	17	65	355	1.27
Switzerland	133	8	612	3.32	Belgium	14	94	425	2.68

encapsulates 549 keywords with a threshold of 10 minimum occurrence of keywords that have appeared in at least ten green-hydrogen publications. The keywords in each cluster are arranged to convey a coherent narrative that explains the essence and scope of the cluster (Donthu et al., 2021), and the explanation for each cluster is developed based on sensemaking. This criterion

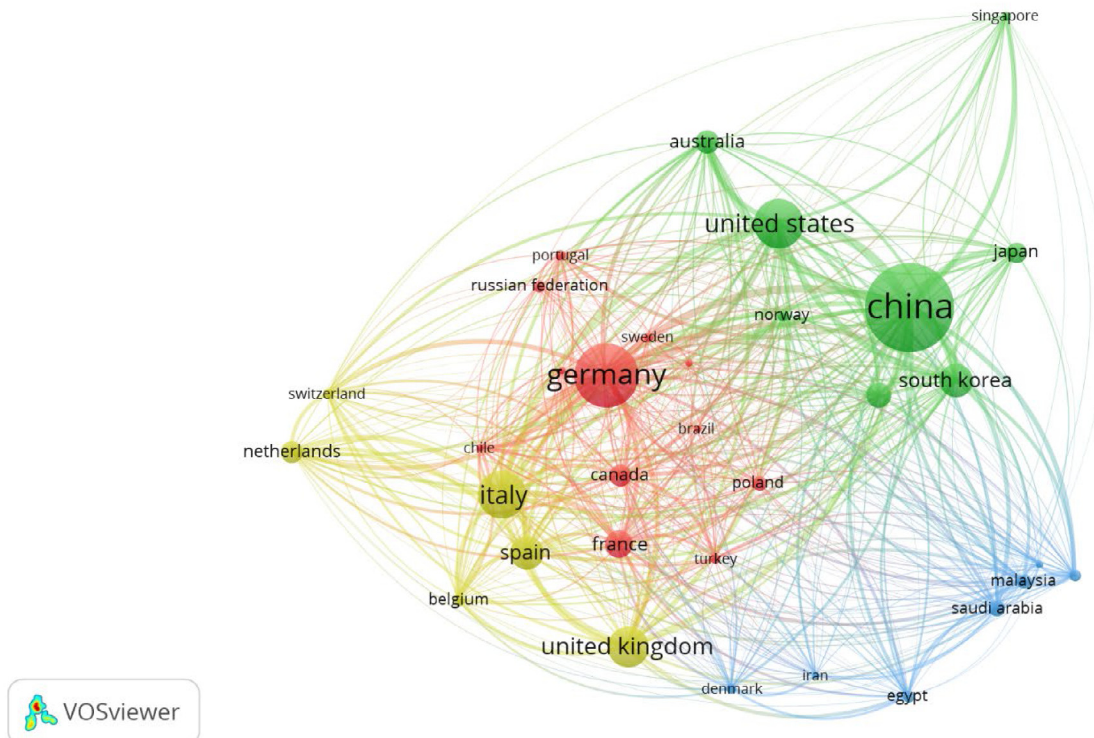

Fig. 3. Bibliographic network of top contributing countries.

Table 10
Top contributing funders according to publications.

Country	Name	TP	TC
China	National Natural Science Foundation of China (NSFC)	83	1,649
	Ministry of Science and Technology of the People's Republic of China (MOST)	21	270
	Chinese Academy of Sciences (CAS)	19	175
	China Scholarship Council (CSC)	11	86
Belgium	European Commission (EC)	14	62
South Korea	National Research Foundation of Korea (NRF)	25	428
	Ministry of Science ICT and Future Planning (MSIP)	10	377
	Ministry of Trade, Industry, and Energy (MOTIE)	8	323
Germany	Federal Ministry of Education and Research (BMBF)	17	197
	German Research Foundation (DFG)	11	101
	Federal Ministry for Economic Affairs and Energy (BMWi)	7	100
Australia	Australian Research Council (ARC)	9	606
	Australian Renewable Energy Agency (ARENA)	7	37
United Kingdom	Engineering and Physical Sciences Research Council (EPSRC)	13	138
Canada	Natural Sciences and Engineering Research Council (NSERC)	11	92

Table 11
Top subject areas based on publications.

Subject Area	TP	%Share	TC	Authors	TC/TP	FWCI
Energy	386	60.1%	3,846	1,555	10	1.7
Engineering	183	28.5%	1,608	838	8.8	1.5
Chemistry	153	23.8%	1,764	809	11.5	1.5
Physics and Astronomy	144	22.4%	1,239	656	8.6	2
Chemical Engineering	125	19.4%	1,031	557	8.2	1.5
Environmental Science	119	18.5%	850	578	7.1	1.7
Materials Science	99	15.4%	1,558	548	15.7	1.9
Mathematics	51	7.9%	157	191	3.1	0.9
Earth and Planetary Sciences	27	4.2%	72	93	2.7	2.7
Computer Science	25	3.8%	40	81	1.6	1.6
Social Sciences	21	3.2%	109	78	5.2	1.8
Business, Management, and Accounting	20	3.1%	57	85	2.8	0.8
Economics, Econometrics, and Finance	11	1.7%	7	32	0.6	0.4
Biochemistry, Genetics and Molecular Biology	10	1.5%	48	78	4.8	1.1

