energies

Article
Emerging Trends and Challenges in Pink Hydrogen Research

Pablo Fernández-Arias [1,*], Álvaro Antón-Sancho [1], Georgios Lampropoulos [2] and Diego Vergara [1,*]

[1] Technology, Instruction and Design in Engineering and Education Research Group (TiDEE.rg), Catholic University of Ávila, C/Canteros s/n, 05005 Ávila, Spain; alvaro.anton@ucavila.es
[2] Department of Applied Informatics, University of Macedonia, 54636 Thessaloniki, Greece; glampropoulos@uom.edu.gr
* Correspondence: pablo.fernandezarias@ucavila.es (P.F.-A.); diego.vergara@ucavila.es (D.V.)

Abstract: Pink hydrogen is the name given to the technological variant of hydrogen generation from nuclear energy. This technology aims to address the environmental challenges associated with conventional hydrogen production, positioning itself as a more sustainable and eco-efficient alternative, while offering a viable alternative to nuclear power as a source of electricity generation. The present research analyzes the landscape of pink hydrogen research, an innovative strand of renewable energy research. The methodology included a comprehensive search of scientific databases, which revealed a steady increase in the number of publications in recent years. This increase suggests a growing interest in and recognition of the importance of pink hydrogen in the transition to cleaner and more sustainable energy sources. The results reflect the immaturity of this technology, where there is no single international strategy and where there is some diversity of research topic areas, as well as a small number of relevant topics. It is estimated that the future development of Gen IV nuclear reactors, as well as Small Modular Reactor (SMR) designs, will also favor the implementation of pink hydrogen.

Keywords: nuclear energy; bibliometric review; hydrogen; pink hydrogen; sustainable energy

check for updates

Citation: Fernández-Arias, P.; Antón-Sancho, Á.; Lampropoulos, G.; Vergara, D. Emerging Trends and Challenges in Pink Hydrogen Research. *Energies* **2024**, *17*, 2291. https://doi.org/10.3390/en17102291

Academic Editors: Sunel Kumar, Dingkun Yuan and Xinlu Han

Received: 23 April 2024
Revised: 6 May 2024
Accepted: 7 May 2024
Published: 10 May 2024

1. Introduction

Nuclear power has been a topic of discussion and debate over the past decades [1–3]. Since the first nuclear power plant was commissioned in Obninsk (Russia) in 1954 [4], until the present day, nuclear power plants have provided a constant source of electricity, contributing significantly to the diversification of electric power generation sources and to the reduction of greenhouse gas emissions in several countries [5]. However, their trajectory has been marked by severe serious accidents such as those that occurred in Chernobyl in 1986 and Fukushima in 2011 [6]. These serious accidents have raised concerns about the safety of nuclear power plants, as well as the management of the nuclear waste they generate [7], and, therefore, have increased the risk perception of the technology in society [8,9], leading to an international debate on its role in the current energy landscape and in the upcoming energy transition [10,11].

However, more than 400 nuclear reactors are still in operation around the world [5,12]. If the Power Reactor Information System (PRIS)—developed and maintained by the IAEA [12]—is taken into account, the United States leads the list with the largest number of operating nuclear power plants, followed by France and China. In the field of nuclear power plants under construction, more than 50 are in this situation, with China leading the list of countries that are in the expansion phase of new nuclear power plants to meet the growing demand for energy. Along with China, India, Turkey, and the United Arab Emirates are also building new nuclear power plants. Finally, 25 nuclear power plants around the world are in suspended operation, while more than 200 are in permanent shutdown.

In this context, the need arises to find new, safer, and more sustainable technological solutions that allow nuclear energy to maintain its fundamental role as a source of electricity generation in the current energy transition towards renewable energies [13]. Gen IV nuclear reactors and Small Modular Reactors (SMRs) are among the different technological solutions proposed [14–16]. However, a promising new technological solution has emerged in recent years, which would give nuclear energy a fundamental role as a source of electricity generation: pink hydrogen [17].

This innovative form of hydrogen production seeks to address some of the challenges associated with conventional nuclear power by using safer and more sustainable processes. Pink hydrogen is produced through thermochemical electrolysis of water, a process that harnesses the heat generated by nuclear reactors to break down water and obtain hydrogen (Figure 1).

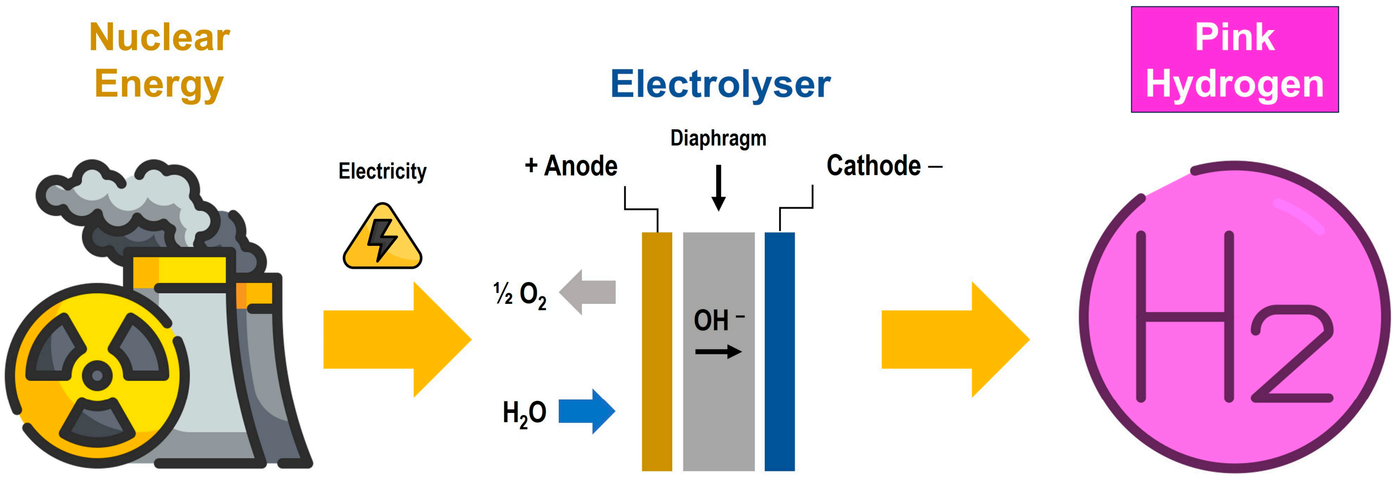

Figure 1. Pink hydrogen production process.

On possible similarities and differences between pink and green hydrogen technologies (Table 1), the only difference between pink hydrogen and green hydrogen is in the source electrical power supply required to generate the electrolysis of water [18,19]. While pink hydrogen uses electrical energy generated by a nuclear reactor, green hydrogen obtains electrical energy from renewable technologies (solar, wind, etc.) [18]. The generation process in both technologies is the same, water electrolysis, and the greenhouse gas emissions generated via water electrolysis are zero.

Table 1. Main parameters comparation of pink and green hydrogen technologies.

Parameter	Pink Hydrogen	Green Hydrogen
Generation process	Water electrolysis	Water electrolysis
Source electrical power supply	Nuclear energy	Eolic or photovoltaic energy
Associated emissions	Net zero emissions	Net zero emissions

The possibilities offered by pink hydrogen are very interesting. Not only does it present a potentially safer alternative to traditional hydrogen production methods, but it can also become a versatile energy carrier. In addition to its direct application as a fuel, pink hydrogen can be integrated into industrial processes and act as an energy storage medium, thus addressing some of the challenges associated with the intermittency of renewable sources. Specifically, generating pink hydrogen at a nuclear power plant offers several advantages that take advantage of the particular capabilities and characteristics of these facilities, among which the following can be highlighted:

- Energy efficiency: Nuclear power plants generate large amounts of heat as a by-product of the nuclear fission process [11,20]. Using this heat for nuclear electrolysis significantly improves system efficiency by harnessing thermal energy that would otherwise be lost.

- Net zero emissions: The production of hydrogen by nuclear electrolysis does not generate direct greenhouse gas emissions [11], which contributes to the sustainability and reduction of the carbon footprint of nuclear power plants.
- Exploitation of existing infrastructure: Nuclear power plants already have a robust and complex infrastructure. Integrating electrolysis for hydrogen production leverages the investments made in these facilities and reduces the need to build new infrastructure.
- Stable and continuous supply: Nuclear power plants provide continuous and stable electricity generation [21]. By using this electricity for electrolysis, a constant supply of hydrogen is guaranteed, which is essential for industrial and energy applications.
- Sustainable technological development: Pink hydrogen promotes sustainable technological development by integrating nuclear technologies with hydrogen production, thus contributing to the diversification of energy sources and the transition to cleaner systems [22].
- Energy storage: Hydrogen production in nuclear power plants can be used as a form of energy storage. The hydrogen produced can be stored and used when needed, contributing to the stability and flexibility of the power grid [23,24].

The viability and continuity of nuclear technology could be boosted by this innovation. As nations seek ways to decarbonize their economies and ensure a stable energy supply, the role of pink hydrogen and its relationship to nuclear power emerges as a critical area of research. Furthermore, highlighting the benefits of pink hydrogen in terms of energy efficiency and waste reduction could improve public perception of nuclear energy by presenting it as part of a broader, sustainable solution for the energy future. However, it is essential to carefully address public concerns and establish effective regulatory frameworks to ensure safe and ethical deployment of this technology.

