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Exploring Iron Oxide's Role in Hydrogen Production: Bibliographic and Bibliometric Analysis

Nandiyanto A. B. D. [1,*], Ragadhita R. [1], Fiandini M. [2], Al Husaeni D. N. [3], Aziz M. [4]
[1]*Departemen Kimia, Universitas Pendidikan Indonesia Jl. Setiabudhi No. 229, Bandung, Indonesia*
[2]*Deparrtemen Pendidikan Ilmu Pengetahuan Indonesia, Universitas Pendidikan Indonesia Jl. Setiabudhi No. 229, Bandung, Indonesia*
[3]*Departemen Computer Science Education, Universitas Pendidikan Indonesia, Jl. Setiabudhi 229, Bandung, Indonesia.*
[4]*The University of Tokyo, Japan*
**Corresponding author, Email address: nandiyanto@upi.edu*

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Abstract: This work used VOSviewer to conduct bibliometric studies on the Scopus database to examine scientific trends in metal oxide oxidation-reduction processes for energy storage systems. This study is supplemented by a literature assessment of the most recent theoretical breakthroughs in iron-based catalysis for hydrogen production and energy storage systems. 1980 related research documents were collected and selected from the Scopus database based on the results of harvesting research documents on related topics using the keywords "iron," "hydrogen," "energy," and "oxide" using Publish or Perish in the last ten years (2014–2023). According to data analysis for the last ten years, publications on connected keywords increased in 2016–2022 from 106 to 332 articles and declined in 2023 to 169 publications. Three types of analysis visualization on the catch data are available to help this study: network visualization, overlay visualization, and density visualization. The findings of this study could help academics identify global research trends relating to the proposed keywords, which may then be utilized as a reference in future research.

Keywords: Bibliometric; Energy storage; Hydrogen; Iron; Water.

1. Introduction

On our globe, atomic hydrogen (H) is chemically bound in natural molecules and products such as water, petroleum, and coal. In contrast, molecular hydrogen (H_2) does not occur naturally in vast quantities on Earth and is only created in small amounts by certain microorganisms, which escape Earth's gravity into the atmosphere due to their low molecular weight (Heift, 2019). Although hydrogen is rare on Earth, it is undeniable that it will be the primary source of energy in the future because it has the highest gravimetric energy density of any known substance (lower calorific value 120 MJ/kg), is non-toxic, and can be obtained from water (Møller *et al.,* 2017). Using water and renewable energy as sustainable materials and energy sources, respectively, researchers have been working for decades on inexpensive and profitable processes to catalyze the decomposition reactions of water into clean molecular hydrogen and oxygen. One of the oldest and commercially practiced methods in the early 20th century for the production of hydrogen from water is the "steam-iron" process

in which iron and water react to produce iron oxide and hydrogen ($3Fe + 4H_2O \rightarrow Fe_3O_4 + 4H_2$) (Ryabchuck *et al*., 2016, Hacker *et al*., 2000).

Because renewable energy (wind, solar, and tides) is unpredictable, hydrogen, regardless of season, can be used as an alternative energy storage that can be kept longer and used when the need arises (Thiryagarajan *et al*., 2022). Hydrogen, the lightest and most abundant element with a high energy content, may be created from both renewable and non-renewable sources, as explained previously that clean hydrogen can be produced by the water electrolysis process (Ryabchuck *et al*., 2016, Hacker *et al*., 2000). Therefore, the hydrogen energy chain is foreseen as one of the key technologies to deal with the problem of climate change and scarce oil resources. Finally, hydrogen can be used to feed fuel cells and generate electricity (and heat) on demand, releasing only water as a by-product and then closing the hydrogen cycle. Such electricity–hydrogen–electricity conversion process is only sustainable if the electricity is generated from renewable energy and cannot be directly injected into the grid, then can be used with fuel cells. Therefore, it is mandatory to add a storage step in the hydrogen chain for time management of hydrogen production and use (Otsuka *et al*., 2003, Dematteries *et al*., 2021).

The development of energy storage systems with high energy density to store renewable energy is crucial to decreasing global warming and developing a low-carbon future. According to recent research, redox reactions involving metal oxides have sparked a lot of interest in applications ranging from chemical looping systems to hydrogen storage (Adanez *et al*., 2012, Hossain and de Lasa, 2008). The metal oxide is reduced and re-oxidized multiple times in a chemical looping mechanism. During this reaction, fuel is transformed into CO_2, and high-grade heat is generated, which is then used to generate power via a steam turbine. It was previously said that hydrogen can be created by splitting the water. According to recent research, redox processes involving metal oxides have sparked a lot of interest for applications in chemical looping systems, production, and even hydrogen storage. Furthermore, a new energy storage system based on a metal oxide redox reaction using a solid oxide fuel cell (SOFC) and H_2-HO as a mediator is presented (Inoishi *et al*., 2012, Xu *et al*., 2011). The metal oxide is employed as a precursor in hydrogen production in this system. Hydrogen is created during the discharging process by metal oxidation by H_2O and is used in the SOFC to generate energy, eventually becoming H_2O. During the charging process, the hydrogen produced by the solid oxide electrolysis cell (SOEC) reacts with metal oxides, producing metals. Metal oxides such as Fe_2O_3, MnO_2, and CuO have a higher energy density than $LiCoO_2$, which is a common positive electrode material in Li-ion batteries (Kosaka *et al*., 2015).