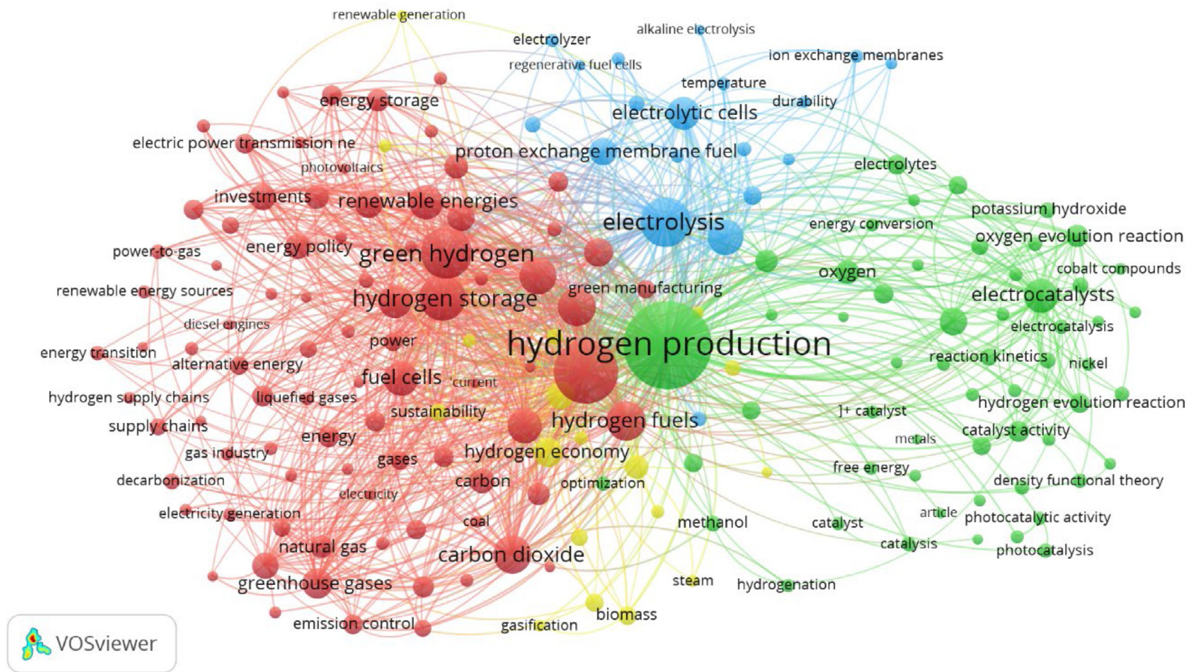

Fig. 4. Co-occurrence of keywords.

for keyword co-occurrence analysis is consistent with the studies of Donthu et al. (2021) and Srivastava and Sivaramakrishnan (2021).

As seen in Table 12, Cluster 1 in red is the largest among all the four clusters consisting of 316 publications (TP) that generated 2680 citations (TC) with a TC/TP of 8.48. The cluster focuses on Green-hydrogen as renewable energy, and the main topics discussed in this cluster include Hydrogen, green-hydrogen, fossil fuels, fuel cells, carbon dioxide, solar power generation, and renewable energies. The most influential publication (TC:111) in this cluster is "Energiepark Mainz: Technical and economic analysis of the worldwide largest Power-to-Gas plant with PEM electrolysis" authored by Kopp et al. (2017) with an average TC/Y of 22.2. The top three cited papers in this cluster were published during 2017–18, reflecting the focus of researchers on green-hydrogen since then.

Cluster 2 shown in green, consists of 286 publications (TP) with 2840 citations (TC) and a TC/TP of 9.93. The cluster focuses on Green-hydrogen production, and the main topics discussed in this cluster include Hydrogen production, electrocatalysts, water splitting, oxygen, oxygen evolution reaction, electrolytes, catalysts. "Metal-Free 2D/2D Phosphorene/g-C3N4 Van der Waals Heterojunction for Highly Enhanced Visible-Light Photocatalytic H2 Production" which was published in 2018 and had the highest citation (TC:480) with TC/Y of 120. Interestingly this publication has the highest TC and TC/Y among the publications in all the clusters. The publication focused on a unique aspect that the generation of green-hydrogen (H2) energy using sunlight is of great significance to solve the worldwide energy and environmental issues and mainly that photocatalytic H2 production is a highly promising strategy for solar-to-H2 conversion.

Cluster 3 in blue color focuses on the green-hydrogen production process. With 131 publications (TP), 1222 citations (TC) and TC/TP of 9.32, the main topics discussed in the cluster are mainly on the production process of green-hydrogen. They include water electrolysis, electrolytic cells, electrolysis, electrolyzers, polyelectrolytes, SOFC, alkaline water electrolysis, and PEMFC. The most influential publication (TC:74) in this cluster is Robust electrocatalysts from an alloyed Pt-Ru-M (M = Cr, Fe, Co, Ni, Mo)-decorated Ti mesh for hydrogen evolution by seawater splitting. The most cited publications (TC) in this cluster are from 2016 and 2017, which reveals the researchers' interest in the various green-hydrogen production processes.