Although there are different bibliometric reviews on hydrogen [25,26], as well as of different generation technologies such as green hydrogen [27,28], at the moment, there is no research that presents a bibliometric review of pink hydrogen. In this sense, the research work developed in this paper is an innovation in this field. In view of this scenario, the present study focuses on analyzing in detail the current situation surrounding pink hydrogen research, examining how this innovation could reshape the future of nuclear energy and contribute to a more sustainable and diversified energy landscape.

2. Materials and Methods

To achieve the research objective, a bibliometric review of scientific publications related to pink hydrogen has been developed. The bibliometric review provides a more comprehensive and objective analysis of the advances in the field accumulated over time [29,30]. As a general work plan (Figure 2), the bibliometric method includes the following phases [31]: Phase I: articles selection; Phase II: compilation of bibliometric data; Phase III: analysis; Phase IV: visualization; Phase IV: interpretation.

Figure 2. Scientific methodology outline.

Regarding the selection of the articles (Phase I, Figure 2), the Scopus bibliographic database was chosen in order to cover the greatest number of scientific results. The articles were selected in April 2024. In addition, to ensure a comprehensive search and that the articles most relevant to the topic were identified in the different bibliometric databases, several keywords were incorporated along with a combination of Boolean operators (e.g., AND, OR, etc.) [32]. Table 2 details the search string used.

Table 2. Search string for bibliometric databases.

Search String
((“hydrogen”) AND (“production” OR “energy” OR “generation”) AND (“generator” OR “electrolysis” OR “electrolyzer”) AND (“nuclear” OR “pink”))

The initial keyword-based search indicated a large number of published articles. To provide greater precision in determining the size of the sample to be analyzed, the PRISMA guidelines [33,34] were used as a reference. According to this PRISMA protocol [35], there are four steps to determine the sample population of a bibliometric review (Figure 3): (i) Identification; (ii) Screening; (iii) Eligibility; (iv) Included.

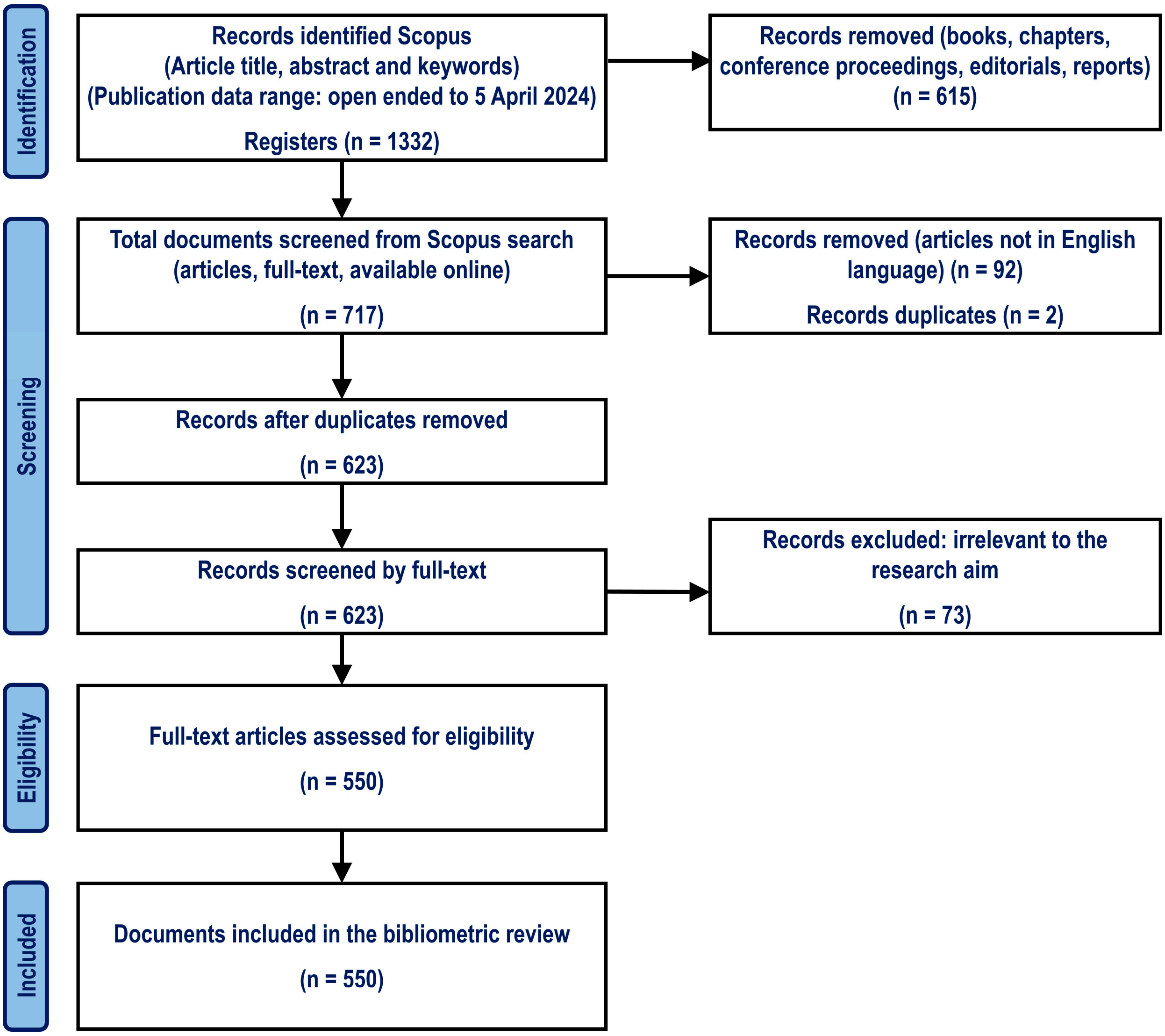

Figure 3. PRISMA protocol used to identify the papers for the bibliometric review.

Subsequently, after applying the search criteria, the articles were retrieved and processed. To analyze the data and carry out the bibliometric analysis, the following software was used: (i) Bibliometrix R-package; (ii) software VOSviewer® 1.6.16.

3. Results

This section shows the results obtained in the bibliometric analysis performed (Phase III, Figure 2). Table 3 shows the main information of the bibliometric analysis performed.

The first study identified in Scopus on hydrogen in nuclear reactors dates back to 1962 [36]. This article analyzed the diffusion of hydrogen in zirconium, a reference material in the construction of the fuel elements of the main nuclear reactor designs; however, it did not clearly address the possibility of generating hydrogen in a nuclear reactor. Since 1962, the annual growth rate in pink hydrogen research has been 5.58%, obtaining an annual average of 13.6 published articles.

Table 3. Main information of the document collection.

Main Information about the Data	Results
Timespan	1962:2024
Sources (journals, books, etc.)	205
Documents	550
Annual growth rate %	5.58
Document average age	13.6
Average citations per doc	34.64
Document Contents	
Keywords plus (ID)	4753
Author's keywords (DE)	1175
Authors	
Authors	1855
Authors of single-authored docs	73
Authors collaboration	
Single-authored docs	81
Co-authors per doc	4.16
International co-authorships %	15.64
Document types	
Article	550

Figure 4 shows the annual trend of publications on pink hydrogen from 2003 to 2023. From 2003 onwards, a significant increase in the number of research articles on the subject is identified, reaching 25 articles in 2009. This trend is similar to that observed in the number of operational nuclear reactors in the world [37]. As a consequence of the accident at Fukushima NPP (Japan) in 2011, the nuclear industry decreased the number of operating reactors from more than 430 to less than 420. Research into the subject declined until 2015, from which point onwards, interest in it increased among the scientific community. In contrast to pink hydrogen research, the nuclear industry has not resurged since 2015 in terms of operating nuclear reactors, with around 415 reactors in operation globally.

As far as the journals are concerned, of the 205 journals identified, the most influential journal on pink hydrogen is clearly "International Journal of Hydrogen Energy" (H-index of 42), in which more than 25% (146 absolute records) of the records found are published. The rest of the identified journals have a residual influence in terms of published results, being less than 4%. In this group, "Nuclear Technology" (H-index of 9) and "Nuclear Engineering and Design" (H-index of 9) stand out, with an influence slightly higher than 3%. As can be seen in Figure 5, the production of sources has been growing over time. The growth started to increase in the early 2000s, as very few articles were published in this research field before. "International Journal of Hydrogen Energy" confirms its predominant position in this field and shows a substantial increase in articles and publications, indicating a growing interest in this topic. The other two relevant journals, "Nuclear Technology" and "Nuclear Engineering and Design", have not experienced a significant upward trend.

