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Bibliometrics Analysis of Emerging Trends in Seawater Electrolysis for Hydrogen Production in Sustainable Energy

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Abstract

The Industrial Revolution created a significant demand for energy, primarily relying on non-renewable resources such as petroleum, natural gas, and coal. While these resources have driven human progress, they have also caused severe environmental issues, including ozone depletion, increased carbon emissions, deforestation, and geopolitical tensions. Addressing these challenges requires the development of stable and sustainable renewable energy sources. The commitment to reducing carbon emissions under the Paris Agreement reflects decades of global efforts to advance renewable energy. Despite advancements in solar and wind energy, their inherent intermittency and dependence on climate conditions limit their ability to fully replace traditional energy sources. Green hydrogen, known for its high energy density and carbon-neutral extraction process, is considered a promising, sustainable renewable energy source. Its production results in only water and heat. By analyzing various research literature on seawater electrolysis, this study statistically and graphically presents key factors, highlighting crucial trends in advancing seawater hydrogen production technology. This research provides important insights and directions for the future development of seawater hydrogen production.

Highlight

1. This field primarily focuses on chemistry, and the lack of integration with experts in electricity or electromagnetism may affect the efficiency and stability of the electrolysis process.

2. Research related to seawater hydrogen production has been increasing year by year, indicating growing global attention in this field.
3. Break throughs are making hydrogen production cheaper, and the fast growth of hydrogen energy use is speeding up our progress toward net-zero carbon emissions. At the same time, it’s helping to ease energy crises caused by geopolitical issues.

Keywords: Seawater Hydrogen, Electrolysis, Bibliometrics, Sustainable, Trends, Renewable energy.

1. Introduction

The world is facing critical energy issues, including global warming, climate change, the fossil fuel crisis, and the greenhouse effect. Additionally, geopolitical risks between nations threaten energy resources. These complex issues require swift action and a commitment to developing renewable energy for a sustainable, low-carbon future. Global warming and climate change have become major global concerns, attracting significant international attention. The increase in extreme weather events, glacier retreat, sea-level rise, and intensified seismic activities highlight the severity of these problems. Their impact extends beyond environmental and human threats, significantly affecting global economic and social stability. Therefore, adopting renewable energy policies is crucial for nations

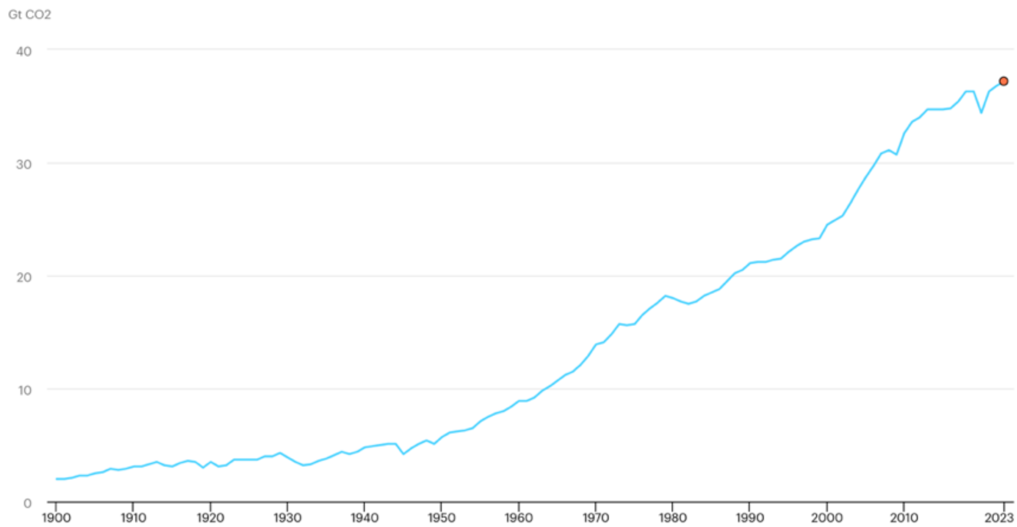

Figure 1: IEA (2024), total increase in energy-related CO2 emissions, 1900-2023, IEA, Paris https://www.iea.o rg/data-and-statistics/charts/total-increase-in-energy-related-co2-emissions-1900-2023, License: CC BY 4.0

to address these challenges collectively. This chart (Figure 1) shows carbon emission statistics from the IEA, rising from 2Gt in 1900 to 37.2Gt in 2023. Despite the Paris Agreement's efforts since 2015 to develop renewable energy and combat global warming, carbon emissions have not decreased as expected. This alarming situation underscores the importance of hydrogen energy in addressing global warming.

The fossil fuel crisis underscores the dangers of over reliance on finite resources. The uneven distribution of energy resources has triggered geopolitical competition and market volatility, causing global economic instability. Accelerating renewable energy development, reducing reliance on non-renewable resources, and promoting energy diversification are key strategies. Renewable sources like solar, wind, hydro, hydrogen, nuclear, and geothermal energy are emerging, offering clean alternatives. Solar and wind energy are becoming significant components of the global energy structure. The development of these sources reduces reliance on finite resources and mitigates environmental impacts [1, 2]. The chart (Figure 2) presents statistical data from 2000 to 2028, illustrating a consistent growth trend for all renewable energy sources (indicated by blue arrows). However, carbon emissions continue to rise yearly. The usage of various energy sources from 1990 to 2021 shows an increase in traditional energy use Table 1. Coal usage has nearly doubled, natural gas usage has more than doubled, and oil usage has increased by 0.5 times. Hydrogen combustion produces only water vapor, achieving zero emissions. Its high energy density makes it an ideal long-term energy source, with wide applications including fuel cell vehicles, industrial production, power generation and energy storage, and it can stabilize renewable energy supplies. Hydrogen is abundant on Earth and can be extracted from water, natural gas, and biomass. Renewable hydrogen is produced through water electrolysis using renewable energy sources such as solar or wind power, ensuring an environmentally friendly and sustainable production process. Water electrolysis for hydrogen production is a renewable and efficient method but currently, most systems use limited freshwater resources. Seawater is abundant and directly electrolyzing seawater can also produce high-purity freshwater, achieving both seawater desalination and hydrogen production. However, the ions microorganisms and particles in seawater can cause side reactions, catalyst deactivation and membrane fouling issues. There are two technical routes for seawater hydrogen production, direct seawater electrolysis and indirect hydrogen production [3, 4]. Indirect hydrogen production involves desalination followed by electrolysis and has been commercialized, but direct seawater electrolysis technology still faces challenges. Through this study, we focus on analyzing and

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understanding the technical hot spots, the distribution of expertise and development trends in seawater electrolysis for hydrogen production. This will be beneficial for the future development of the hydrogen energy sector.

Table 1: Total energy/(M)/ Unit: TJ

Year	Coal	Natural	Nuclear	Hydro	Wind,solar,etc.	Biofuels, waste	Oil
1990	93,0	69,6	22,0	7,6	1,5	30,7	135,5
2021	168,1	145,9	30,6	15,4	16,8	58,4	182,2

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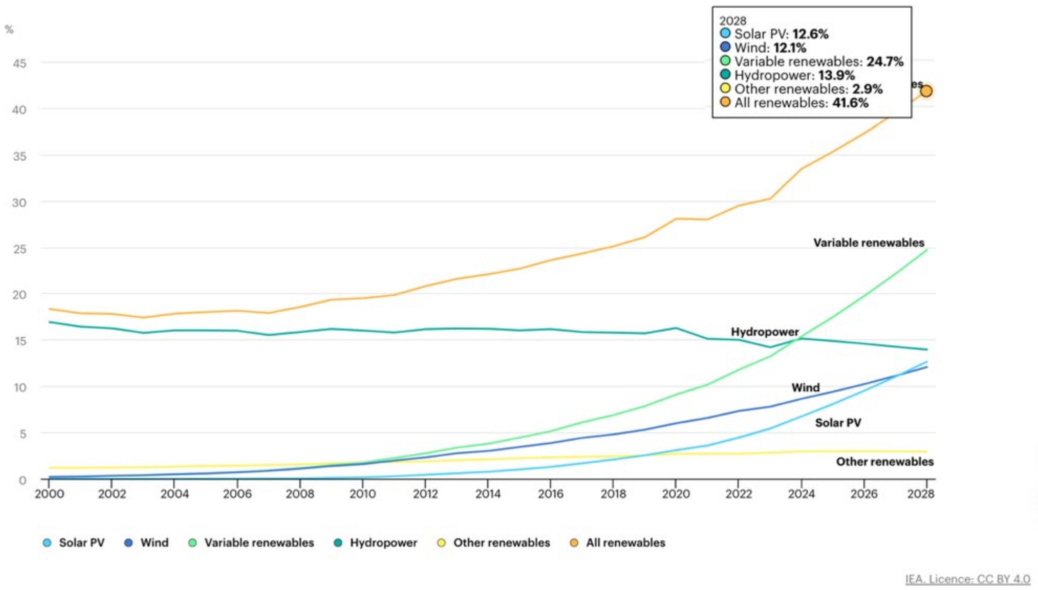