With 129 publications (TP) and 1,189 citations (TC) and with a TC/TP of 9.2, Cluster 4 in yellow color is the smallest. The most influential publication (TC:67) in this cluster is from 2020 i.e., "Rationally designed indium oxide catalysts for CO2 hydrogenation to methanol with high activity and selectivity" with TC/Y of 33.5. The central theme in this cluster is green-hydrogen economy, with the main topics being Hydrogen economy, biomass, sustainability, steam reforming, hydrogen fuels, and gasification. Since publications from 2020 have started figuring among the top most cited publications, this shows the growing importance of green-hydrogen as a research area.

The major keywords in Cluster 1 may be grouped under the research theme "Green-hydrogen as renewable energy" and Cluster 2 under the theme "Green-hydrogen production". Cluster 3 may be grouped under the theme "Green-hydrogen production process" and Cluster 4 under the theme "Green-hydrogen economy". If in 2016-17 the focus was on the Green-hydrogen production process and in 2017–18 on Green-hydrogen production and renewable energy, the focus slowly shifted to the Green-hydrogen economy from 2018–20, indicating the interest of researchers in the economic aspects of Green-hydrogen and commercialization on a larger scale.

3.2.2. Research topics with prominence

Given the recentness of research about green-hydrogen, we have used prominence percentiles to gauge the momentum or visibility of the research topic. Three indicators in Scival are used to calculate the momentum of the topic, namely — citation counts, views, and average CiteScore. Combining prominence percentile, publication growth, and FWCI, we highlight new hotspots of green-hydrogen research.

Table 13 shows fifteen research topics ranked based on prominence percentile. The research topics have considerable prominence percentiles that range from 99.99 to 98.774. Three topics with high prominence percentile are Oxygen Production (99.998) followed by Water Splitting (99.979) and Cathodes (99.941) and

Table 12
Research themes based on keywords.

Cluster	Research Theme	Major keywords	TP	Most influential publications	Year	TC	TC/Y
1	Green-hydrogen as renewable energy	Hydrogen, green-hydrogen, hydrogen storage, fossil fuels, fuel cells, carbon dioxide, solar power generation, renewable energies	316	Energiepark Mainz: Technical and economic analysis of the worldwide largest Power-to-Gas plant with PEM electrolysis.	2017	111	22.2
				Role of MoSe2 on nanostructures WO3-CNT performance for photocatalytic hydrogen evolution.	2018	85	21.3
				Enhanced performance and durability of low catalyst loading PEM water electrolyzer based on a short-side chain perfluorosulfonic ionomer.	2017	77	15.4
2	Green-hydrogen production	Hydrogen production, electrocatalysts, water splitting, oxygen, oxygen evolution reaction, electrolytes, catalysts	286	Metal-Free 2D/2D Phosphorene/g-C3N4 Van der Waals Heterojunction for Highly Enhanced Visible-Light Photocatalytic H2 Production.	2018	480	120.0
				Nanoporous Zn-doped Co3O4 sheets with single-unit-cell-wide lateral surfaces for efficient oxygen evolution and water splitting.	2018	98	24.5
				Defective and ultrathin NiFe LDH nanosheets decorated on V-doped Ni3S2 nanorod arrays: A 3D core–shell electrocatalyst for efficient water oxidation.	2019	78	26.0
3	Green-hydrogen production process	Water electrolysis, electrolytic cells, electrolysis, electrolyzers, polyelectrolytes, SOFC, alkaline water electrolysis, PEMFC	131	Robust electrocatalysts from an alloyed Pt-Ru-M (M = Cr, Fe, Co, Ni, Mo)-decorated Ti mesh for hydrogen evolution by seawater splitting.	2016	74	12.3
				A system approach in energy evaluation of different renewable energies sources integration in ammonia production plants	2016	73	12.1
				Polymer electrolyte membrane water electrolysis: Restraining degradation in the presence of fluctuating power	2017	72	14.4
4	Green-hydrogen economy	Hydrogen economy, biomass, sustainability, steam reforming, hydrogen fuels, gasification,	129	Rationally designed indium oxide catalysts for CO2 hydrogenation to methanol with high activity and selectivity	2020	67	33.5
				Green-hydrogen production potential for developing a hydrogen economy in Pakistan	2018	65	16.3
				Design of Ni-ZrO2@SiO2 catalyst with ultra-high sintering and coking resistance for dry reforming of methane to prepare syngas	2018	57	14.3

makeup 15 percent of the total publication share. This shows that these research topics have prominent publications that account for their large shares.

Hydrogen Economy and regenerative fuel cells have many publications and publication shares. However, they have a prominence percentile of less than 99% and are likely to be research frontiers. While Biohydrogen has the most considerable FWCI of 2.7, the gap between FWCI ranges from 2.7 to 0.59. Further, the ranking of FWCI fluctuates considerably between the top fifteen research topics with momentum. Therefore, research topics get high momentums from large TP, prominent share, and prominence percentile. The issues with the largest TP of 90, 60, and 49 are Hydrogen Economy, Oxygen Production, and Electrolysis. These values are considerably more significant than Dry Reforming Methane's lowest ranking research topic. However, their publication shares are 10.86, 0.57, and 4.69.