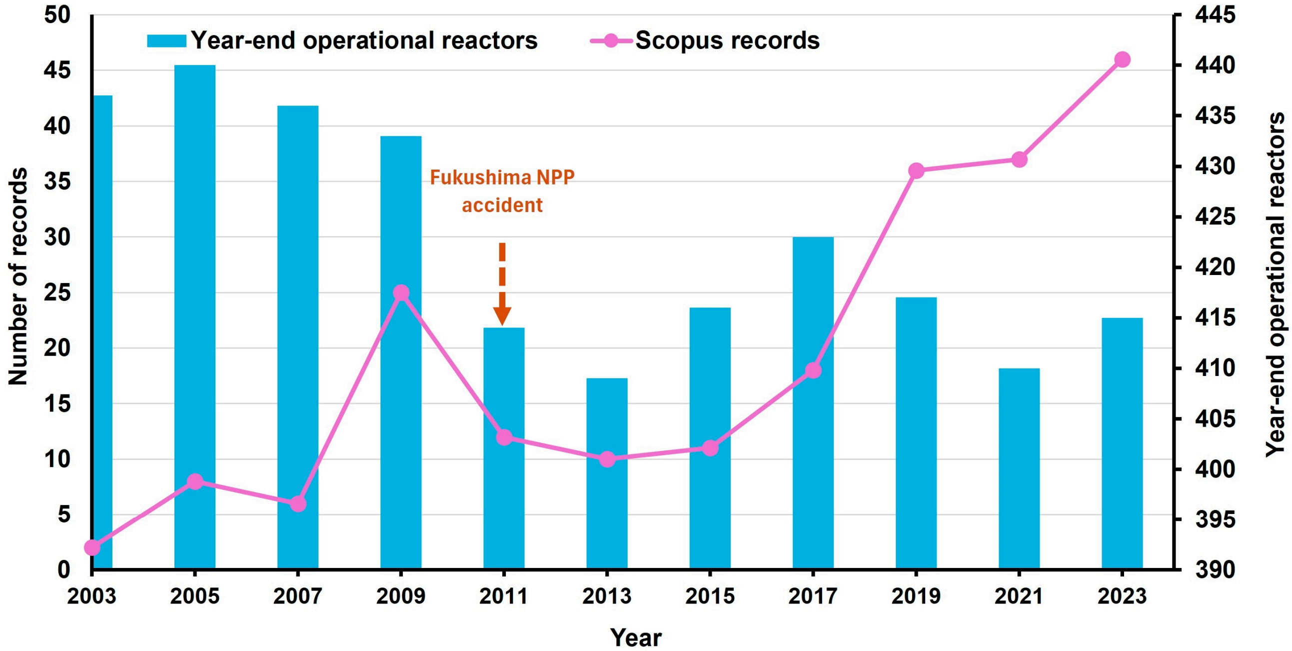

Figure 4. Pink hydrogen records by year (2003–2023) and year-end operational reactors (data collected from Scopus database in April 2024 and from [1]).

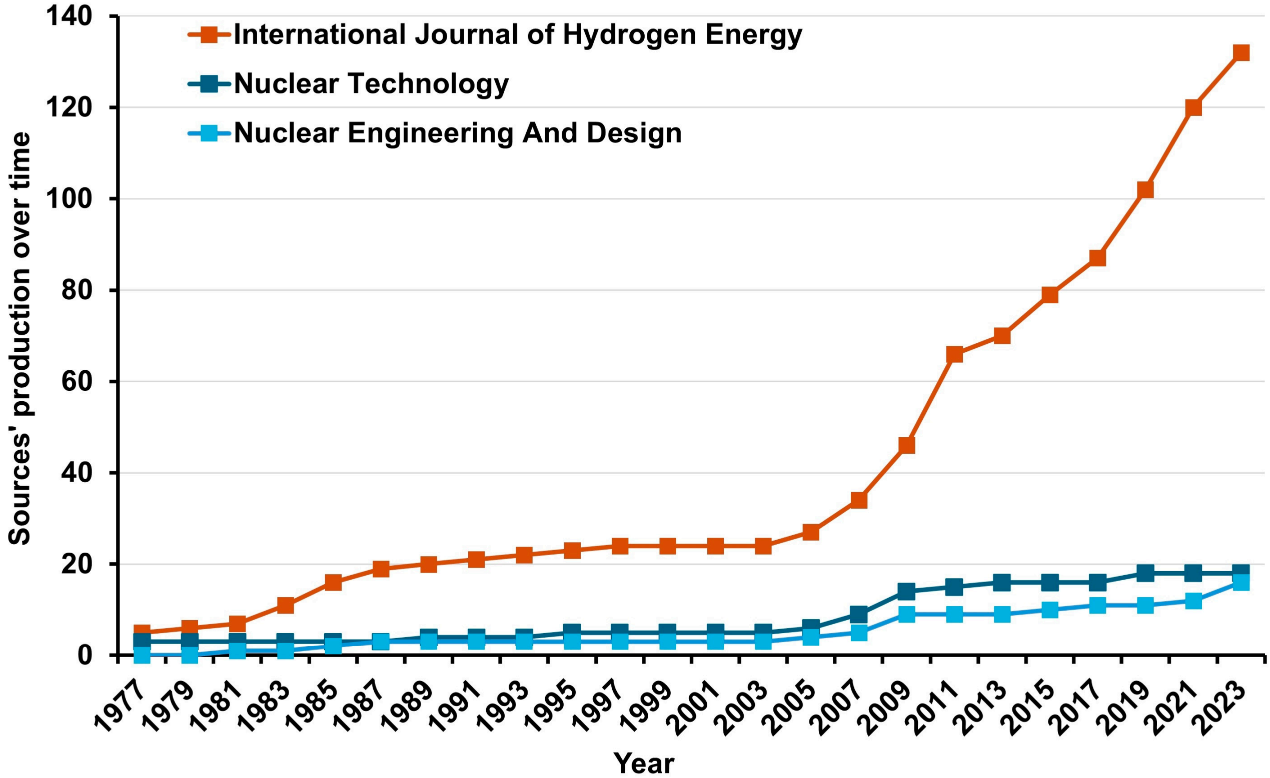

Figure 5. Source production over time (1997–2023) (data collected from Scopus database in April 2024).

Table 4 shows the Top 10 authors' local impact during 1962–2024. Within the Top 3, we find that author I. Dincer has an H-index of 18 and since 2008 has published 25 scientific papers related to pink hydrogen. These papers have received a total of 1523 citations. He is followed by authors M.A. Rosen and G.F. Naterer, with an H-index of 13 and 10, respectively, and a total number of citations of more than 700. Continuing with the authorship analysis, of the 1855 authors identified, only 73 are authors of single-author papers. The number of single-authored documents is 81 and the average number of authors per article is 4.16.

Table 4. Top 10 authors' local impact during 1962–2024. TC (Total Citations), NP (Number of Pub-lications), and PY (Publication Year Start).

R	Author	h_Index	TC	NP	PY_Start
1	Dincer, I.	18	1523	25	2008
2	Rosen, M.A.	13	977	14	1995
3	Naterer, G.F.	10	700	12	2008
4	Easton, E.B.	7	487	7	2009
5	Suppiah, S.	7	464	8	2009
6	Gabriel, K.	6	511	6	2008
7	Fowler, M.	5	473	5	2008
8	Li, Y.	5	583	7	2014
9	O'Brien, J.E.	5	445	6	2009
10	Pioro, I.	5	439	5	2009

In terms of productivity, evaluated through the number of articles published, Y. Li is the most productive author in recent years. Conversely, the impact was evaluated considering the number of citations received each year. I. Dincer, M.A. Rosen, and G.F. Naterer are the authors receiving the most citations per year, with an uninterrupted series of citations from 1995 to 2023. Finally, Lotka's law allows quantification of the relative concentration of authors in the subject [38]. Lotka's law was applied to the results obtained using the bibliometrix R package. The results obtained show that the majority of the 1855 authors identified (87% of the total) published only one article, while only 10% of the authors published between two and three articles in the most recent years. Only three authors published more than 10 articles on pink hydrogen.

Figure 6 shows the results if the authorship analysis is performed in terms of co-citation network. The objective of co-citation is to determine which authors, from the co-citations of others, are the most representative in terms of research [7]. As can be seen, there are three clusters or sets of authors most significant in pink hydrogen research. In Cluster I, there are 13 authors with a minor relevance, while in Cluster II, there are the most relevant authors (Table 4), among them I. Dincer and M.A. Rosen. In Cluster I there are only seven authors, among them G.F. Naterer, one of the most relevant authors in the field (Table 4), who acts as a link in terms of co-citation between the authors of Clusters II and III. Cluster III includes other relevant authors in the field, such as S. Suppiah, A. Odukoya, and K. Gabriel.

Table 5 shows a more detailed analysis of the Top 5 most prominent countries in pink hydrogen research, including the number of articles published, the number of authors producing, Single Country Publications (SCP), Multiple Country Publications (MCP), and finally MCP/TP, where TP is the total number of publications (MCP ratio). As can be seen, the United States of America is the dominant country in terms of number of articles published, followed by China, Canada, Japan, and the United Kingdom. It is worth noting that in these countries, collaboration with authors from other countries is very low and that except for the case of the United States of America, which has a frequency of 15.5%, the rest of the countries have a frequency of publication from the sample of 550 articles identified of less than 10%. The United Kingdom, with a lower number of authors than the rest of the countries, manages to position itself among the five most productive countries in research on pink hydrogen.