Currently, the investigation of mechanisms that promote metal oxide redox reactions is very important and possibly leads to highly efficient energy storage systems. However, research related to systematic reviews to identify research trends, provide information, and assess the quality of the development of research topics related to hydrogen energy storage by metal oxides still does not provide sufficient information. Therefore, a bibliometric analysis was conducted for this research topic to analyze the literature related to metal oxide redox reactions for hydrogen production and energy storage systems. Bibliometric analysis is a method of conducting systematic reviews that identifies research trends and current concerns based on the history of a publication to acquire an overview of a research field and create results with more in-depth content analysis (Lrhoul *et al*., 2022, Salhi and Dafali, 2023). Many studies on bibliometric analysis were recently conducted to understand the research trends on a certain issue (Al Husaeni and Nandiyanto, 2022a, Al Husaeni and Nandiyanto, 2022b, Al Husaeni and Nandiyanto, 2023, Bilad, 2022, Fauziah, 2022, Hamidah *et al*., 2020, Hammouti, 2010, Hirawan *et al*., 2022, Kurniati *et al*., 2022, Luckyardi *et al*., 2022, Morante-Carballo *et al*., 2022, Mudzakir *et al*., 2022, Mulyawati and Ramadhan, 2021, Nandiyanto and Al Husaeni, 2022,

Nandiyanto *et al*., 2021, Nandiyanto *et al*., 2023a, Nandiyanto *et al*., 2020, Nordin, 2022, Nandiyanto *et al*., 2023b, Hofifah and Nandiyanto, 2024, Nandiyanto *et al*., 2024).

2. Discovery of Fe oxide reduction route to Fe via organic decomposition

The iron-making industry contributes around 70% to CO_2 emissions. To overcome these problems, an environmentally friendly iron-making method is needed. One of them is the method of reducing Fe oxide to Fe from the decomposition of organic matter or commonly known as bio-ironmaking. Historically, this method adopts a chemical looping combustion (CLC) (Lancee *et al.,* 2014). The use of organic matter as a substitute for coal, coke, and coke offers tremendous potential in providing CO_2 mitigation without consuming extra energy. In general, iron production mostly uses the hematite phase of iron oxide (Fe_2O_3) (Zuo *et al.,* 2018). Due to its abundance and high oxygen storage activity. **Figure 1** describes the route of reduction of Fe oxide (Fe_2O_3) to Fe from the decomposition of organic matter (C_xH_y). In this process, the iron oxide phase of hematite and organic materials are used as raw materials. The presence of organic matter acts as a supplier of carbon and iron oxide-reducing agents. In the process, organic matter is burned with iron oxide, where the oxygen lattice in the iron oxide is used to oxidize organic matter to produce CO_2 and H_2O. Meanwhile, the reduction of iron oxide undergoes a transformation from the hematite-phase iron oxide (Fe_2O_3) to the wustite-phase (Fe_xO), and finally to metal iron (Fe) through direct contact with carbon (C) from organic matter (C_xH_y) (Kudo *et al.,* 2013).

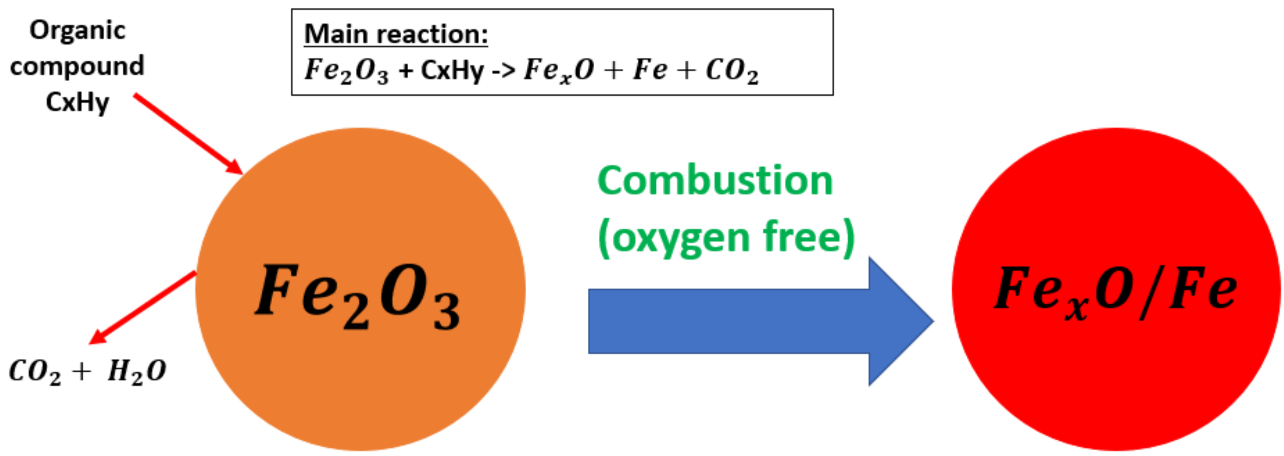

Figure 1. Schematic of the route reduction oFe_2O_3 to Fe from organic decomposition (Lin *et al*., 2018)