3.2.3. Related research topics

Related topics cover a similar research interest to the topic authors are looking at based on text matching. They can help authors identify related areas of research that are not necessarily citing their area of interest. These related topics can be used to expand authors' reading lists and identify new researchers to follow or with whom to collaborate. Related topics are computed using deep learning embeddings based on the titles and abstracts of the publications. These are long vectors that express the semantics of a publication. The vectors of a topic are created by aggregating the vectors of the publications that make up the topic. The relatedness score is calculated by looking at the common vectors between the Topics, computing the strength between these vectors, and converting that into a percentile.

Table 14 shows a ranked list of related topics based on relatedness scores. The top three related research topics are described as follows.

1. Related topics focussed on technological progress, sustainable technology, and environmental regulations regarding green-hydrogen have the highest relatedness (93.8%) to topics such are biodiesel, diesel engines, and engine cylinders.
2. Next comes related topics such as core industries, air quality monitoring, and greater China, with the relatedness of 92.80% to topics such as hydrogen storage, hydrides, and dehydrogenation.

In the third position, we have related topics like distillation, reactors, and Iran with relatedness of 92.10% to topics such as distillation, optimization, and distillation columns.

3.2.4. Keyphrase analysis

Several studies have used keyphrase analysis to identify research hotspots for a topic (Zhou and Wang, 2021; Parnianifard et al., 2018). Scival extracts top keyphrases through text mining in titles and abstracts of the documents. Keyphrases are matched against a single unified thesaurus spanning all major disciplines

Table 13
Top research topics based on prominence percentile.

Topic	Prominence percentile	TP	FWCI
Oxygen Production; Electrocatalysts	99.998	60	1.31
Water Splitting; Cobalt Phosphide	99.979	29	1.84
Cathodes; Bismuth Vanadium Tetraoxide	99.941	11	1.15
Compressed Air Energy Storage; Electricity Storage	99.879	25	2.34
Rural Electrification; Microgrid; Energy Systems	99.866	15	0.59
Battery Electric Vehicles; Alternative Fuel Vehicles	99.821	11	1.35
Dry Reforming Methane; Steam Reforming; Synthesis Gas	99.751	7	2.19
Methane Production; Natural Gas Substitutes	99.672	13	1.91
Biohydrogen; Photofermentation; Hydrogen Production	99.648	10	2.70
Fischer–Tropsch Reaction; Light Olefins	99.644	8	0.76
Anion-exchange Membranes; Alkaline Fuel Cells	99.584	10	2.39
Production of Methanol; Hydrogenation	99.58	9	2.56
Electrolysis; Regenerative Fuel Cells; Alkaline Water	98.905	49	1.01
Regenerative Fuel Cells; Yttria-stabilized Zirconia	98.852	8	1.27
Hydrogen Economy; Refueling; Hydrogen Fuel Cells	98.774	90	2.47

Table 14
Related research topics.

Related topics	Topic cluster	Relatedness	TP
Technological Progress; Sustainable Technology; Environmental Regulations	Biodiesel; Diesel Engines; Engine Cylinders	93.80%	12
Core Industries; Air Quality Monitoring; Greater China	Hydrogen Storage; Hydrides; Dehydrogenation	92.80%	14
Distillation; Reactors; Iran	Distillation; Optimization; Distillation Columns	92.10%	8
Storage System; Automobile Industry; Inverter	Wind Turbines; Wind Power; Asynchronous Generators	91.90%	7
Oxyfuel; Dioxotechnetium; Carbon Capture	Amines; Carbon Dioxide; Flue Gases	91.40%	175
Clean Air Act; Systems Engineering Process; Climate Policy	Distillation; Optimization; Distillation Columns	90.30%	21
Automatic Frequency Control; Kore; Fuel Cells	Proton Exchange Membrane Fuel Cells (PEMFC); Electrocatalysts; Electrolytic Reduction	90.20%	22
Petrochemical Industry; Non-Energy Use; Greenhouse Gas Emissions	Amines; Carbon Dioxide; Flue Gases	90.10%	22

to create a list of standardized keyphrases. A list of standardized keyphrases is selected for each publication based on Inverse Document Frequency (IDF).

Keyphrases in green-hydrogen research were identified using Scival, and the top ten keyphrases were ranked based on total publications (TP), total citations (TC), and FWCI are shown in Fig. 5. Keyphrases like Hydrogen, Hydrogen Production, Hydrogen fuel, Hydrogen Economy, Electrolysis, Fuel Cell shown in green color are growing. Keyphrases like gas emissions, biofuel, and motor vehicles shown in blue are exhibiting a declining trend. In contrast, keyphrases like energy security, refueling, and the transport sector shown in gray color have stabilized.