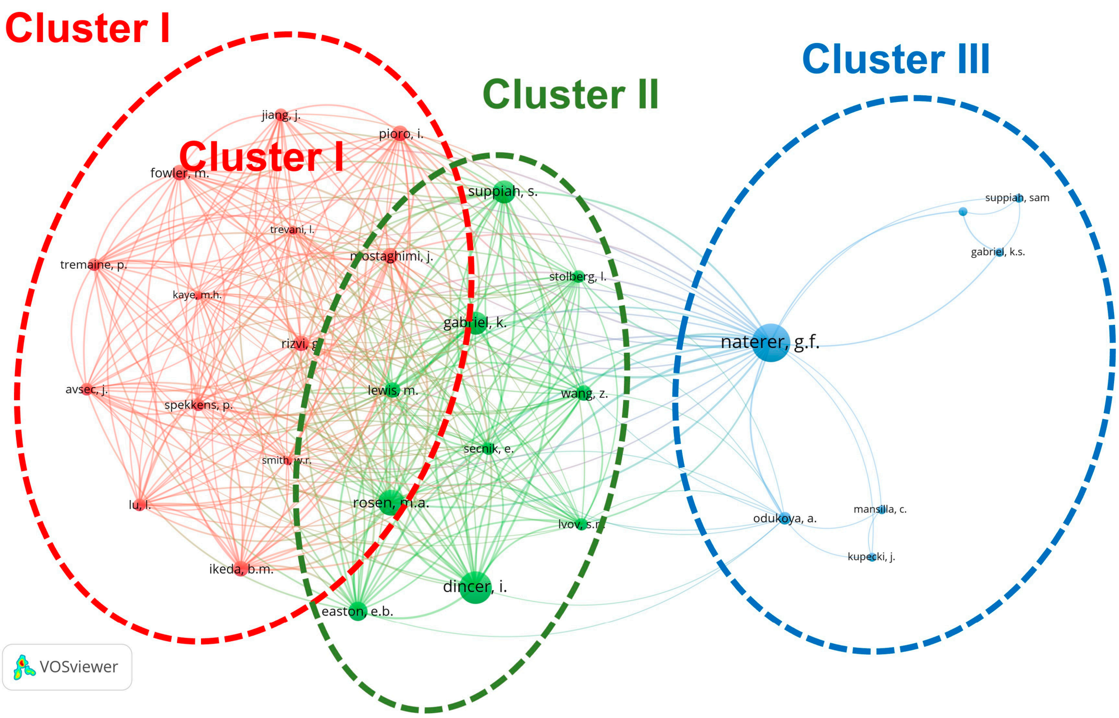

Figure 6. Authors with the highest number of co-citations (1962–2024). Source: developed by the authors in VOS Viewer software 1.6.16.

Table 5. Top 5 scientific production by country according to authors' affiliation (1962–2024). Number of Articles, Number of Authors, SCP (publications with authors from a single country), MCP (Multiple Country Publications), Frequency of publication, and MCP ratio.

R	Country	Articles	Authors	SCP	MCP	Freq	MCP Ratio
1	United States of America	85	494	78	7	0.155	0.082
2	China	54	327	42	12	0.098	0.222
3	Canada	42	236	32	10	0.076	0.238
4	Japan	25	165	25	0	0.045	0
5	United Kingdom	18	76	12	6	0.033	0.333

To conclude the authorship analysis, if we analyze the network of the authors' countries of affiliation (Figure 7), the 550 articles analyzed are distributed in more than 50 countries. In line with the previous results, the influence of the most productive countries (Table 5) and others that also have some influence, such as the Russian Federation, India, Spain, South Korea, Italy, Poland, and Turkey, can be clearly observed.

Table 6 presents the analysis of pink hydrogen research according to the most relevant affiliations. As already seen in the Top 5 countries (Table 5), the dominant country in terms of number of articles is the United States of America, and the Idaho National Laboratory topped the list of most relevant affiliations with a total of 47 publications, followed by the University of Ontario Institute of Technology (Canada), with 44. The Tsinghua University (China) was the third most prolific institution with 32 publications. The Hokkaido University (Japan) and The National RandD Institute for Cryogenics (Romania) are the last affiliations of this Top 5, with 16 articles, respectively.

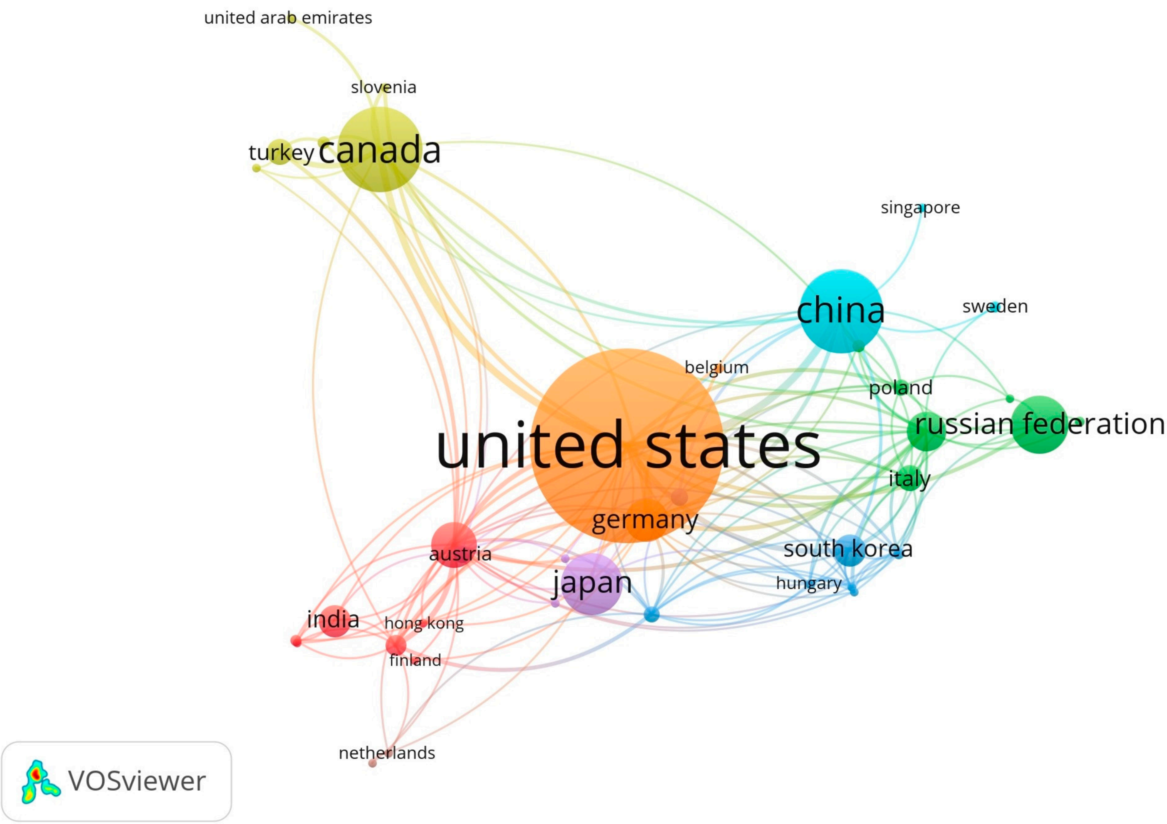

Figure 7. Network of authors' countries of affiliation (1962–2024). Source: developed by the authors in VOS Viewer software 1.6.16.

Table 6. Top 5 most relevant affiliations (1962–2024).

R	Affiliation	Country	Articles
1	Idaho National Laboratory	United States of America	47
2	University of Ontario Institute of Technology	Canada	44
3	Tsinghua University	China	32
4	Hokkaido University	Japan	16
5	National Research and Development Institute for Cryogenic and Isotopic Technologies	Romania	16

In terms of the number of citations, Table 7 shows the countries with the highest number of citations. In the period 1962–2024, the United States of America, China, Canada, Turkey, and Germany are the countries with the highest number of citations on pink hydrogen. It is noteworthy that Turkey and Germany are among the countries with the highest number of citations (Table 7) but are not among the most productive countries (Table 5).

Looking further into the citation analysis, if we analyze the articles with the highest number of citations (Table 8), the article "Potential importance of hydrogen as a future solution to environmental and transportation problems" [39] is the one with the highest number of global citations, i.e., 1042 citations and an average of 61.29 citations per year, followed by "A comparative technoeconomic analysis of renewable hydrogen production using solar energy" [40], with 626 citations and an average of 69.56 citations per year. The Top 5 is completed by the article "Current status, research trends, and challenges in water electrolysis science and technology" [41], with 410 citations and an average of 82.00 per year.

Table 7. Most cited countries (1962–2024). TC (Total Citations), Average article citation.

R	Affiliation	TC	Average Article Citation
1	United States of America	4687	55.10
2	China	3722	68.90
3	Canada	2016	48.00
4	Turkey	1378	114.80
5	Germany	797	99.60
6	United Kingdom	684	38.00
7	Japan	454	18.20

Table 8. Most global citations (1962–2024). TC (Total Citations), TC per year, Normalized TC.

R	Affiliation	Reference	Total Citations	TC Per Year	Normalized TC
1	Balat, M. (2008)	[2]	1042	61.29	12.54
2	Shaner, M.R. (2016)	[3]	626	69.56	9.46
3	Qiu, W. (2018)	[4]	611	87.29	6.89
4	Smiglak, M. (2014)	[5]	439	39.91	10.08
5	Grigoriev, S.A. (2020)	[6]	410	82.00	8.84

Author keywords in articles are a tool that helps indexers and search engines find relevant papers. If database search engines can find the authors' keywords, it will increase the number of people reading the manuscript and is likely to result in more citations [42–44]. Similarly, this information can be used to identify research trends in pink hydrogen. The 50 most frequently used keywords in the articles are presented in the form of a word tree. The TreeMap in Figure 8 presents the potential keywords, with "electrolysis" and "hydrogen production" being the most used. Other relevant keywords are "carbon dioxide", "hydrogen storage", "energy efficiency", "nuclear power plants", "nuclear reactors", and "electrochemistry". It should be noted that "pink hydrogen" does not appear among the 50 most relevant keywords in the field.