Figure 2: IEA (2024), Share of renewable electricity generation by technology, 2000-2028, IEA, Paris https://www.i ea.org/data-and-statistics/charts/share-of-renewable-electricity-generation-by-technology-2000-2028, License: CC BY 4.0

2. Literature Review

The Paris Agreement [5]is a historic global climate accord aimed at addressing global climate change [6]. Adopted by the Conference of the Parties to the United Nations Framework Convention on Climate Change in 2015, the agreement officially entered into force in 2016. Its objective is to limit the increase in global average temperature to well below 2 degrees Celsius above postindustrial levels, while pursuing efforts to limit the temperature increase to 1.5 degrees Celsius to mitigate the impacts of extreme weather events and sea-level rise. The Paris Agreement is legally binding, requiring each party to develop specific action plans (known as nationally determined contributions) to reduce greenhouse gas emissions and undergo regular monitoring and review. Methods of hydrogen production include direct and indirect use of seawater [7]. Direct utilization involves electrolysis or photolysis, while indirect utilization requires desalination and purification of seawater to convert it into high-purity freshwater before hydrogen production. Seawater hydrogen production faces several technical challenges [8–10]. Seawater contains a significant number of impurities which can impact the efficiency of the hydrogen production process, particularly causing to electrode blockage and catalyst deactivation during electrolysis. Additionally, chloride ions in seawater may cause corrosion of the anode, affecting the progress of the oxygen production reaction [11–13]. Furthermore, there is competition between the oxygen chloride reaction and oxygen evolution reaction at the anode, posing challenges for the hydrogen production process. Seawater direct electrolysis is a method of directly electrolyzing seawater to produce hydrogen and oxygen. In recent years, significant strides have been made in seawater hydrogen production, particularly in the realm of direct seawater electrolysis. These advances have been driven by significant investments from countries around the world and have resulted in significant progress. It is worth noting that Dr. Xie Heping, a distinguished academician of the Chinese Academy of Sciences, has made significant contributions in this field. His research has focused on the efficacy of direct seawater electrolysis for hydrogen generation. Dr. Xie's work has successfully transitioned from theoretical exploration to practical application, underscoring the pivotal role of hydrogen energy in the future landscape of renewable resources [14]. Additionally, research teams at the University of Adelaide in Australia have also played a significant role in advancing direct seawater electrolysis methodologies [15], this study aims to conduct a comprehensive analysis of the developmental trajectories and scholarly literature relevant to seawater electrolysis. By reviewing existing literature libraries, you can gain insights into publication trends and various trend indicators of hydrogen research in various countries. Furthermore, this analysis seeks to quantify the extent of scholarly output in this domain, providing valuable metrics for evaluating the state of research and identifying areas for further exploration [16]. Bhutto. explored the potential and development activities of hydro power, highlighting the role and challenges of hydro power in clean energy supply [17], which provides insights into the development of seawater electrolysis

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technology [18–21] discussed the material challenges in nuclear energy, emphasizing the critical role of materials science in the development of energy technologies, which is also applicable to the research on electrocatalysts in seawater electrolysis technology. Speckmann, F. W., Keiner, D. and Birke, K. P. [22] analyzed the technology and diffusion of renewable energy, providing a theoretical foundation for understanding the application of seawater electrolysis technology in the field of renewable energy. Becker, W. L., Penev, M., and Braun, R. J. (2019). studied the efficiency of hydrogen production from renewable resources, pointing out the challenges and opportunities in the economic feasibility and efficiency of this technology [23]. Konoplyanik, A. studied the promotional impacts of green power products on renewable energy sources, proposing direct and indirect eco-effects [24]. Amrouche, emphasized the importance of energy storage technologies in renewable energy systems [25], providing references for the energy integration of seawater electrolysis technology, Liu (2024) showcased an energy-saving hydrogen production method through chlorine-free hybrid seawater splitting coupled with hydrazine degradation [26], emphasizing the development of new reaction path-ways. Huang et al. examined the trends in global research in forest carbon sequestration [27], which parallels the potential of seawater electrolysis technology in reducing carbon emissions. Raman conducted a bibliometric analysis of green hydrogen research, summarizing the major advancements and future directions in this field [28]. Tarhan and C¸ investigated hydrogen storage methods, highlighting the importance of efficient hydrogen storage technologies for the application of hydrogen energy [29]. Zhao, B. explored the anomalous hydrogen evolution behavior induced by locally generated hydronium ions in high-pH environments, showcasing new hydrogen production mechanisms in highly alkaline environments [30]. Van De Graaf studied the geopolitics and international governance of hydrogen, proposing the strategic position of hydrogen energy in the global energy market [31]. Yu et al. developed a sandwich-like NiCoN/Ni_xPINiCoN[1] micro sheet

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[1] **1. NiCoN**

- **NiCoN** stands for **Nickel-Cobalt Nitride**, comprising elements Nickel (Ni), Cobalt (Co), and Nitrogen (N).
- **Applications and Properties**: Nickel-Cobalt Nitride is commonly used in electrocatalysis and energy storage applications, such as in hydrogen evolution reactions (HER) and oxygen evolution reactions (OER) in water electrolysis. This compound is valued for its conductivity, chemical stability, and relatively low cost. It also offers excellent catalytic activity and corrosion resistance, making it suitable for stable operation at high current densities.

2. NixPINiCoN

array catalyst [32], enhancing the efficiency of seawater electrolysis hydrogen production, demonstrating innovations in catalyst design.

3. Methodology and Data source

When we organize the collected literature data, which includes sorting journal titles, author names, affiliations, author keywords, and citation counts, we subsequently conduct data purification using Biblioshiny software in R language to ensure data accuracy and consistency. During the evaluation phase, researchers analyze citation counts, publication trends, international cooperation among countries, authorship and collaborations, journals, and highly cited journals, as well as related keywords [28]. Finally, research findings are reported in the form of tables, data graphs, and key terms. It's important to note that some keywords may not be included. This research methodology corresponds to a "Systematic Literature Review" (SLR) in management studies. SLR is a method used to systematically gather, assess, and interpret existing research to provide a comprehensive summary and insights into specific research questions or topics [33]. This approach is widely applied in management research to ensure comprehensiveness, transparency, and repeatability of studies.

3.1 Methodology

The R language, developed by Robert Clifford Gentleman in 1995, it is a free and open-source programming language for statistical computing and graphics. It's based on the S language and offers rich statistical functions, flexibility, scalability, and extensive community support. R is widely used in bibliometric analysis, which evaluates the output, trends, and impact of literature [34]. It's a key application include data processing and cleaning, where R handles large volumes of literature data efficiently, statistical analysis, supporting various methods and models to help

- **NixPINiCoN** indicates a variable composition of Nickel-Cobalt Nitride, possibly incorporating the variable **x** and another element **P** (Phosphorus), allowing for adjustment of specific element proportions within the compound.
- **Applications and Properties**: Materials like NixPINiCoN, with flexible compositions, are optimized for various applications, such as in fuel cells, supercapacitors, and hydrogen production through water electrolysis. Adding phosphorus not only reduces costs but also improves the stability of the material under low to medium temperature conditions.

researchers understand trends and correlations, and visualization, generating diverse charts and plots that aid in the intuitive presentation of bibliometric analysis results. R is an open-source nature and extensive package support enable researchers to extend its functionality. By analyzing literature data from the Web of Science (WOS) using R, we identify trends in desalination technology from 2017 to 2023. We examine keywords, authors, institutions, and countries to understand the evolution of topics related to seawater desalination technology. Co-authorship analysis using Bibloshiny reveal the collaborative structure among article authors.

3.2 Data Sources

WOS (Web of Science) is used to retrieve data for this study's bibliography. The Web of Science database, established by the Institute for Scientific Information (ISI) in 1956, was founded by Eugene Garfield in the 1960s and is a pioneer in information retrieval. Web of Science is known for its multidisciplinary scope, high-quality literature re- sources, citation indexing, and robust search capabilities. It indexes articles primarily in major citation indexes like SCI (Science Citation Index), SSCI (Social Sciences Citation Index), and EI (Engineering Index). These indexes include academic journal articles, conference papers, patents, and other publications across natural sciences, social sciences, and engineering technology. Consequently, articles in Web of Science are high-quality, well-regarded, and widely cited by researchers. The primary reason for using WOS in this study is the high quality of its indexed literature, including SCI, SSCI, or EI indexing. This ensures the reliability and accuracy of the data, enhancing the precision of the study's conclusions.