Based on total publications (TP) and citations (TC), keyphrases greens, Hydrogen, and hydrogen production occupied the top three spots, as shown in Table 15. Ranking based on FWCI led to a completely different set of keyphrases — Solar, Electrocatalysts, Solar generators, indicating that publications with these keyphrases are attracting a higher than an average number of citations

3.3. Alignment with UN Sustainable Development Goals (SDG)

The UN Sustainable Development Goals (SDG) are specific objectives for research that address real-world challenges by 2030. Authors can earn SDG labels for their work, which will boost their visibility and impact their funding applications while demonstrating the benefit of their research. Today only 10% of world academic research output is related to the 17 SDG (Wastl et al., 2020). While analyzing how green-hydrogen researchers contribute to SDG, we have focused on two specific SDG, namely, Affordable and Clean Energy (SDG 7) and Climate Action (SDG 13), relevant to our green-hydrogen research topic, and the results are shown in Table 16. Both these SDG have the most significant number of publications and citations. They also have AAS of 9.61 and 13.78, respectively, indicating interest in green-hydrogen in social media platforms.

Countries with the most significant number of publications aligned with the SDG are portrayed in Table 17. Looking at specific SDGs, China, Germany, and the US are the most critical contributors to green-hydrogen publications that align with SDG.

Curiously we looked at the Sustainable Development Report (Sachs et al., 2021) to understand where each country stands about achieving the 17 SDG and specifically looked at an indicator in SDG 7 (affordable and clean energy) in total primary energy supply (%) that had relevance to the green-hydrogen research. In the SDG report, countries are ranked by their overall score. A country's overall score indicates whether it is on track to achieve all 17 SDGs. A score of 100 indicates that all SDGs have been achieved.

Germany, which is second highest in green-hydrogen publications and is ranked 4th in the SDG index, has 14.6% as a share of affordable and clean energy in the total primary energy supply. The United States, ranked third in publications and is ranked 32nd in the SDG index, has a somewhat lower 7.9% share of affordable and clean energy in the total primary energy supply. Italy, ranked 26th in the SDG index, has the highest 18.2% share of affordable and clean energy in the total primary energy supply.

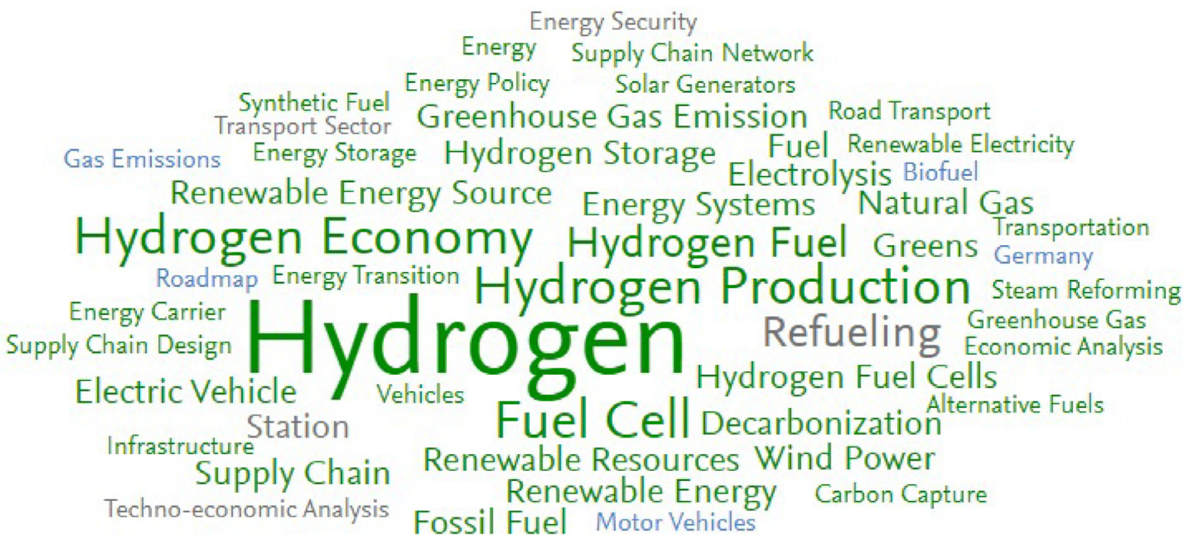

Fig. 5. Keyphrases about green-hydrogen research. Color legend: declining A A A growing.

Table 15
Top keyphrases according to publications, citations, and citation impact.

Ranked by publications				Ranked by citations				Ranked by citation impact			
Keyphrases	TP	TC	FWCI	Keyphrases	TC	TP	FWCI	Keyphrases	FWCI	TP	TC
Greens	609	6,128	10.6	Greens	6,128	609	10.6	Solar	21.5	73	2,229
Hydrogen	565	5,607	10.6	Hydrogen	5,607	565	10.6	Electrocatalysts	16.7	69	698
Hydrogen Production	326	4,072	13.3	Hydrogen Production	4,072	326	13.3	Solar Generators	15.1	64	1,579
Electrolysis	215	2,051	11.9	Solar	2,229	73	21.5	Oxygen Evolution Reaction	15.1	49	457
Renewable Energy	138	1,117	9.2	Renewable Resources	2,057	108	13.5	Natural Gas	14.5	59	1,161
Catalyst	123	1,285	10.2	Electrolysis	2,051	215	11.9	Hydrogen Evolution	14.5	37	525
Renewable Resources	108	2,057	13.5	Hydrogen Storage	1,628	95	10.7	Hydrogen Economy	14.2	62	790
Renewable Energy Source	96	711	10.6	Solar Generators	1,579	64	15.1	Renewable Resources	13.5	108	2,057
Hydrogen Storage	95	1,628	10.7	Catalyst	1,285	123	10.2	Wind Power	13.4	56	469
Fuel	83	766	9.2	Natural Gas	1,161	59	14.5	Hydrogen Production	13.3	326	4,072