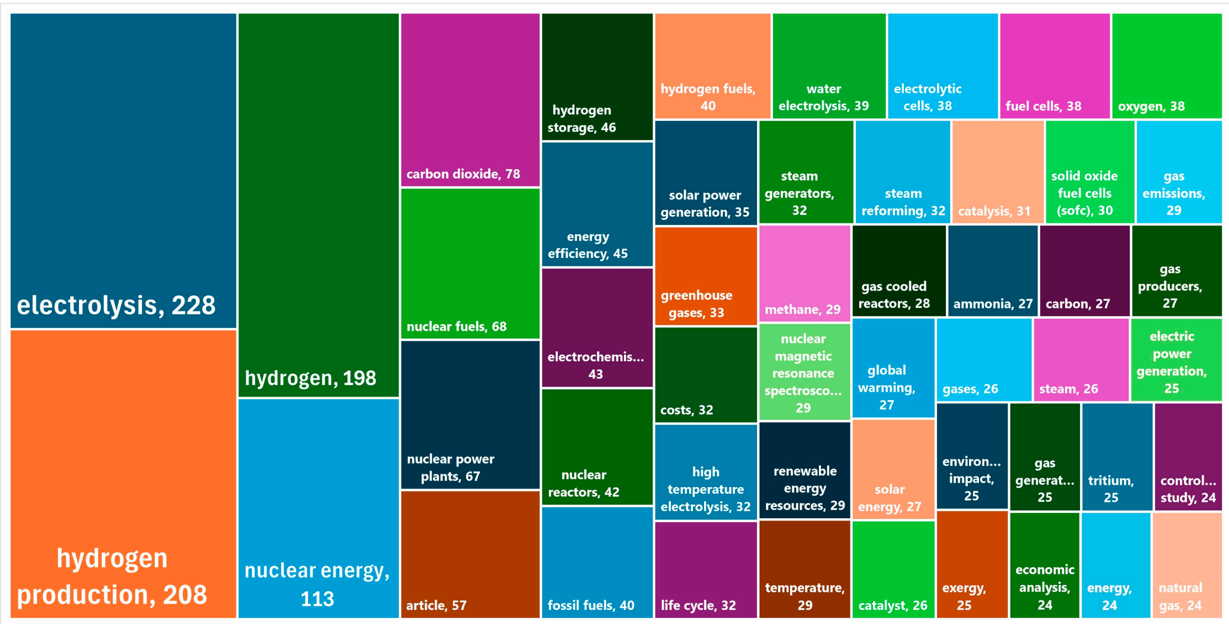

Figure 8. Word TreeMap (1962–2024) (data collected from Scopus database in April 2024).

Finally, with regard to the analysis of keywords through co-occurrence (Figure 9), the keywords most frequently used to classify the 550 articles in the sample are identified and analyzed. From this analysis, the most frequent topics in the analyzed area stand out.

Of the 550 results found, 5326 keywords were identified. Of these, 379 words appeared more than five times, equivalent to approximately 7% of the total number of keywords, while 1328 keywords, 25% of the total, were repeated on more than two occasions. Seven clusters were obtained, among them Cluster I (215 items, green) with reference keywords such as "catalysis", "reaction analysis", "electron transport", and "synthesis". Cluster II (207 items, red) includes keywords such as "nuclear fuels", "hydrogen production", "steam", "electrolytic cells", and "gas-cooled reactors". Finally, in Cluster III (66 items, orange) the most-used keyword, "electrolysis", stands out.

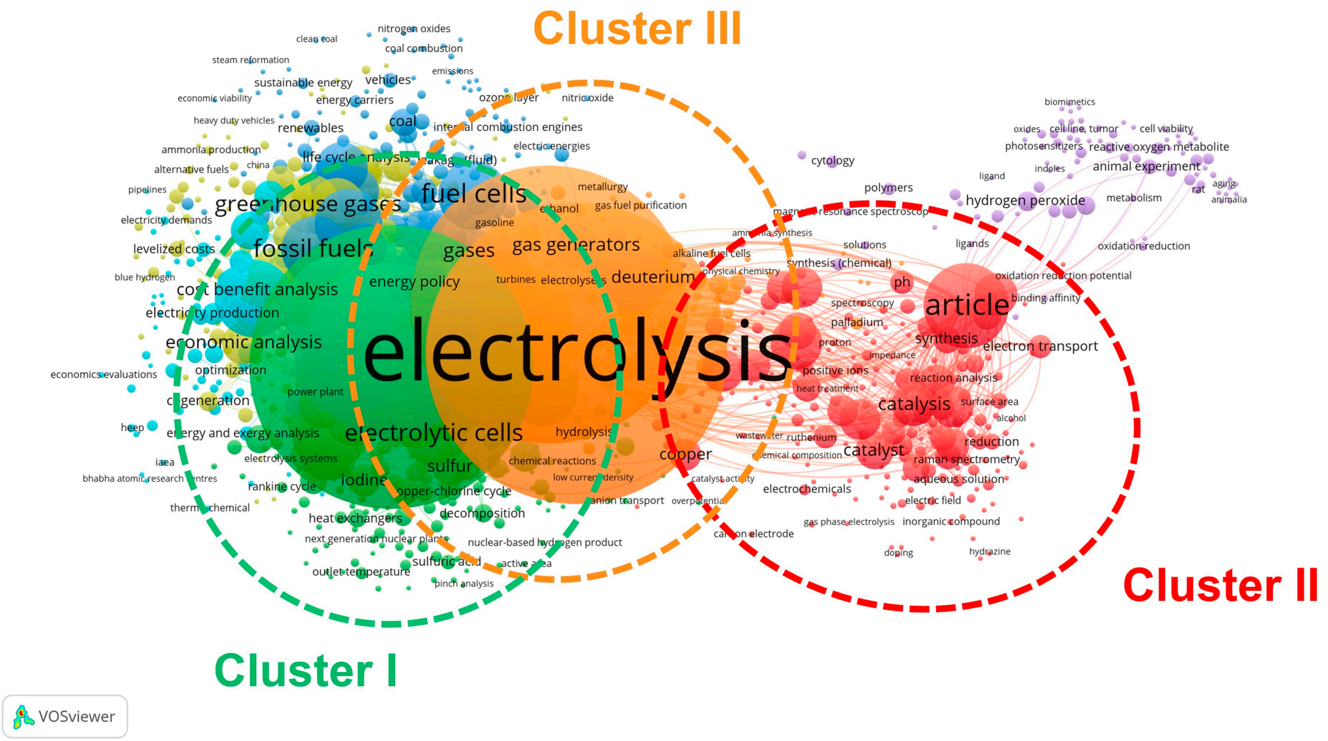

Figure 9. Keyword trends and cluster structure (1962–2024). Source: developed by the authors in VOS Viewer software 1.6.16.

4. Discussion

The analysis of the frequency of use of the most relevant keywords over time (Figure 10) provides an overview of the trends in pink hydrogen research. In other words, it explains the evolution of the popularity of the different concepts over time [45].

Based on recent articles, it is clear that concepts such as "electrolysis" and "hydrogen" have increased in importance mainly since 2003 and continue to be the most relevant concepts. A different case is that of the concept "hydrogen production" whose frequency of use has increased since 2007, to position itself in the Top 3 of the most relevant concepts in pink hydrogen. These three concepts, together with "nuclear energy" are the only ones that managed to reach more than 100 uses per year. Concepts such as "carbon dioxide", "nuclear power plants", "hydrogen storage", and "energy efficiency" have a lower frequency of use over time than the rest, not reaching 100 occurrences per year.

To represent the degree of development and importance of current research and to expose the lines of research in trend, a thematic map has been developed (Figure 11). The bubbles represent groups of keywords (themes). Their names are the most relevant keywords based on their co-occurrence. The map shows four quadrants: (i) motor themes (high density and centrality); (ii) basic themes (low density and high centrality); (iii) niche themes (high density and low centrality); (iv) emerging/declining themes (low density and centrality) [46]. In the case of pink hydrogen research, no terms are found in the motor and emerging/declining themes quadrants. In the niche themes quadrant are "nuclear magnetic resonance spectroscopy" and "catalysis"; however, in the basic themes quadrant are the terms "electrolysis", "hydrogen production", and "hydrogen".

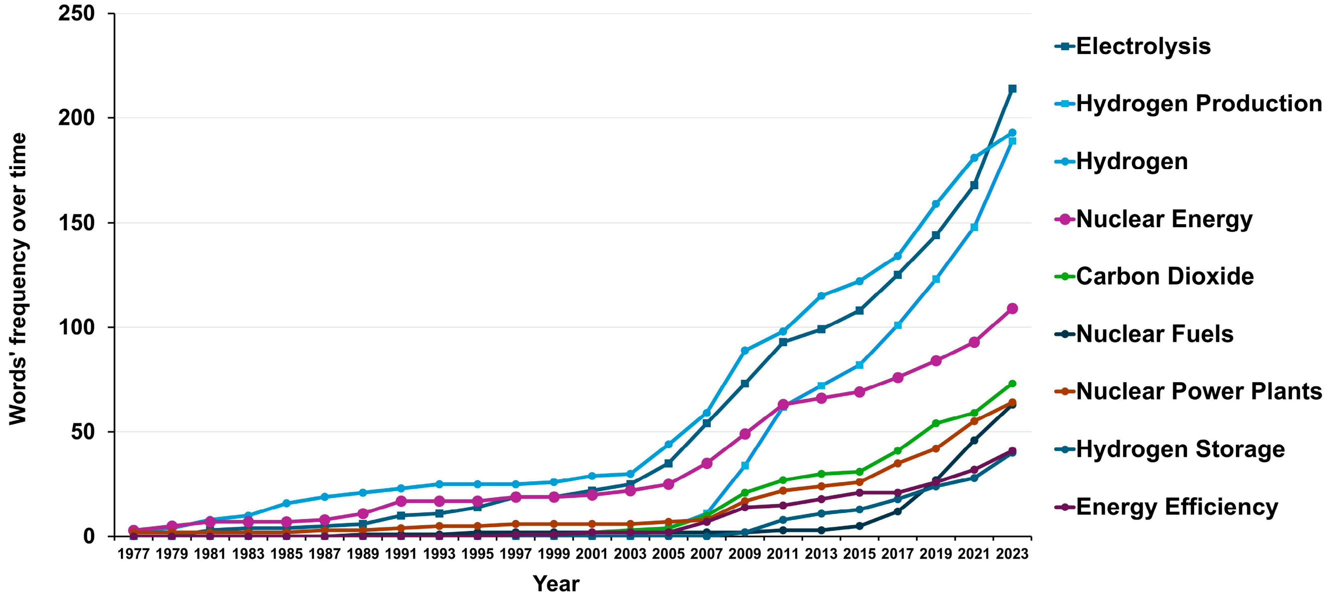

Figure 10. Words' frequency over time (1962–2024).