4. Results

The research focused on scholarly articles related to seawater electrolysis for hydrogen production from 2013 to 2023. A total of 13,864 relevant papers.
The study collected and analyzed data using the Web of Science (WOS) database, employing R language and Biblio-shiny software for data mining based on keywords such as "trend" "hydrogen," and "seawater electrolysis" According to Bradford's Law, over 80% of relevant articles were published in the International Journal of Hydrogen Energy. The charts (Figure 3) indicate that the main research focuses on Hydrogen Evolution Reaction (HER), Oxygen Evolution Reaction

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(OER), hydrogen production, and electrocatalysis. Significant progress has been made, but developing cost-effective and efficient catalysts remains challenging.
For instance, a 2016 article on bifunctional oxygen electrocatalysts derived from metal-organic frameworks has been cited 2,070 times, highlighting its efficiency in oxygen reduction and evolution reactions. Additionally, a 2014 study on nanoparticles grown on carbon fiber paper as HER electrocatalysts has been cited 1,213 times, demonstrating their stability and efficiency. A 2020 study on self-supported transition metal-based electrocatalysts

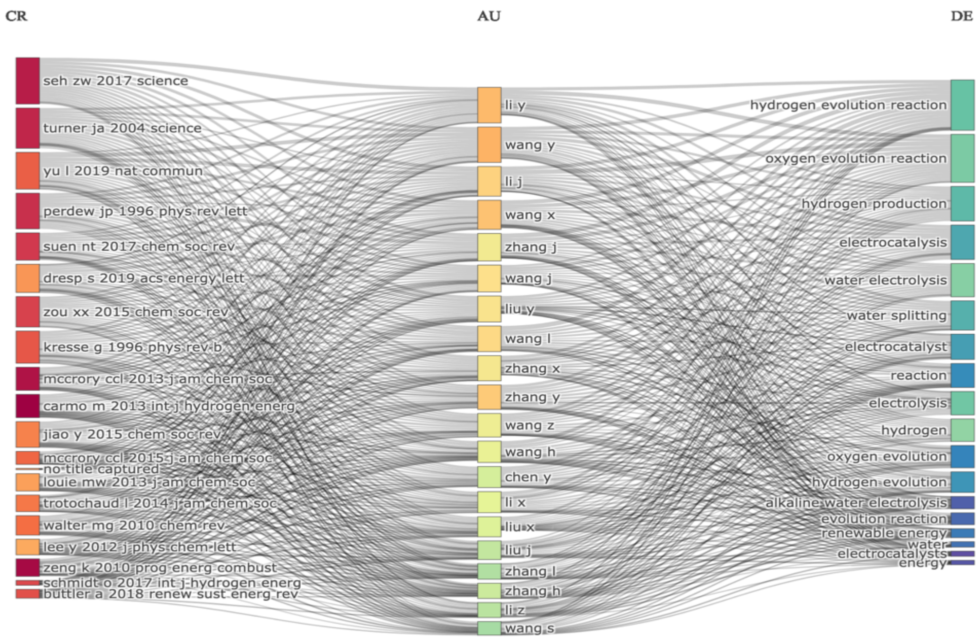

Figure 3: The Sankey of sources, authors, and keywords

for hydrogen and oxygen evolution reactions has received 1,043 citations. These studies are crucial for developing sustainable and efficient energy systems, with their high citation rates indicating significant influence within the scientific community.

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4.1 Data analysis

The data (Table 3) show the number and proportion of different types of academic documents within the overall literature. According to the data in the table, journal articles are the predominant form of literature, totaling 12,995, which accounts for 97.75% of the total. This indicates that researchers primarily publish their findings through journal articles. The remaining research materials are very few, accounting for approximately 0.25%.

4.1.1 Annual indicators of publications

In this research field, trends in annual publication indicators show development dynamics over specific periods. The increasing number of publications reflects the growing importance and popularity of research in this area [35] Figure 6. Although research on hydrogen energy started in 1979, it truly accelerated in 2014. The sharp rise from 439 publications in 2014 to 2,963 in 2023 indicates rapid development in seawater hydrogen production research. Analyzing the top ten most-cited journals related to seawater electrolysis for hydrogen production valuable insights. The citation count of a journal reflects its influence and authority in a specific field. For instance, the International Journal of Hydrogen Energy (INT J HYDROGEN ENERG) ranks first with 47,354 citations, under- coring its central role in hydrogen energy research. Other highly cited journals, like the Journal of the American Chemical Society (J AM CHEM SOC) and Journal of Materials Chemistry A (J MATER CHEM A), also show their notable impact in the fields of chemistry and materials science.

The high citation counts of these journals span multiple disciplines such as chemistry, materials science, energy, and environmental science. This indicates that seawater electrolysis for hydrogen production is a multidisciplinary research area, drawing researchers from various academic backgrounds to address related issues. The high citation numbers also reflect the strong interest from researchers in this filed. As the importance of renewable energy and green technologies grow, seawater electrolysis for hydrogen production has become a research hotspot [36]. Many articles in these highly cited journals likely address challenges such as electrolyte corrosion, catalyst efficiency, and economic feasibility. By analyzing these papers, researchers can identify existing technological bottlenecks and potentially find new solutions for future researchers. The data in Table 3 highlights the significant position and broad impact of seawater electrolysis for hydrogen production in current academic research, underscoring its importance and future potential in the field of hydrogen energy [37].

Table 2: Top 5 Highly cited articles

Rank	Title	SR	TC	TCP	PY	NTC
1	A metal-organic framework-derived bifunctional oxygen electrocatalyst	Guan d, 2021, adv mater	2,070	230.00	2016	34.67
2	Electrodeposition of hier- archically structured three-dimensional nickel-iron elec- trodes for efficient oxygen evolution at high current den- sities	Qureshi f, 2022, renew Sust energ rev	1,601	160.10	2015	26.82
3	Aanion-exchange mem- branes in electrochemical energy systems	Reiter g,2015 Int J Int J left cycle assess	1,486	135.09	2014.	23.93
4	Iin situ cobalt-cobalt oxide/n- doped carbon hybrids as su- perior bifunctional electro- catalysts for hydrogen and oxygen evolution	Ahmad j 2021,IEEE access	1,479	147.90	2015	24.77
5	Nanoparticles grown on car- bon fiber paper: an efficient and stable electrocatalyst for hydrogen evolution reaction	Chen jia-zhi cjz, 2016, chin j anal chem	1,213	110.27	2014	19.54

TC: **Total Citation, TCP: Total Citation per Year, NTC: Normalized Total Citation**

4.1.2 Highly cited publications

Highly cited publications refer to research papers that have significantly higher citation counts compared to other documents in the same field and period. These publications are typically used to measure the impact and importance of the research. Usually, the top 1% or top 10% of papers with the highest citation counts are considered highly cited, indicating that the work has been widely recognized and referenced. These indicators play a crucial role in scientific research evaluation and rankings. Here, we conduct a statistical analysis of citation data to identify key rankings in research literature related to seawater hydrogen production.

The h-index [38] measures both the productivity and citation impact of a researcher's publications. It is defined as the number of papers (h) that have been cited at least h times each. The formula for calculating the h-index is:

$$h = max\{h|c(h) \geq h\}$$

Where c(h) is the number of citations for the h-th most vited paper.

The g-index [38] improves on the h-index by giving more weight to highly cited papers. Its calculated such that the top g articles received together at least g^2citations, the formula for the g-index is.

$$g = max\left\{g|\sum_{i=1}^{g} C(i) \geq g^2\right\}$$

For example, the studies by Wagner, Zhang, and Leydesdorff [39] and Hausdorff and Bornmann [40] discuss methods for identifying and analyzing highly cited papers and their impact on research evaluation. In the field of seawater hydrogen production research, rankings based on total citations, citations per year, and normalized citations of publications reveal key trends and insights (Table 2). These highly cited publications highlight the development dynamics of this field, especially after 2014, with a significant increase in the quantity and quality of research Theses data indicate that seawater hydrogen production research is a rapidly growing area. Although related studies began as early as 1979, the real breakthrough occurred in 2014. The number of publications increased from 439

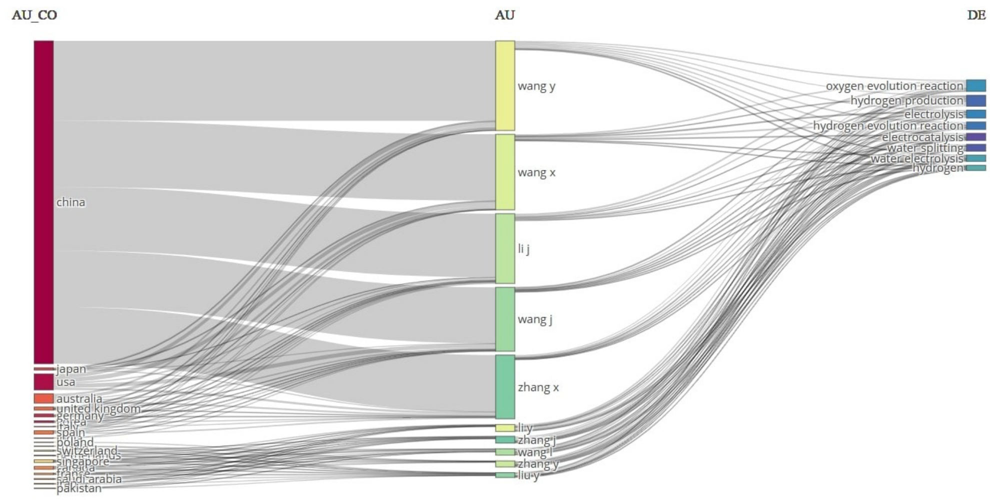

Figure 4: The top 10 of most productive countries

in 2014 to 2963 in 2023 (Figure 4), showing sustained growth in research activity. The number of highly cited

publications have shown a steep growth curve since 2014, reflecting the increasing importance and interest in this research area. Most of these studies are published in high-impact journals such as Nature Energy, Nature Communications, and the Journal of the American Chemical Society. The high impact factors of these journals further attest to the wide recognition and importance of these studies. For instance, the article by XIA BY published in Nature Energy in 2016, with 2070 citations, ranks first, demonstrating its significant influence in this field. In terms of annual citations, these publications have continued to receive attention over the years, indicating their lasting relevance and importance in scientific research. For example, the article by Sivanantham A. (2016) receives an average of 130.33 citations per year, showing its sustained impact. Highly cited publications reveal significant contributions from certain researchers and institutions in this field. These publications may come from specific prolific researchers and institutions, and studying their collaboration patterns may help understand research trends and dynamics. These publications often involve the development and application of new technologies, materials, or methods, which are the main drivers pushing forward seawater hydrogen production research. By deeply analyzing these highly cited publications, we can better understand the current status and future direction of seawater hydrogen production research. These studies not only enhance our understanding of seawater hydrogen production but also provide a valuable foundation and direction for future research. The studies by Wagner, Z hang, and Leydesdorff (2022) and Leydesdorff and Bornmann (2012) discuss methods for identifying and analyzing highly cited papers and their impact on research evaluation. These data indicate that seawater hydrogen production research is a rapidly growing area. Although related studies began as early as 1979, the real breakthrough occurred in 2014. The number of publications increased from 439 in 2014 to 2963 in 2023 (Figure 4), showing sustained growth in research activity.