Table 16
Green-hydrogen research alignment with UN Sustainable Development Goals (SDG).

SDG	TP	TC	AAS
7 Affordable and Clean Energy	634	5,633	9.61
13 Climate Action	393	3,495	13.78
12 Responsible Consumption and Production	26	71	2.44
11 Sustainable Cities and Communities	6	13	0
2 Zero Hunger	1	0	0
3 Good Health and Well Being	1	0	0
6 Clean Water and Sanitation	1	0	0
8 Decent Work and Economic Growth	1	1	0
16 Peace, Justice and Strong Institutions	1	2	4

We specifically looked at publications whose research was aligned with Affordable and Clean Energy (SDG 7) and Climate Action (SDG 13) due to their relatedness to the green-hydrogen topic. As seen in Table 18, the top two publications (TC:823, TC:480) are the same as the two most influential publications, as per Table 7. This indicates that the publications aligned to SDG 7 & SDG 13 are the most influential and that affordable and clean energy and climate action are increasingly becoming an area of study about green hydrogen. This is further strengthened by the publication titled "Toward practical solar hydrogen production an artificial photosynthetic leaf-to-farm challenge" which features in top publications aligned with SDG 7 and SDG 13 (TC:284) and features the third most influential publication as well as per Table 7.

Under UN SDG, we also analyzed the various Fields of Research (FoR) for green-hydrogen. FoR classification is a component of the Australian and New Zealand Standard Research Classification (ANZSRC) system. Table 19 shows FoRs ranked by total publications (TP) under three SDG, namely — SDG 7 (Affordable and Clean Energy), SDG 13 (Climate Action), and SDG 12 (Responsible Consumption and Production). Engineering as a field of research contributes the highest number of publications in SDG 7 (TP:413), SDG 13 (TP:277), and SDG 12 (TP:19), respectively. Chemical science is the second-highest contributor to SDG 7 (TP:236), SDG 13 (TP:124), and SDG 12 (TP:11), respectively. The top eight FoRs belong to engineering, indicating a growing interest in research on renewable energy and sustainable energy sources.

4. Conclusions

This paper discusses and analyzes the research trends and potential of green-hydrogen, produced by the electrolysis of water and from renewable energy sources while posing no threat to the environment.

We analyzed 642 Green-hydrogen research publications by 2809 authors from 73 countries published between 2016 and 2021. The overall citations per publication are high at 9.4. An average of 29.9% of publications per year have international co-authors. Open Access publications increased and accounted for about 44% of the total publications. Noteworthy is the output of over 50% of the publications from the Top 10% Journal Percentiles, confirming the high-quality output and the interest of the top journals in the topic of green-hydrogen. The versatility of possible applications of stored hydrogen is the reason why research on this technology occupies an important place among R&D works related to renewable energy infrastructure (Widera, 2020). China,

Table 17
Countries with the most significant number of publications aligned with UN SDG.

SDG	China	Germany	USA	Italy	UK	S Korea	Australia	India	France	Spain
7 Affordable and Clean Energy	99	63	50	37	32	30	29	22	21	21
13 Climate Action	46	37	30	24	24	17	20	11	12	17
SDG Index Rank	57	4	32	26	17	NA	35	120	8	20
Share of renewable energy in total primary energy supply (%)	NA	14.6	7.9	18.2	12.4	NA	7.1	NA	10.68	14.7

Table 18
Publications aligned with SDG 7 and SDG 13.

SDG	Title	TC	Year	TC/Y
7 Affordable and Clean Energy 13 Climate Action	A comparative overview of hydrogen production processes	823	2017	164.6
7 Affordable and Clean Energy	Metal-Free 2D/2D Phosphorene/g-C3N4 Van der Waals Heterojunction for Highly Enhanced Visible-Light Photocatalytic H2 Production	480	2018	120.0
7 Affordable and Clean Energy 13 Climate Action	Hydrogen Production by PEM Water Electrolysis - A Review	337	2019	112.3
7 Affordable and Clean Energy 13 Climate Action	Toward practical solar hydrogen production, an artificial photosynthetic leaf-to-farm challenge	284	2019	94.7
7 Affordable and Clean Energy	Bifunctional Heterostructured Transition Metal Phosphides for Efficient Electrochemical Water Splitting	116	2020	58.0

Table 19
Fields of Research (FoR) under UN SDG according to publications.