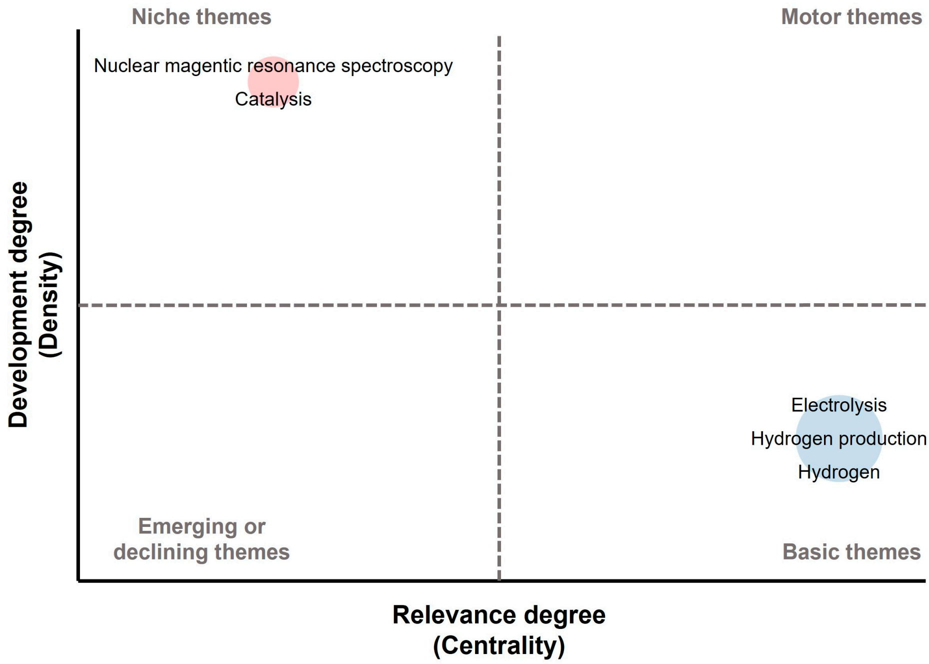

Figure 11. Thematic map on the degree of importance and development of the lines of research (1962–2024) (data collected from Scopus database in April 2024).

On the other hand, the Multiple Correspondence Analysis (MCA) of the keywords (Figure 12) shows the conceptual structure of the keywords associated with the articles on pink hydrogen included in this study. The conceptual structure maps provide a more detailed view of the closeness and divergence in the research area, so that it is possible to identify the smallest number of factors that may represent the relationship between several variables [47]. In these conceptual structure maps, there are two main dimensions (Dim. 1 and Dim. 2) that were identified by factor analysis of the data. Combined, these two dimensions allow a more complete understanding of the structure and relationships within the analyzed data set, contributing to the identification of important patterns and trends [48]. In dimension 1 (Dim. 1), variables with high factor loadings in this dimension are considered to have a strong association or to be correlated with each other. In this case, the degree of association in Dim 1 is 45.65%. In dimension 2 (Dim. 2), variables with high factor loadings in this dimension can be considered to have different or differential behavior compared to those in Dim. 1. In this case, the additional variability of the data in Dim 2 is 17.74%. It is observed that the variables are grouped in a cluster (network), in which most of the concepts have a strong association between the variables (Dim 1) and yet do not have a significant variability in both directions of the factor space (Dim 2). The concepts included in this cluster such as "water electrolysis", "nuclear energy", or "hydrogen production", are closely correlated, but have less variability. Keywords that are close to the central point indicate that they have received a lot of attention in recent years [49] and are therefore close to the general theme. In view of these keyword results, it is possible to determine that there is no close relationship between the keywords and, consequently, pink hydrogen research lacks keywords of general relevance.

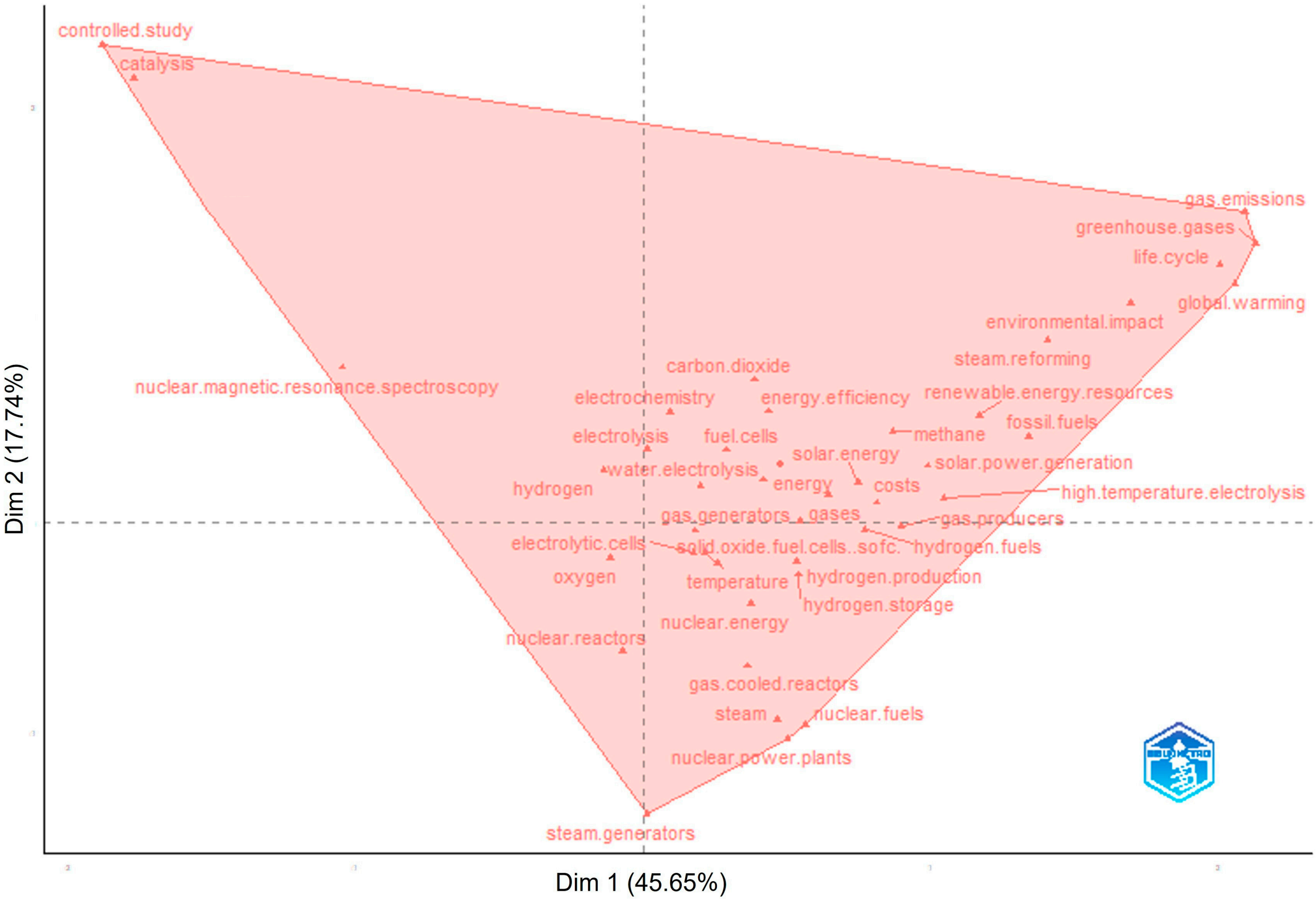

Figure 12. Multiple Correspondence Analysis (MCA) (1962–2024) (data collected from Scopus database in April 2024).

To conclude, in the countries with the highest scientific productivity in pink hydrogen research (Table 5), the following variables are compared (Figure 13): (i) Scopus results on "pink hydrogen" (Table 3); (ii) citations (Table 7); (iii) nuclear power plants in operation [12]; (iv) nuclear power plants under construction [12]. According to the results obtained, it is possible to affirm that in the countries where there is a greater interest in pink hydrogen research, there is also high nuclear energy development. The United States and China lead both pink hydrogen research and the development of the nuclear industry, in view of the results found in Scopus and the number of nuclear power plants in operation and under construction. Canada, Japan, and the United Kingdom are in an intermediate position, with a lukewarm development of research in the field and a less developed nuclear industry. In this scenario, the United States and China have a preferential position when it comes to deploying pink hydrogen technology in their nuclear power plants, both in operation and under construction.