Table3: Document type

Rank	Document type	No.	%
1	Article	12,995	97.75%
2	Early access	387	0.027%
3	Proceedings paper	338	0.024%
4	Review	124	0.0004%
5	Review; early access	6	0.0004%
6	Book chapter	4	0.00028%
7	Data paper	2	0.00014%
8	Correction	2	0.00014%
9	Meeting abstract	2	0.00014%
10	Publication with expression of concern	1	-
11	Retracted publication	1	-
12	Editorial material	1	-
13	Letter	1	-

Total documents: 13,864

Other notable journals (Table 4) include the Journal of Materials Chemistry A, which has rapidly gained high impact since its launch in 2014. With an h-index of 68, a g-index of 100, and an m-index of 6.182, it has accumulated 13,110 total citations, underlining its importance in the field of materials chemistry. Similarly, ACS Catalysis, Applied Catalysis B-Environmental, and Energy & Environmental Science are also highly influential in their respective research domains, significantly contributing to scientific research and technological advancements. Overall, these journals hold pivotal positions in their scientific research areas, and the high-quality research they publish plays a crucial role in driving the development of their respective fields.

Table4; Top 10 citation count of journal

Rank	Source	Articles
1	Int j hydrogen energy	47,354
2	J am chem soc	17,728
3	J mater chem	16,010
4	Angew chem int edit	15,092
5	Electrochim ACTA	14,958
6	J power source	13,976
7	Energ environ SCI	13,555
8	Adv mater	12,445
9	Nat commum	11,053
10	Apple catal b-environ	10,569

4.1.3 Journal Overview and Impact Parameter Analysis

The "Sources Local Impact" is a key metric for gauging a journal's influence in specific research fields by looking at how often and widely it's cited. This helps researchers pick the right journals to submit their work to boosting their impact and fostering academic collaboration. Funding and evaluation bodies also use this metric to make more informed decisions. So, Sources' Local Impact is a crucial tool for understanding a journal's importance in its field. It's the velocity of the projectile when it is far from the center. For simpler cases, such as scattering from a hard sphere, the relationship simplifies to:

$$Local\ impact = \sum_{i=1}^{n} (C_i x W_i)$$

C_i is the contribution or influence score of sources i in the local context. This could be measured by local citation count, usage metrics, participation in local events, or relevance to local issues. W_i *is* weight assigned to the contribution of source i, reflecting its importance or relevance in the local context. The n is the total number of sources considered. In the fields of hydrogen energy, materials chemistry, catalysis, environmental science, and energy, several journals have gained significant recognition due to their high impact. The relationship between the impact parameter b and the scattering angle θ can be expressed with the following equation:

$$\theta = \pi - 2b \int_{r_{min}}^{\infty} \frac{dr}{r^2 \sqrt{1 - \left(\frac{b}{r}\right)^2 - \left(\frac{2U}{mu_\infty^2}\right)}}$$

It's the velocity of the projectile when it is far from the center. For simpler cases, such as scattering from a hard sphere, the relationship simplifies to:

$$b = R \cos(\theta/2)$$

The R is the radius of the sphere. In the fields of hydrogen energy, materials chemistry, catalysis, environmental science, and energy, several journals have gained significant recognition due to their high impact. These journals include International Journal of Hydrogen Energy, Journal of Materials Chemistry A, ACS Catalysis, Applied Catalysis B: Environmental, Energy & Environmental Science, Applied Energy, ACS Applied Materials & Interfaces, Electro chemical Acta, Journal of Power Sources, and Nature Communications. The academic impact of these journals can be measured using various metrics, including the h-index, g-index, m-index, total citations (TC) and the number of published articles (NP). The h-index reflects the quantity of high-quality research published by a journal, the g-index considers the distribution of citation counts more broadly, and the m-index which is the h-index divided by the number of years of the researcher's career, compares the academic impact of researchers at different career stages.

Total citations and the number of published articles respectively indicate the overall impact and productivity of a journal. Among these journals, the International Journal of hydrogen energy stands out as the most prominent. Since its inception in 1992, it has been a leading journal in the field of hydrogen energy research. It boasts a h-index of 80, g-index of 122, and an m-index of 2.424, demonstrating the high quality and significant impact of the papers it publishes. With over 37,000 total citations, this journal has established a critical presence in hydrogen energy research, showcasing its extensive influence and publishes a large volume of high-quality research articles annually, significantly contributing to the advancement of hydrogen energy technologies.

Additionally with 1,343 published articles, it highlights its substantial contribution to the field.

Table 5: The top 10 Journal Overview and Impact Parameter

Source	h_index	g_index	m_index	TC	PY
International journal of hydrogen energy	80	122	2.424	37,102	1992
Journal of materials chemistry A	68	100	6.182	13,110	2014
Acs catalysis	62	105	4.769	11,529	2012
Applied catalysis b-environmental	60	87	3.158	9153	2006
Energy and environ-mental science	55	98	4.583	15,213	2013
Applied energy	54	83	4.154	8,757	2012
Acs applied materials and interfaces	51	77	4.636	7,868	2014
Electrochimica ACTA	50	75	4.545	9,326	2014
Journal of power source	49	72	4.083	7,960	2013
Nature communcations	47	90	4.273	12,514	2014

4.2 Analysis of the countries/ regions, institutions, and authors

Analyzing the roles of countries/regions (Table 6), institutions, and authors in academic research is a crucial data-driven study [41]. Such analyze primarily rely on extensive academic literature data from databases like Web of Science (WOS), Scopus and others, which record publication details of various academic journals and conference papers, including authorship, affiliations, and publication locations. MCP represents the number of publications co-authored by researchers from multiple countries. These publications have at least two authors from different countries. The formula for MCP is as follows:

$$MCP = \sum_{i=1}^{n} MCP_i$$

SCP represents the number of publications authored solely by researchers from a single country. The formula for SCP is as follows:

$$SCP = \sum_{i=1}^{n} SCP_i$$

Where MCP_i/SCP_i represents the i-th multiple country collaboration publication. These analyses [42] provide academic researchers with tools and methodologies for in-depth exploration of specific research domains. Moreover, they serve as crucial reference points for policymakers and research institutions, promoting the advancement of academic research and deeper international collaboration. Vividly illustrates the situation of major countries in literature publication from 1979 to 2024, including total publication numbers, single-country publications (SCP), multiple-country collaborations (MCP), publication frequency, and MCP ratio.Table 6:

Rank	Country	Article	SCP	MCP	Freq.	MCP_ Ratio
1	CHINA	5725	4565	1160	0.413	0.203
2	USA	1016	694	322	0.073	0.317
3	KOREA	991	766	225	0.071	0.227
4	GERMANY	679	508	171	0.049	0.252
5	INDIA	574	448	126	0.041	0.22
6	JAPAN	495	401	94	0.036	0.19
7	ITALY	357	248	109	0.026	0.305
8	CANADA	266	178	88	0.019	0.331
9	SPAIN	264	177	87	0.019	0.33
10	U.K.	238	122	116	0.017	0.487

The top 10 countries/ regions, SCP: Single-country publications MCP: multiple-country collaborations Freq: publication frequency, MCP Ratio:

The data highlights both the enthusiasm for and the challenges of international collaboration. China leads with a total of 5,725 articles, showcasing its significant influence in the research field and the impressive efforts and achievements of the Chinese academic community. However, despite having a substantial number of multiple-country publications (1,160), China's MCP ratio is only 0.203, which is somewhat concerning. This indicates that China's level of international collaboration still has room for improvement compared to other countries. The United States and South Korea follow in second and third place, with 1,016 and 991 articles, respectively. The U.S. boasts an MCP ratio of 0.317, reflecting its active participation in global academic collaboration, which is truly exciting! This means that U.S. research is widely and deeply engaged in cooperation with other countries. South Korea's MCP ratio is 0.227, slightly lower than that of the U.S., but still demonstrates strong performance in international collaboration. Germany, India, Japan, Italy, Canada, Spain, and the United Kingdom also play important roles in the academic world. Germany's MCP ratio of 0.252 indicates its proactive stance in international collaboration. Particularly notable are Italy, Canada, and Spain, who's high MCP ratios show that their research is well-integrated into the global collabo- ration network, which is both uplifting and encouraging. Although the United Kingdom has a relatively lower total publication count (238 articles), its MCP ratio of 0.487 is highly impressive, revealing the UK's strong potential and active involvement in international collaboration. Overall, these data not only showcase the outstanding performance of countries in the research field but also reveal varying degrees of international cooperation. While some countries exhibit remarkable performance in international collaboration, which is exciting, others have relatively lowed collaboration ratios. This leaves us hopeful for the future of global academic cooperation, eagerly anticipating more countries actively engaging in international research efforts and working together to advance academic progress.