Fields of Research	SDG 7 (Affordable and Clean Energy)	SDG 13 (Climate Action)	SDG 12 (Responsible Consumption and Production)
Engineering	413	277	19
Chemical Sciences	236	124	11
Physical Chemistry	223	118	8
Materials Engineering	157	87	3
Environmental Engineering	152	113	11
Chemical Engineering	132	92	8
Interdisciplinary Engineering	41	29	0
Inorganic Chemistry	29	9	1
Economics	20	14	0
Applied Economics	16	11	0

Germany, and the US are the most significant contributors to green-hydrogen publications aligned with SDG. China has the most considerable number of publications that the Chinese government funds. This paper only looks at outputs (i.e. papers and citations). It is also important to look at inputs (i.e., investments and spending on R&D). In many countries, the implementation of green hydrogen on the path to compacting climate change and being the key to decarburization is gradually increasing (IEA, 2019). China has a strong commitment to reducing carbon emissions with ambitious targets. As such China has made significant investments in alternative propulsion for vehicles, first with electric vehicles and now also with green hydrogen. While most of the top institutions are from Europe and Asia, the top citations per publication TC/TP are from Australia.

We find networks of four journal research clusters that provide new information on the nature of journal contributions to green-hydrogen research. These belong to clusters of materials chemistry, hydrogen energy and cleaner production, applied energy, and fuel cells. Three indicators in Scival are used to calculate the momentum of the topic, namely — citation counts, publication views, and average CiteScore. Combining prominence percentile, publication growth, and FWCI, we highlight new hotspots of green-hydrogen research from different perspectives. Three topics with high prominence percentile are Oxygen Production (99.998) followed by Water Splitting (99.979) and Cathodes (99.941) and take up 15 percent of the total publication shares. Hydrogen Economy and regenerative fuel cells have many publications and publication shares. Ranking based on FWCI led to entirely different set keyphrases — Solar, Electrocatalysts, Solar generators, indicating that publications with these keyphrases were getting more citations.

We find four major thematic distributions of green-hydrogen research based on keyword co-occurrence networks: hydrogen storage, hydrogen production, electrolysis, and the hydrogen economy.

1. Hydrogen Storage — Research in solid-state hydrogen storage material is an important area of research. Green-hydrogen supports energy security by diversifying the supply of energy and storing and converting energy between Hydrogen and electricity (Clark II and Rifkin, 2006). Hydrogen Storage is an enabling technology for fuel-cell-powered vehicles, portable and stationary power. An important area of research is in new hydrogen storage materials. Other topics in this cluster include renewable energies, energy storage, Inverter, Asynchronous Generators, Wind turbines, solar power generators, and Automobile Industry.

2. Hydrogen Production — Hydrogen is an energy carrier that can store, move, and deliver energy produced from other sources. Encouragingly, our keyphrase analysis showed that Fuel Cell is an increasing keyphrase in the green-hydrogen publications suggesting an increase in research that directly supports SDG7 and SDG11. Regenerative fuel cells have many publications (TP) and publication share but a lower prominence percentile and are likely to be a research frontier. This cluster includes Hydrogen production, Hydrogen, solar power generation, fossil fuels, and refueling.

3. Electrolysis — Electrolysis is a technological tool for enhancing the production of green-hydrogen and allows for the industrial application of Hydrogen. In the green-hydrogen research, the Electrolysis keyphrase had the third-largest TP of 49. Photocatalytic decomposition of water to Hydrogen is a crucial research area. Three topics with high prominence percentile are Oxygen Production (99.998) followed by Water Splitting (99.979) and Cathodes (99.941) and take up 15 percent of the total publication shares

4. Hydrogen Economy — The transport sector, energy security motor vehicles green-hydrogen has a high production cost driven by the cost of electrolyzer and electricity. Research and development of lower-cost fuel cells and industry-scale deployment

of electrolyzers used in industrialization and transportation will lower the production cost and sustainably support the Green-hydrogen economy. Hydrogen economy includes transportation, vehicles, shipping, steelmaking, heating, and aviation.

We consider increasing declining and stabilized keyphrases to understand the research direction. Keyphrases analysis shows that Hydrogen Production, Hydrogen fuel, Hydrogen Economy, Electrolysis, and Fuel Cell are growing, suggesting higher research interest in the above four thematic clusters. In contrast, keyphrases such as gas emissions, biofuel, and motor vehicles show a declining trend. The keyphrases such as energy security, refueling, and the transport sector have stabilized.

Noteworthy in this study is that most of the research was aligned to Affordable and Clean Energy (SDG 7) and Climate Action (SDG 13), including 96.5% of the TP, 99% of the TC, and 78.4% of the TP Attention Altmetric Score. Some countries, such as Germany, with high green-hydrogen publications, have a high SDG Index Rank and a good share of renewable energy in the total primary energy supply, demonstrating their commitment to research and practice. Italy, which is ranked 26th in the SDG index, has the highest 18.2% share of renewable energy in the total primary energy supply.