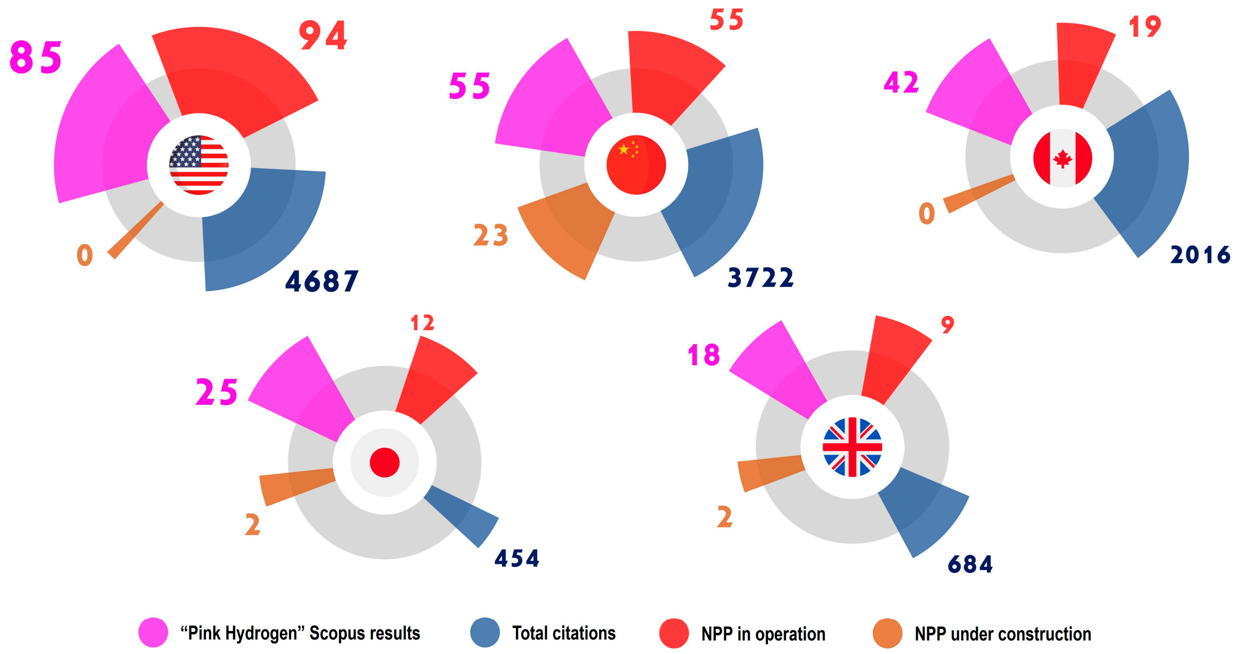

Figure 13. International comparison of different variables around pink hydrogen (data collected from Scopus database and PRIS IAEA [7] in April 2024).

5. Conclusions

Pink hydrogen uses the electrical energy generated in a nuclear reactor to produce hydrogen from the water electrolysis process. Given the interest generated by the different hydrogen generation technologies in the face of the current challenges of energy transition, the present work makes a global review of the evolution of the technology. The bibliographic database selected for this review is Scopus.

Taking into account the average age of the 550 articles analyzed in this research, 13.6 years, and the low productivity per author, 0.29 article/author, pink hydrogen is still in an early stage of development as a clean and renewable energy source, but the annual growth rate of 5.58% reflects a progressive increase of interest in the subject by the scientific community. The results obtained in the analysis of the reference authors in the field reflect that only the three most relevant authors have more than 10 publications on pink hydrogen. This data reflects a certain immaturity of the subject.

The analysis of the keywords and the Multiple Correspondence Analysis (MCA) reflect the generality of the most relevant keywords used, little oriented towards the technical development of the technology, as well as the non-existence of a close relationship between these terms, being used in common on few occasions. The thematic map of Thermes has reflected a reduced number of emerging terms, which reflects research lacking in innovation and differentiating elements.

Finally, the results obtained in the analysis of the relationship between nuclear energy and pink hydrogen research in the most relevant countries in the field indicate that the United States of America, China, Canada, Japan, or the United Kingdom are the countries that show the greatest interest of their scientific community in pink hydrogen technology. Likewise, they are also the most influential in terms of citations. However, if these results are compared with the development of the national nuclear industry, in terms of nuclear power plants in operation and under construction, the United States of America and China have a predominant position in terms of potential for the development of pink hydrogen. The rest of the nuclear powers, Canada, Japan, and the United Kingdom, have a lower potential for the development of this technology.

Despite the immaturity of pink hydrogen research, it is expected that this technology, as well as the rest of the technologies related to hydrogen as an energy carrier, will play an important role in the coming years in the transition towards a more sustainable energy future, offering a promising alternative to fossil fuels and helping reduce greenhouse gas emissions. Therefore, it is foreseeable that the future development of Gen IV nuclear reactors as well as Small Modular Reactor (SMR) designs will also favor the implementation of pink hydrogen as a source of electricity generation and storage.

Future lines of research, through the bibliometric review, may include the following: (i) analyzing the efficiency and economic viability of pink hydrogen production processes in comparison with other forms of hydrogen production; (ii) identifying technical advances in pink hydrogen storage and distribution systems for integration into the energy infrastructure.

Author Contributions: Conceptualization and methodology, P.F.-A. and D.V.; validation, P.F.-A., Á.A.-S. and D.V.; formal analysis, P.F.-A.; investigation, P.F.-A., Á.A.-S. and D.V.; writing—original draft preparation, P.F.-A., Á.A.-S. and D.V.; writing—review and editing, P.F.-A., Á.A.-S., G.L. and D.V.; supervision, Á.A.-S., G.L. and D.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research has been supported by Diputación de Ávila (Spain) for the project 2020–2024 PT 2022_002, in the framework of CTC, Innovation and Entrepreneurship of the Territorial Development Programme of Ávila and its Surroundings.

Data Availability Statement: The data are available upon request to the corresponding authors.

Acknowledgments: The authors wish to acknowledge the financial support provided by the following Spanish Institutions: Diputación de Ávila (Spain) for the project 2020–2024 PT 2022_002, in the framework of CTC, Innovation and Entrepreneurship of the Territorial Development Programme of Ávila and its Surroundings.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Abbott, D. Keeping the Energy Debate Clean: How Do We Supply the World's Energy Needs? *Proc. IEEE* **2010**, *98*, 42–66. [CrossRef]
2. Pearce, J.M. Limitations of Nuclear Power as a Sustainable Energy Source. *Sustainability* **2012**, *4*, 1173–1187. [CrossRef]
3. Patriotta, G.; Gond, J.P.; Schultz, F. Maintaining Legitimacy: Controversies, Orders of Worth, and Public Justifications. *J. Manag. Stud.* **2011**, *48*, 1804–1836. [CrossRef]
4. Toshinsky, G.; Petrochenko, V. Modular Lead-Bismuth Fast Reactors in Nuclear Power. *Sustainability* **2012**, *4*, 2293–2316. [CrossRef]
5. Fernández-Arias, P.; Vergara, D.; Orosa, J.A. A Global Review of PWR Nuclear Power Plants. *Appl. Sci.* **2020**, *10*, 4434. [CrossRef]
6. Sato, A.; Lyamzina, Y. Diversity of Concerns in Recovery after a Nuclear Accident: A Perspective from Fukushima. *Int. J. Environ. Res. Public. Health* **2018**, *15*, 350. [CrossRef] [PubMed]
7. Fernández-Arias, P.; Vergara, D.; Antón-Sancho, Á. Global Review of International Nuclear Waste Management. *Energies* **2023**, *16*, 6215. [CrossRef]
8. Takebayashi, Y.; Lyamzina, Y.; Suzuki, Y.; Murakami, M. Risk Perception and Anxiety Regarding Radiation after the 2011 Fukushima Nuclear Power Plant Accident: A Systematic Qualitative Review. *Int. J. Environ. Res. Public Health* **2017**, *14*, 1306. [CrossRef] [PubMed]
9. McBeth, M.K.; Warnement Wrobel, M.; van Woerden, I. Political Ideology and Nuclear Energy: Perception, Proximity, and Trust. *Rev. Policy Res.* **2023**, *40*, 88–118. [CrossRef]
10. Pralle, S.; Boscarino, J. Framing Trade-Offs: The Politics of Nuclear Power and Wind Energy in the Age of Global Climate Change. *Rev. Policy Res.* **2011**, *28*, 323–346. [CrossRef]
11. Dehner, G.; McBeth, M.K.; Moss, R.; van Woerden, I. A Zero-Carbon Nuclear Energy Future? Lessons Learned from Perceptions of Climate Change and Nuclear Waste. *Energies* **2023**, *16*, 2025. [CrossRef]
12. IAEA. The Power Reactor Information System (PRIS). Available online: https://pris.iaea.org/PRIS/home.aspx (accessed on 8 April 2024).