4.2.1 Citation analysis

Citation analysis is a research method used to evaluate and understand the impact and contributions of academic articles, researchers, or journals in the academic community [43]. This analysis involves counting and analyzing the number of times a piece of literature is cited to determine the scholarly influence of a particular article or researcher. Resents the annual citation data from 1979 to 2023(Table 7), including the number of publications each year, total citations, average citations per paper, and the corresponding years. The data reveals that from 1979 to 1999, the average citations per paper were generally low. For example, the figures for 1979 and 1991 show an average citation count of 0, likely due to the relatively small number of publications in those years or the fact that citations were still growing. Between 1995 and 1999, although there was a slight increase in the average citations per paper, the overall trend remained steady, indicating that these publications were gradually gaining attention from the academic community.

From 2000 to 2010, the average citations per paper began to rise, marking a dynamic period. For instance, the average citation count for 2001 was exceptionally high (254), reflecting the significant impact of a few influential papers from that year. The average citation count for 2008 also reached 105.50, indicating high levels of attention and citation during that period. Although there was a slight decline in citation counts between 2009 and 2010, the publications from this time still made important contributions to the field.

From 2011 to 2024, there were interesting fluctuations in the average citations per paper. The years 2012 and 2013 saw relatively high average citation counts of 77.67 and 117.09, respectively, highlighting the positive impact of the publications from those years on the academic community. However, over time, the data shows a slight decline in average citations. This change may suggest that newer publications are still in the process of gaining attention or that the focus of the academic community has shifted. Additionally, since the data for 2024 is insufficient for a full year, it will not be included in the analysis.

Table 7: Annual citation analysis

Year	MTCArt	N	MTCY	CY
1979	0.00	2	0.00	46
1991	0.00	1	0.00	34
1992	35.00	1	1.06	33
1993	76.00	1	2.38	32
1995	48.50	2	1.62	30
1996	31.67	3	1.09	29
1997	19.67	6	0.70	28
1998	22.67	3	0.84	27
1999	6.00	3	0.23	26
2001	254.00	2	10.58	24
2003	96.80	5	4.40	22
2004	109.30	10	5.20	21
2005	57.33	6	2.87	20
2006	79.31	13	4.17	19
2007	104.67	12	5.82	18
2008	105.50	14	6.21	17
2009	52.14	14	3.26	16
2010	46.92	13	3.13	15
2011	29.56	16	2.11	14
2012	77.67	24	5.97	13
2013	117.09	23	9.76	12
2014	62.26	437	5.66	11
2015	59.91	507	5.99	10
2016	60.00	667	6.67	9
2017	52.97	801	6.62	8
2018	48.52	991	6.93	7
2019	40.50	1190	6.75	6
2020	31.75	1483	6.35	5
2021	23.22	1820	5.80	4
2022	10.71	2523	3.57	3
2023	2.48	2799	1.24	2

MTCA: Mean TC per Art. TCY: Mean TC per Year CY: Citable Years

4.2.2 The most productive countries/regions

In bibliometrics analysis, the analysis of "the most productive countries/regions" is primarily used to evaluate the academic research output of different countries or regions within specific subjects or fields. Such studies typically explore several key aspects. By quantifying the number of publications from each country or region within specific subjects or fields, it provides a clear depiction of their performance in research activities. This quantification not only helps researchers and academic institutions understand their position on the global research stage but also provides policymakers and funding agencies with important references for evaluating the effectiveness of research investments. Additionally, it showcases international collaboration patterns and the distribution of influence among different countries or regions. By analyzing the number of co-publications and collaborative networks, it assesses the state of academic exchange globally and facilitates the identification of potential international collaboration opportunities, thereby furthering the deepening and development of global scientific cooperation.

The Sankey diagram （Figure 4） illustrates the global contributions in the research fields of oxygen evolution reaction, hydrogen production, and electrolysis, emphasizing the close connections between countries, authors, and research topics. From the diagram, it is evident that China's research contributions in these fields are particularly prominent, showcasing China's leading position in new energy technology and clean energy production. The total number of publications from each country or region within a specific period is calculated as:

$$TP_{country} = \sum_{i=1}^{n} P_i$$

where $TPcountry$ is the total number of publications from a country, Pi represents the i-th publication, and n is the total number of publications in the research field. Other countries such as Japan, the United States, Australia, and the United Kingdom also make significant contributions, but their research output is noticeably less compared to China. China's research is mainly concentrated among a few prolific authors, such as Wang Y, Wang X, Li J, and Zhang X. These authors are shown to be connected to multiple research topics in the diagram, reflecting their significant contributions in the fields of oxygen evolution reaction, hydrogen production, and electrolysis. The presence of these prolific authors indicates that China has established a robust academic network in these research areas, which not only promotes scientific progress but also facilitates the efficient allocation and utilization of resources. In terms of research topics, oxygen evolution reaction and hydrogen production are the main focuses, highlighting the global emphasis on new energy technologies. This is particularly important in the context of seeking sustainable development and addressing climate change, as these studies have significant practical applications. Breakthroughs in these areas are expected to have a profound impact on the future energy ecosystem.

Regarding global scientific collaboration and international influence, the prominent performance of Chinese researchers not only enhances China's international standing in these fields but also attracts more opportunities for international cooperation. This could further consolidate and expand China's leading position in these research areas. At the same time, the development of these research fields depends on the support of governments and research institutions in various countries. The investment in policies and funds will play a crucial role in future research directions and outcomes. Figure5 provides an intuitive representation of the global contributions in the research fields of oxygen evolution reaction, hydrogen production, and electrolysis. It highlights China's leading position and the strong academic network behind it, while also pointing out the development trends and potential impacts in the areas of new energy technology and clean energy production.

4.2.3 The most relevant affiliations

The chart (Figure 5) shows the number of articles published by different universities in a specific research field, with the top ten universities ranked as follows: Tsinghua University (430 articles), University of Chinese Academy of Sciences (404 articles), Qingdao University of Science and Technology (341 articles), University of Science and Technology of China (333 articles), Tianjin University (300 articles), Nanyang Technological University (292 articles), Huazhong University of Science and Technology (272 articles), Jilin University (258 articles), Wuhan University (252 articles), and Wuhan University of Technology (246 articles). This chart illustrates the academic output of various universities in the research field, reflecting their research activity and influence through the number of articles published. Tsinghua University ranks first with 430 articles, demonstrating its leading position in the research field, supported by its strong research capabilities and abundant resources. The University of Chinese Academy of Sciences follows closely with 404 articles, indicating its significant role as a national research institution.

Qingdao University of Science and Technology and the University of Science and Tech- nology of China rank third and fourth with 341 and 333 articles respectively, showcasing their strong research capabilities in the field. Tianjin University ranks fifth with 300 articles, highlighting its notable impact in the field.

Nanyang Technological University, an internationally renowned research university, ranks sixth with 292 articles, indicating its influence in the global academic community. The number of articles published by Huazhong University of Science and Technology, Jilin University, Wuhan University, and Wuhan University of Technology also exceeds 200, demonstrating their active research presence in the field. This chart clearly shows the academic

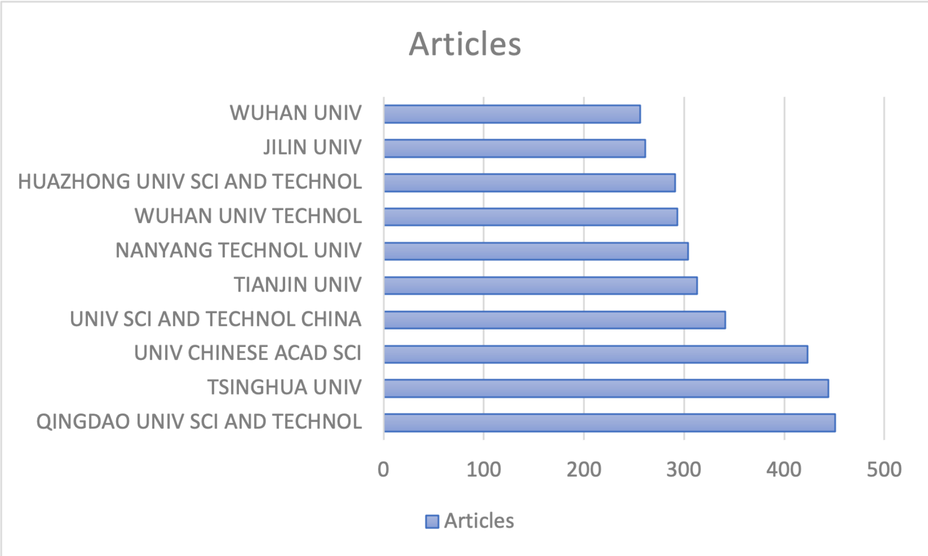

Figure 5: Most_Relevant_Affiliations_bibliometrix

output of each university in the specific research field, reflecting their research strength and influence. Tsinghua University and the University of Chinese Academy of Sciences lead in this field, while other universities also exhibit strong research capabilities. This analysis helps to understand the research performance of each university in the relevant field, providing references for further collaboration and resource allocation. These institutions are primarily from China, with Nanyang Technological University being from Singapore.