There has been an increased demand from world leaders to fight against climate change since 2015, which also points to the increase in research on sustainable energy solutions. In 2015, world leaders meeting at the 21st Conference of the Parties (COP21) in Paris set ambitious new goals in the fight against climate change which was followed up by a leaders' summit at the 25th Conference of the Parties (COP25) took place in Madrid, Spain, on December 2, 2019. The World Leaders Summit COP26 in 2021 brought together the 197 parties to the UN Framework Convention on Climate Change (UNFCCC). At the beginning of 2021, more than 30 countries have released hydrogen roadmaps, with governments worldwide funding more than \$ 70 billion, and 75 countries, which account for more than half of world GDP, setting zero carbon ambitions. The global hydrogen market is expected to grow from 70 million tonnes in 2019 to 120 million tonnes in 2024 (Safari and Dincer, 2020). More than 200 hydrogen projects are now in the value chain, with 85% of global projects coming from Europe, Asia, and Australia, and activity in America, the Middle East, and North Africa is also fast catching up. The total number of completed projects will exceed \$ 300 billion in hydrogen spending by 2030 — the equivalent of 1.4% of the Global Energy Fund. With the advent of hydrogen-scale projects, the cost of producing Hydrogen could continue to fall. However, short-term costs are not enough for change as short-term production of pure Hydrogen, value chains for electrolysis, and carbon management needs to be increased.

Countries from Asia and developing economies such as India are well-suited for Hydrogen production, due to the availability of both solar PV and onshore wind, and solar PV has the lowest renewable generation costs, with both solar PV and the onshore wind among the cheapest in the world (NREL, 2020). If India were to scale up green-hydrogen production, solar PV would be the primary source of renewable electricity. Annual additions of distributed PV are increasing thanks to policy initiatives in China, the European Union, and India stimulating the deployment of commercial and residential projects. The cost-competitive target price for green-hydrogen production is US\$2/kg. The expected reduction in solar PV wind power cost and policy support for increasing the installed capacity of expected electrolyzer plant capital cost will drop significantly as installed capacity increases and overtime (Beagle et al., 2021). Overall, the demand for biofuel is expected to more than double to near 9% a year. The policy discussions in the United States, Europe, India, and China will profoundly impact biofuel prospects in the next five years. If implemented, policies under discussion in these countries would account for two-thirds of this growth and Asia would account for the most significant upside surpassing Brazil to become the second-largest biofuel producer globally.

Green-hydrogen is an emerging area of study, with most of the research aligned to Affordable and Clean Energy (SDG 7) and Climate Action (SDG 13). 50% of the publications from 2016-to 2021 are from the Top 10% Journal Percentiles, confirming the high-quality output and the interest of the top journals in the topic of green-hydrogen. In the future, the countries would be focusing on zero-carbon ambitions with the COP26 World Leaders Summit giving a renewed thrust. With more than 200 hydrogen projects in the value chain, the focus in the future would be on a green hydrogen economy and a cost-competitive target price for mass adoption. Hydrogen is not yet close to being cost-competitive for electricity purposes or mobility purposes (Dong et al., 2022). Hydrogen is a promising energy vector/carrier, but today's production and exploitation methods are not in line with long-term environmental and energy goals (Jovan and Dolanc, 2020). Green hydrogen has a role in achieving a highly electrified net-zero economy. The potential usage of green hydrogen will depend on more than its environmental friendliness. Economic, technical, and safety factors must be assessed (Atilhan et al., 2021). A combination of private-sector collaboration and policy support may drive the initial ramp-up of clean hydrogen production and use to reach 50 million tonnes by 2030, and this needs to be probed more. In the future, studies may be carried out to understand what it will take to accelerate the usage of green hydrogen in the future to achieve net-zero, how to make the hydrogen economy possible and developing transport and storage infrastructure for green hydrogen. Further studies may be carried out on the hydrogen production cost of green, blue, and gray hydrogen. Green hydrogen presents opportunities for economic growth and job creation (Abad and Dodds, 2020), and this aspect too may be probed in future research.

5. Limitations

Like any bibliometric study, this study also has some limitations and considerations limiting the current study findings. Bibliometric data from scientific databases are not produced exclusively for bibliometric analysis and, therefore, can contain errors. Some articles on green-hydrogen research may have been missed if green-hydrogen is not mentioned in the title, abstract, or keywords. In the statistical analysis part, this may have resulted in some discrepancies. Both citation impact and co-citations tend to develop over time. The number of citations depends on the article's age, and the older the article more maybe its citations (Biemans et al., 2007). There are some limitations with the tools used in this study, i.e., Scival Field Weighted Citation Impact & Altmetrics. Field Weighted Citation Impact should not be interpreted as a direct measure of research quality, and the limitation of Altmetrics is that it does not consider the sentiments of mentions made about research objects and thus does help understand the positive or negative attention that a publication has received. Attention does not necessarily indicate that the article is necessary or even of quality, and the score may indicate popularity with the public, but not necessarily quality research.

CRediT authorship contribution statement

Raghu Raman: Conceptualization, Methodology, Data curation, Writing and editing. **Vinith Kumar Nair:** Writing and editing, Data curation. **Veda Prakash:** Data curation, Visualization. **Anand Patwardhan:** Reviewing and editing, Information. **Prema Nedungadi:** Writing, Reviewing and editing, Information.

Declaration of competing 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.

Data availability

The data that has been used is confidential.

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