13. Heredia Yzquierdo, J.; Sánchez-Bayón, A. The European Transition to a Green Energy Production Model: Italian Feed-in Tariffs Scheme & Trentino Alto Adige Mini Wind Farms Case Study. *Small Bus. Int. Rev.* **2020**, *4*, 39–52. [CrossRef]
14. Merk, B.; Litskevich, D.; Whittle, K.R.; Bankhead, M.; Taylor, R.J.; Mathers, D. On a Long Term Strategy for the Success of Nuclear Power. *Energies* **2017**, *10*, 867. [CrossRef]
15. Harto, A.A.W.; Agung, A.; Ridwan, M.K.; Li, G.; Du, B.; Liu, L.; Chen, X.; Lai, X.; Ai, Y.; Rahmanta, M.A.; et al. Nuclear Power Plant to Support Indonesia's Net Zero Emissions: A Case Study of Small Modular Reactor Technology Selection Using Technology Readiness Level and Levelized Cost of Electricity Comparing Method. *Energies* **2023**, *16*, 3752. [CrossRef]
16. Abram, T.; Ion, S. Generation-IV Nuclear Power: A Review of the State of the Science. *Energy Policy* **2008**, *36*, 4323–4330. [CrossRef]
17. Sadik-Zada, E.R. Political Economy of Green Hydrogen Rollout: A Global Perspective. *Sustainability* **2021**, *13*, 13464. [CrossRef]
18. Zhou, Y.; Li, R.; Lv, Z.; Liu, J.; Zhou, H.; Xu, C. Green Hydrogen: A Promising Way to the Carbon-Free Society. *Chin. J. Chem. Eng.* **2022**, *43*, 2–13. [CrossRef]
19. Arcos, J.M.M.; Santos, D.M.F. The Hydrogen Color Spectrum: Techno-Economic Analysis of the Available Technologies for Hydrogen Production. *Gases* **2023**, *3*, 25–46. [CrossRef]
20. Horvath, A.; Rachlew, E. Nuclear Power in the 21st Century: Challenges and Possibilities. *Ambio* **2016**, *45*, 38–49. [CrossRef]
21. Lechtenböhmer, S.; Samadi, S. Blown by the Wind. Replacing Nuclear Power in German Electricity Generation. *Environ. Sci. Policy* **2013**, *25*, 234–241. [CrossRef]
22. Brook, B.W.; Alonso, A.; Meneley, D.A.; Misak, J.; Blees, T.; van Erp, J.B. Why Nuclear Energy Is Sustainable and Has to Be Part of the Energy Mix. *Sustain. Mater. Techno.* **2014**, *1–2*, 8–16. [CrossRef]
23. Züttel, A. Materials for Hydrogen Storage. *Mater. Today* **2003**, *6*, 24–33. [CrossRef]
24. Eberle, U.; Felderhoff, M.; Schüth, F. Chemical and Physical Solutions for Hydrogen Storage. *Angew. Chem. Int. Edit.* **2009**, *48*, 6608–6630. [CrossRef] [PubMed]
25. Catumba, B.D.; Sales, M.B.; Borges, P.T.; Ribeiro Filho, M.N.; Lopes, A.A.S.; de Sousa Rios, M.A.; Desai, A.S.; Bilal, M.; Santos, J.C.S. dos Sustainability and Challenges in Hydrogen Production: An Advanced Bibliometric Analysis. *Int. J. Hydrogen Energy* **2023**, *48*, 7975–7992. [CrossRef]
26. Kar, S.K.; Harichandan, S.; Roy, B. Bibliometric Analysis of the Research on Hydrogen Economy: An Analysis of Current Findings and Roadmap Ahead. *Int. J. Hydrogen Energy* **2022**, *47*, 10803–10824. [CrossRef]
27. Fernández-Arias, P.; Antón-Sancho, Á.; Lampropoulos, G.; Vergara, D. On Green Hydrogen Generation Technologies: A Bibliometric Review. *Appl. Sci.* **2024**, *14*, 2524. [CrossRef]
28. Raman, R.; Nair, V.K.; Prakash, V.; Patwardhan, A.; Nedungadi, P. Green-Hydrogen Research: What Have We Achieved, and Where Are We Going? Bibliometrics Analysis. *Energy Rep.* **2022**, *8*, 9242–9260. [CrossRef]
29. Corsini, F.; Certomà, C.; Dyer, M.; Frey, M. Participatory Energy: Research, Imaginaries and Practices on People' Contribute to Energy Systems in the Smart City. *Technol. Forecast. Soc. Chang.* **2019**, *142*, 322–332. [CrossRef]
30. Nerur, S.P.; Rasheed, A.A.; Natarajan, V. The intellectual structure of the strategic management field: An author co-citation analysis. *Strateg. Manag. J.* **2008**, *29*, 319–336. [CrossRef]
31. Maier, D.; Maier, A.; Aşchilean, I.; Anastasiu, L.; Gavriş, O. The Relationship between Innovation and Sustainability: A Bibliometric Review of the Literature. *Sustainability* **2020**, *12*, 4083. [CrossRef]
32. Extremera, J.; Vergara, D.; Rodríguez, S.; Dávila, L.P. Reality-Virtuality Technologies in the Field of Materials Science and Engineering. *Appl. Sci.* **2022**, *12*, 4968. [CrossRef]
33. Cortese, T.T.P.; de Almeida, J.F.S.; Batista, G.Q.; Storopoli, J.E.; Liu, A.; Yigitcanlar, T. Understanding Sustainable Energy in the Context of Smart Cities: A PRISMA Review. *Energies* **2022**, *15*, 2382. [CrossRef]
34. Regona, M.; Yigitcanlar, T.; Xia, B.; Li, R.Y.M. Opportunities and Adoption Challenges of AI in the Construction Industry: A PRISMA Review. *J. Open Innov. Technol. Mark. Complex.* **2022**, *8*, 45. [CrossRef]
35. Rocha, G.d.S.R.; de Oliveira, L.; Talamini, E. Blockchain Applications in Agribusiness: A Systematic Review. *Future Internet* **2021**, *13*, 95. [CrossRef]
36. Cupp, C.R.; Flubacher, P. An Autoradiographic Technique for the Study of Tritium in Metals and Its Application to Diffusion in Zirconium at 149° to 240 °C. *J. Nucl. Mater.* **1962**, *6*, 213–228. [CrossRef]
37. IAEA. Nuclear Power Capacity Trend. Available online: https://pris.iaea.org/PRIS/WorldStatistics/WorldTrendNuclearPowerCapacity.aspx (accessed on 6 April 2024).
38. Hinojo-Lucena, F.-J.; Aznar-Díaz, I.; Cáceres-Reche, M.-P.; Romero-Rodríguez, J.-M. Artificial Intelligence in Higher Education: A Bibliometric Study on its Impact in the Scientific Literature. *Educ. Sci.* **2019**, *9*, 51. [CrossRef]
39. Balat, M. Potential Importance of Hydrogen as a Future Solution to Environmental and Transportation Problems. *Int. J. Hydrogen Energy* **2008**, *33*, 4013–4029. [CrossRef]
40. Shaner, M.R.; Atwater, H.A.; Lewis, N.S.; Mcfarland, E.W. A Comparative Technoeconomic Analysis of Renewable Hydrogen Production Using Solar Energy. *Energy Environ. Sci.* **2016**, *9*, 2354. [CrossRef]
41. Grigoriev, S.A.; Fateev, V.N.; Bessarabov, D.G.; Millet, P. Current Status, Research Trends, and Challenges in Water Electrolysis Science and Technology. *Int. J. Hydrogen Energy* **2020**, *45*, 26036–26058. [CrossRef]
42. Qiu, W.; Xie, X.-Y.; Qiu, J.; Fang, W.-H.; Liang, R.; Ren, X.; Ji, X.; Cui, G.; Asiri, A.M.; Cui, G.; et al. High-Performance Artificial Nitrogen Fixation at Ambient Conditions Using a Metal-Free Electrocatalyst. *Nat. Commun.* **2018**, *9*, 3485. [CrossRef] [PubMed]

43. Smiglak, M.; Pringle, J.M.; Lu, X.; Han, L.; Zhang, S.; Gao, H.; Macfarlane, D.R.; Rogers, R.D. Ionic Liquids for Energy, Materials, and Medicine. *Chem. Commun.* **2014**, *50*, 9228. [CrossRef]
44. Baiyegunhi, T.L.; Baiyegunhi, C.; Pharoe, B.K. Global Research Trends on Shale Gas from 2010–2020 Using a Bibliometric Approach. *Sustainability* **2022**, *14*, 3461. [CrossRef]
45. Sharma, A.; Shenoy, S.S. Bibliometric Portrait of the Theory of Community-Based Enterprise: Evolution and Future Directions. *Cogent Bus. Manag.* **2024**, *11*, 2315685. [CrossRef]
46. Romero-Perdomo, F.; Carvajalino-Umaña, J.D.; Moreno-Gallego, J.L.; Ardila, N.; González-Curbelo, M.Á. Research Trends on Climate Change and Circular Economy from a Knowledge Mapping Perspective. *Sustainability* **2022**, *14*, 521. [CrossRef]
47. Iman, B.; Yuadi, I.; Sukoco, B.M.; Purwono, R.; Hu, C.-C. Mapping Research Trends With Factorial Analysis in Organizational Politics. *Sage Open* **2023**, 13. [CrossRef]
48. Nica, I.; Chiriță, N. The Dynamics of Commodity Research: A Multi-Dimensional Bibliometric Analysis. *Commodities* **2024**, *3*, 127–150. [CrossRef]
49. Ejaz, H.; Zeeshan, H.M.; Ahmad, F.; Bukhari, S.N.A.; Anwar, N.; Alanazi, A.; Sadiq, A.; Junaid, K.; Atif, M.; Abosalif, K.O.A.; et al. Bibliometric Analysis of Publications on the Omicron Variant from 2020 to 2022 in the Scopus Database Using R and VOSviewer. *Int. J. Environ. Res. Public Health* **2022**, *19*, 12407. [CrossRef]