4.2.4 The cooperation Co-Citation Network of the authors

The primary purpose of this network is to help identify key figures in a specific research field, understand their collaborative relationships, and citation patterns. We can see which authors are central to the field, their interactions with others, and how these collaborations are formed. This also helps us discover the main research groups within the field and understand their interconnections. Additionally, this network can promote collaboration among researchers. When looking for significant collaborators in a specific field, this network provides valuable guidance. By observing the changes in these citation relationships over time, we can also understand the development trends of the field, seeing which research directions are emerging and which are declining. The co-citation network of authors is a very useful analytical tool that helps us better understand the structure and dynamics of academic re- search, identify the most important researchers in a field and their collaboration patterns. The co-citation count between two authors A and B represents the number of times the works of these two authors are cited together in other documents [44]. The formula is:

$$C_{A,B} = \sum_{i=1}^{n} \delta_i (A, B)$$

$C_{A,B}$ is the co-citation count between authors A and B, $\delta i(A, B)$ is an indicator function that equals 1 if both authors A and B are cited in the ith document, and n is the total number of documents. Co-Citation Strength [42] is measures the strength of the co-citation relationship between two authors. A common formula is:

$$S_{A,B} = \frac{C_{A,B}}{\sqrt{C_A \cdot C_B}}$$

$S_{A,B}$ is the co-citation strength, C_A and C_B are the total citation counts for authors A and B, respectively. It (Figure 6) shows data on the co-citation network of multiple authors across different clusters, including each author's betweenness centrality, closeness centrality, and PageRank indices. These indicators reflect the authors' influence and importance within the research network. The data in the table reveals that representative authors in Cluster 1(red color), such as Carmo, M. [45], Zeng K [46], and Ursúa A (2012) [47], have high betweenness and close- ness centrality, indicating their crucial role as bridges connecting different research subfields. These authors might be leading figures in their research areas, connecting multiple research groups and facilitating knowledge exchange and dissemination. In Cluster 2(blue color), representative authors like McCrory CCL. [48], She, ZW (2017), and Turner JA. [49] have high PageRank scores, indicating they are highly cited and influential in academia. Their work significantly contributes to the field and is frequently referenced by other researchers, likely forming core literature in the field. Cluster 3 includes authors like Schmidt O. [50], Buttler A. (2018), and Kumar S. (2019), who have moderate betweenness and

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closeness centrality, suggesting they have a certain level of connectivity and influence within the research network. These authors may represent emerging research areas, gradually gaining more attention and citations. Clusters 4 to 6 have a smaller proportion in this study compared to the first three clusters; therefore, their analysis is temporarily omitted.

Through this chart we can clearly see the status and influence of various authors in the research network. Authors with high betweenness centrality usually play a key role in connecting different research groups, those with high closeness centrality maintain close

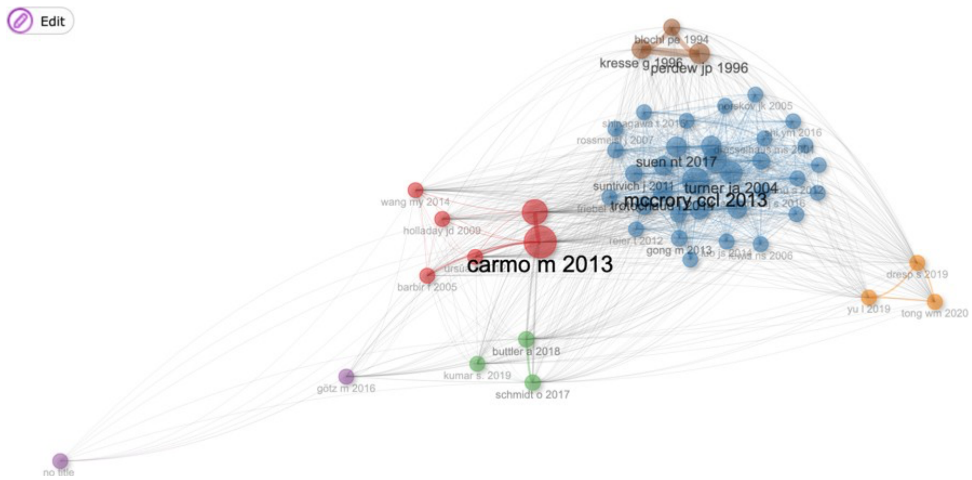

Figure 6: Co-citation Network analysis

academic ties with other important authors, and those with high PageRank show their high influence in academia. This data helps us understand the roles of different authors in academic research, identify leading figures and core literature, as well as emerging research forces.

4.3 Keywords analysis

A word cloud analysis was conducted on 13,864 documents retrieved from the WOS database based on the key- word "Production Trends of Seawater Electrolysis Hydrogen" The word cloud analysis was generated using the biblio-shiny package in RStudio, where the size of each word represents its frequency of occurrence.

The words cloud (Figure 7) showcases the most frequently occurring keywords in the research fields of electro- catalysis and hydrogen production. By analyzing the size and color of these words, we can understand the primary focus areas and research trends in these fields [51]. In the word cloud (Author’s keywords), "performance" is the most prominent keyword, indicating that researchers place significant emphasis on improving the performance of catalysts and systems. This likely involves enhancing the activity, stability, and durability of catalysts to improve the efficiency of hydrogen production and water electrolysis processes. Other notable keywords include "electro- catalysts" "hydrogen production" and "catalysts," highlighting that electrocatalysts and hydrogen production are central themes of the research. Researchers are focused on developing and improving electrocatalysts to increase hydrogen production efficiency, while also exploring various types of catalyst materials, particularly nanoparticles, to enhance catalytic processes. The keyword "water electrolysis" refers to the process of producing hydrogen through water electrolysis, a critical technology in this field. "Oxidation" and "reduction" are essential electro- chemical processes that researchers are keenly interested in. Secondary keywords such as "efficiency" "hydrogen evolution" and "energy" further emphasize the research objectives of enhancing efficiency and promoting hydrogen generation and utilization.

Keywords like "electrodes" and "nanosheets" indicate researchers’ interest in electrode materials and structures, which are crucial for improving electrochemical reaction performance. Supplementary keywords such as "stability", "fuel-cells" and "graphene" reflect the diversity and breadth of research, with stability being a vital indicator for evaluating the long-term performance of catalysts, fuel cells being an important application for hydrogen utilization, and graphene being widely studied for its exceptional electrochemical-properties.

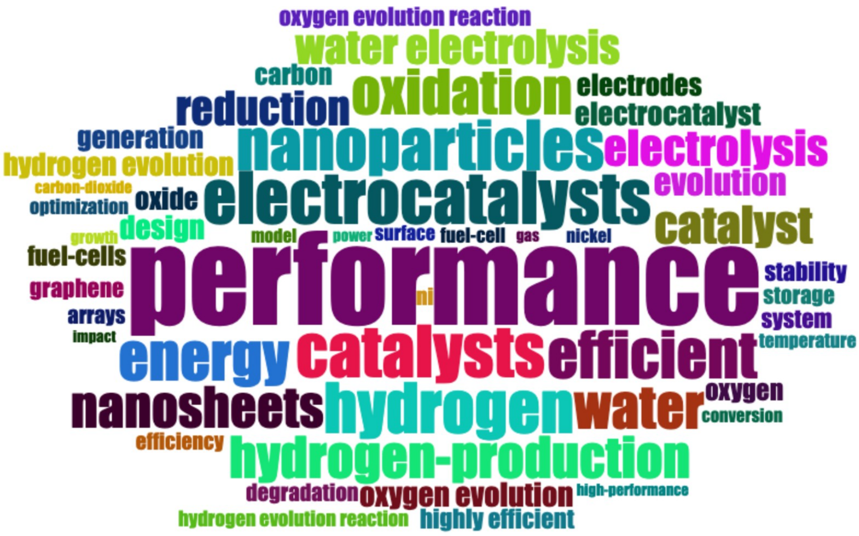

Figure 7: Words cloud by electrolysis of seawater.

The words cloud analysis, we can observe the main research focuses and trends in the fields of electrocatalysis and hydrogen production. Researchers are primarily interested in improving the performance, efficiency, and stability of catalysts and systems while also exploring new materials and technologies to promote hydrogen production and utilization. These keywords provide a clear overview, helping us understand the key research priorities and future development directions in these fields.

4.4 Co-occurrence analysis

This co-occurrence analysis (Figure 8) graph illustrates the relationships and co-occurrence patterns between different keywords in the research fields of electro catalysis and hydrogen production. Each node in the graph represents a keyword, and the size of the nodes indicates the frequency of that keyword's appearance in the literature [52]. The lines between nodes represent the frequency with which these keywords co-occur in the same document, and the thickness of the lines indicates the strength of the co-occurrence. This visualization helps us understand the interrelationships between keywords and the structure of the research field. The visual analysis of Co-Occurrence Analysis must use three related calculations: Co-Occurrence Matrix, Jaccard Similarity, and Co-Occurrence Strength, as de- scribed below, the basis of co-occurrence analysis is constructing a co-occurrence matrix, where each element represents the frequency of two items (such as keywords) appearing together in the same document.

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$$M(i,j) = \sum\nolimits_{k=1}^{n} \delta_k(i)\delta_k(j)$$

M(i,j) represents the co-occurrence count of items i and j, $\delta k(i)$ indicates whether item i is present in the k-th document. Jaccard Similarity: Used to measure the similarity between two items. The calculation formula is:

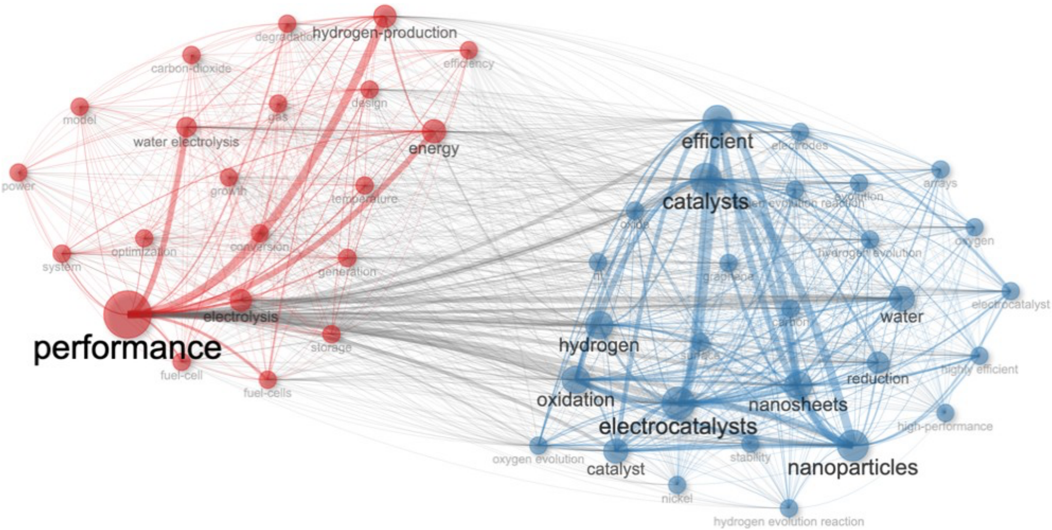

Figure 8: Co-occurrence analysi

In the graph (Figure 8), keywords form two main clusters based on their co-occurrence relationships. The red cluster on the left revolves around the keyword "performance" indicating that performance is one of the core themes in the research. Keywords closely linked to "performance" include "electrolysis" "hydrogen production" "energy," and "efficiency". These terms show researchers focus on improving electrolysis performance and hydrogen production efficiency, emphasizing the importance of performance in energy conversion and storage. Other keywords in the red cluster, such as "water electrolysis", "degradation", "design" and "conversion" further indicate efforts in designing and optimizing electrolysis systems and studying degradation phenomena during the electrolysis process.

The blue cluster on the right is centered around keywords such as "catalysts", "electrocatalysts" and "nanoparticles" highlighting the significance of catalysts and nanomaterials in this research area. These keywords are closely related to "hydrogen" "water", "oxidation" and "reduction" reflecting researchers' efforts to explore new catalyst materials to enhance hydrogen production efficiency and

reaction rates. Other keywords like “nanosheets” “electrodes,” and “graphene” show interest in various materials and structures, especially nanostructures and advanced materials, for improving electrochemical reaction performance.
The entire co-occurrence network graph also shows some connections between the red and blue clusters, indicating overlaps and complement arities between the two main research themes. For example, “efficiency” appears in both clusters, showing that improving efficiency is a common research goal in both areas.

Through this co-occurrence analysis graph, we can clearly see the main research focuses and trends in the fields of electro catalysis and hydrogen production. Researchers are primarily interested in improving the performance and efficiency of electrolysis systems and exploring new catalyst materials and nanostructures to promote hydrogen production and energy conversion. This analysis not only helps us understand the overall structure of the research field but also predicts future research directions and potential collaboration opportunities.

4.5 The trend analysis

Collect literature data such as publication year, keywords, authors, and institutions from academic databases, then clean and standardize the data. Next, calculate the frequency of each keyword in different years to generate keyword trend graphs. Use topic modeling techniques to extract latent topics and analyze their changes over time. Trend analysis in bibliometrics primarily involves three key calculations [53]: Term Frequency Analysis, Relative Growth Rate, and Exponential Smoothing. Term Frequency Analysis: The method calculates the frequency of a specific term or keyword over different time periods to identify trends.

$$TF_t = \frac{f_t}{\sum_{t'} f_{t'}}$$

TF_t represents the term frequency in a specific time, ft is the occurrence count of the term in that period, and $\sum_{t'} f_{t'}$ is the total count of the term across all time periods. Relative Growth Rate (RGR): The measures the rate of increase of a research topic over time.

$$RGR = \frac{TF_{t+1} - TF_t}{TF_t}$$

TF_{t+1} is the term frequency in the subsequent period, and TF_t is the term frequency in the current period. Exponential Smoothing: This technique is used to smooth out data series to identify long-term trends.

$$S_t = \alpha X_t + (1 - \alpha)\, St - 1$$

S_t is the current smoothed value, X_t is the current observed value, α is the smoothing constant (between 0 and 1), and $S_t - 1$ is the previous smoothed value. This chart (Figure 9) illustrates the trend analysis of keywords within a specific research field. Each point on the chart represents the frequency of a keyword in a particular year, with the size of the point indicating the occurrence frequency of the keyword. The horizontal axis spans from the year 2000 to 2023, while the vertical axis lists the keywords. The size of each point reflects how often the keyword appeared in that year, the larger the point, the higher the frequency of the keyword.

Several keywords in the chart, such as "heterostructure”, “catalysts", "electrocatalysts" and "hydrogen evolution" have shown significant growth trends over the past decade. This indicates that these topics are becoming increasingly important in research and have become hot research focuses. Other keywords like "green hydrogen" and "solar hydrogen" appear later in the chart but show a rapid growth rate, suggesting they are relatively new research topics quickly becoming research hotspots. Certain keywords, such as "hydrogen production", "fuel cells" and "electrochemical properties" have been consistently present throughout the time range, demonstrating their ongoing importance in research. In contrast, some keywords, such as "aqueous solution" and "nickel-iron" had high frequencies in the early years but have decreased or stagnated in recent years, suggesting that research activity on these topics has diminished, or they have been replaced by new technologies or methods.

Based on the trends in the chart (Figure 9), we can predict the research directions and focuses for the coming years. Topics like "heterostructure", "catalysts", "electrocatalysts" and "green hydrogen" are expected to continue growing due to their strong research momentum and broad application prospects. Emerging topics like "solar hydrogen" and "green hydrogen" are likely to attract more research resources and attention, becoming future research hotspots in line with the increasing global demand for renewable energy and green technologies. Mature research areas like "hydrogen production" and "fuel cells" will continue to maintain stable research activity, as these topics have established solid foundations and are important in practical applications. Keywords like "aqueous solution" and "nickel iron" may further decrease, as these topics might be replaced by new technologies, materials, or methods.

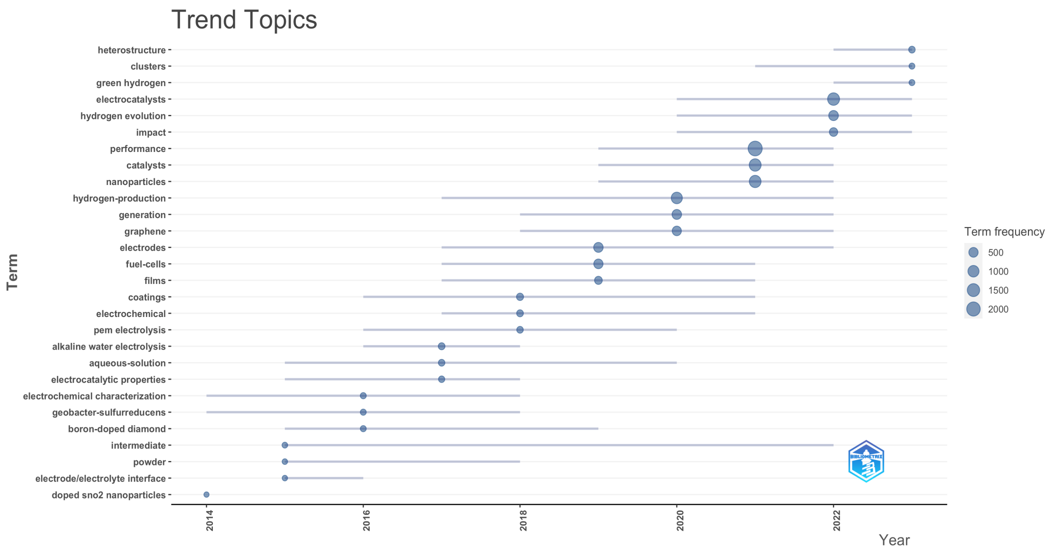

Figure 9: Trend analysis

5. Discussion and Conclusion

Seawater electrolysis is emerging as a promising clean energy technology, warranting a thorough examination of its status and development trends [54]. Empirical studies indicate that most experts engaged in seawater electrolysis research are from the field of chemistry, with a noticeable paucity of specialists from electronic-related disciplines. This imbalance potentially neglects the critical contributions of electronic experts in managing current control and understanding electromagnetic effects during the electrolysis process. Contemporary research predominantly focuses on the effects of electrolyte formulations on hydrogen and oxygen evolution reactions. Optimizing these formulations and modifying electrodes are considered pivotal for enhancing system efficiency and stability. However, other relevant areas require further investigation, underscoring the necessity for interdisciplinary collaboration involving chemistry, electronics, materials science, and electromagnetism experts [55]. China's investment in hydrogen energy research surpasses that of other nations. Analytical data reveal that China has allocated substantial resources to hydrogen energy research, particularly in achieving significant breakthroughs in direct seawater electrolysis for hydrogen production, thereby establishing a leading global position in the hydrogen energy sector. This is a noteworthy phenomenon in the field. The analysis of patents related to hydrogen production methods and processes is indispensable [56]. Patent citation analysis can provide valuable insights into estimating target patents, elucidating technological relationships between companies, market value, and development strategies. Seawater electrolysis for hydrogen production faces challenges such as impurities and salts that corrode electrodes and reduce catalyst efficiency. Therefore, developing corrosion-resistant and efficient electrode materials and catalysts, improving energy efficiency, and reducing costs for large-scale commercialization are key research directions.

With the continuous development of seawater hydrogen production technology as shown in (Table 8), significant advancements have been made in electrolyze technology, particularly in material selection and catalytic efficiency. Early Alkaline Water Electrolyzes (AWE) primarily utilized nickel-based electrodes, known for their corrosion resistance and compatibility with saline seawater environments. Later, Solid Oxide Electrolyze Cells (SOEC) incorporated high-temperature stable oxide materials, which effectively reduced energy consumption, making them ideal for efficient hydrogen production. Proton Exchange Membrane (PEM)[2] technology introduced highly conductive precious metals and Nafion membranes, which, despite their high cost, offered excellent separation efficiency at low temperatures and significantly boosted hydrogen output.

More recently, the development of Alkaline Anion Exchange Membrane (AEM)[3] technology has enabled the use of non-precious metal catalysts, reduced costs and making the technology suitable for medium to low-temperature operations. The latest Bifunctional Catalyst Solution (BF-Catalyst) employs ruthenium-based catalysts capable of catalyzing dual reactions, further enhancing hydrogen evolution efficiency and improving corrosion resistance in seawater environments.

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[2] The **Proton Exchange Membrane (PEM)** is a special type of membrane material widely used in fuel cells and water electrolysis technology, especially in hydrogen production and utilization. The primary function of PEM is to allow protons (H^+ ions) to pass through while blocking electrons and other ions, thus enabling the separation and conduction of electrochemical reactions.

[3] The **Alkaline Anion Exchange Membrane (AEM)** is a special type of ion exchange membrane that allows anions (such as hydroxide ions OH^-) to pass through while blocking other ions. AEM technology is primarily used in fuel cells and water electrolysis, especially playing a crucial role in hydrogen production and electrochemical energy conversion. The AEM system differs from the traditional acidic Proton Exchange Membrane (PEM) system, offering some unique advantages.

Together, these technological advances have significantly increased the efficiency of seawater hydrogen production, paving the way for future clean energy solutions. The following chart (Figure 10) illustrates the trends in hydrogen production costs (per cubic meter) and oil prices (per liter) from 2010 to 2023. The blue line represents the gradual decrease in the cost of seawater-based hydrogen production over time, while the red dashed line shows fluctuations in oil prices. The chart (Figure 10) reveals that as oil prices rise or fluctuate, hydrogen becomes more appealing as an alternative energy source. Furthermore, technological advancements have steadily lowered hydrogen production costs, especially in recent years, accelerating the commercialization of hydrogen energy.Despite the challenges in energy efficiency and cost, seawater electrolysis technology holds substantial potential in the clean energy domain. Continuous research and innovation are essential to develop more efficient and stable technologies, facilitating commercialization and supporting the global energy transition and sustainable development. Multidisciplinary collaboration among experts in chemistry, electronics, materials science, and electromagnetism can expedite technological advancements and address existing challenges comprehensively [57]. This study elucidates the current state and prospective directions of seawater electrolysis technology, highlighting the importance of interdisciplinary cooperation and ongoing innovation.

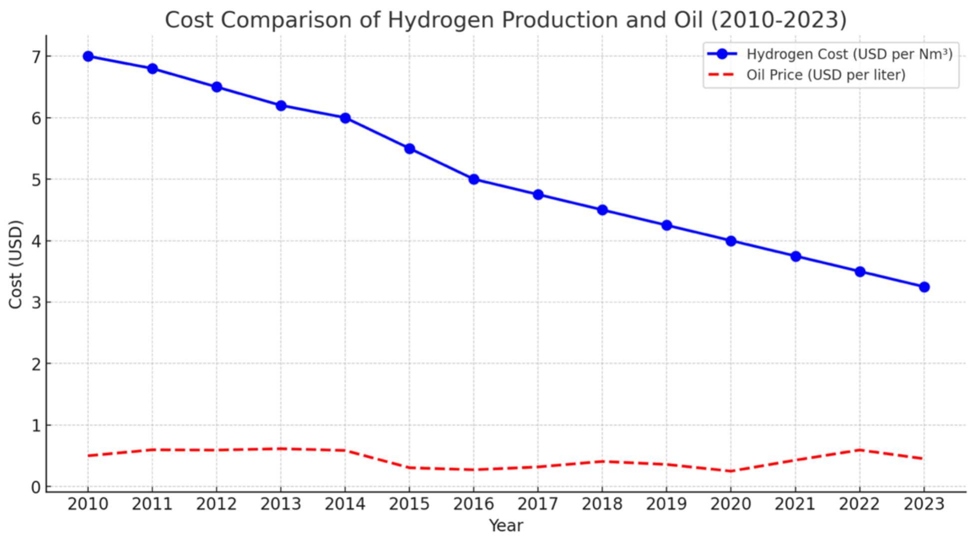

Figure 10, Price Trend Chart of Oil and Hydrogen, source by https://www.eia.gov/dnav/pet/pet_pri_spt_s1_d.htm, Data Compilation - Author

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Table 8, Development and Application of Electrolyze Technologies and Key Materials (2014-2023)

Year Range	Electrolyze Type	Key Materials	Material Characteristics and Advantages
2014-2016	Alkaline Water Electrolyze (AWE)[4]	Nickel-based electrodes (Nickel, Nickel-Cobalt alloy)	High corrosion resistance, high electrocatalytic activity, suitable for saline environments in seawater
2016-2018	Solid Oxide Electrolyzer Cell (SOEC)[5]	Perovskite oxides ($La_{0.6}Sr_{0.4}CoO_{3-\delta}$), YSZ	Good stability at high temperatures, reduced energy consumption, suitable for efficient hydrogen production
2018-2020	Proton Exchange Membrane (PEM)	Platinum, Iridium, Platinum-Iridium alloy, Nafion membrane	High conductivity, excellent separation, suitable for low-temperature electrolysis but high cost, limited by precious metals
2020-2022	Alkaline Anion Exchange Membrane (AEM)	Non-precious metal catalysts (Ni, Fe, Co-based), AEM membrane	Low cost, suitable for medium to low-temperature operation, good hydrogen production rate

Declaration

1. During the preparation of this work, the authors used [SCISPACE/Editing service] for [article editing and language, and semantic correction]. After using this tool/service, the authors reviewed and edited the content as needed and assume full responsibility for the content of the publication.
2. The authors declare that they have no known competing financial interests or

[4] Alkaline Water Electrolysis (AWE) is a technology that uses electrical energy to split water into hydrogen and oxygen in an alkaline environment, typically using potassium hydroxide (KOH) or sodium hydroxide (NaOH) solution as the electrolyte. AWE technology is widely used in hydrogen production due to its mature technology and relatively low cost.

[5] Solid Oxide Electrolyze Cell (SOEC) is an efficient water splitting technology that uses solid oxide as the electrolyte to conduct the electrolysis reaction of water. SOEC typically operates in high-temperature environments (around 700 to 1000°C), utilizing electrical energy to split water into hydrogen and oxygen. Compared to traditional alkaline water electrolysis technology, SOEC operates at high temperatures, improving efficiency and effectively utilizing thermal energy to reduce electrical energy consumption.

personal relationships that could have appeared to influence the work reported in this paper.

3. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for- profit sectors.

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