3. Recent theoretical Material and Method

3.1 Present status of hydrogen advances in iron-based catalysis for hydrogen production

The majority of researchers and specialists believe that hydrogen has great potential as an energy source in the future. The world's energy demand has increased due to three factors: population growth, economic growth, and the industrialization of developing countries. According to Balat (2008), global hydrogen production was nearly 44.5 million tons per year or 500 Bm^3 by the end of 2008, and energy demand is expected to reach 600–1000 EJ by 2050 (Hosseini and Wahid, 2016). According to Hosseini and Wahid (2016) hydrogen production, storage, and utilization are promising technologies for future energy supply. Currently, fossil fuel resources, such as coal, natural gas, and crude oil, supply approximately 80% of global energy demand (Hosseini and Wahid, 2014). Oil consumption is expected to reach 18.3 million barrels by 2040, which will be replaced by hydrogen-fuel cell-powered vehicles (cars and light trucks) because hydrogen-powered vehicles have been studied to be 2.5 times more efficient than gasoline-fueled vehicles, resulting in a total net energy saved by using petroleum of

approximately 11 million barrels/day of all hydrogen production through petroleum reforming (Armor, 2005).

3.2 Recent theoretical advances in hydrogen production

In industry, there are several technologies for producing hydrogen, one of the most advanced being hydrocarbon reforming (Dincer and Acar, 2015). Hydrocarbon reforming technology uses natural gas as a raw material on a large scale because it is the most ideal, abundant, and inexpensive. However, in addition to using natural gas as a feedstock for hydrogen production, other feedstocks, such as ethanol and methanol, may also be used because they are easy to handle and widely available (Rakib *et al.*, 2010). Here, chemical looping reforming (CLR) and chemical looping water splitting (CLWS) for hydrogen production are initially discussed. CLR and CLWS are two related technologies for combined hydrogen production with CO_2 capture. CLR is the processing of natural gas utilizing methane reforming to produce syngas using a metal oxide looper as an oxygen carrier, for example, CaO, Fe_2O_3, NiO, BaO, CuO, Al_2O_3, and others.

Generally, the CLR process for syngas production is carried out in a packed bed reactor. The CLR process is divided into three steps, namely reduction, oxidation, and steam reforming. The first step is the oxidation of the oxygen carrier by using oxygen from the air fed to the reactor. This reaction is exothermic and occurs at a relatively high temperature (higher than 800 °C). The second step is the reduction, to reduce the oxygen carrier and oxidize the fuel in the reactor (such as off-gas) using the oxygen from the oxygen carrier, producing H_2O and CO_2.

Furthermore, the O_2 product is stored as a reactant for other processes. The third step of steam reforming is carried out by utilizing the heat that is obtained from the oxidation stage. Yang *et al***.** (2022) reported that the Fe-based oxygen carrier in the methane system could perform well in transferring oxygen and reducing fuel. The process starts with Fe_2O_3 and goes through a phase of change to Fe_3O_4, after which it gradually reduces with CH_4 to create FeO/Fe. With the production of CO_2 and H_2O (R1), the complete oxidation of CH_4 is the primary reaction in stage 1. In the meantime, some CH_4 oxidation takes place, mostly in stages 2 and 3, to create syngas (R2 and R3). The amount of lattice oxygen available for CH_4 oxidation increases with a deeper reduction of iron oxide, and CH_4 cracking which is mostly mediated by Fe occurs to produce hydrogen and carbon precipitate (R4) (Zhou *et al*., 2023, Zheng *et al.,* 2022). A more concise schematic of the methane CLR step using Fe as the oxygen carrier is shown in **Figure 2**.

Besides CLR using methane as fuel, CLR technology is also applicable to renewable sources, one of which is the biomass used for hydrogen production. The CLR process for biomass is almost the same as CLR for methane. **Figure 3** is a chemical iteration of reforming biomass. Solid biomass is mixed directly with a gasified oxygen carrier. Steam gasification of biomass requires heat because it is an endothermic reaction, whereas air gasification of biomass is an exothermic process. After all, a part of the biomass is burned with oxygen. CLR technology by high-purity biomass and CO_2 sequestration can be generated by direct chemical repetition of biomass without purification technology, which could reduce energy consumption (Keller *et al*., 2016, Wei *et al.,* 2021). Meanwhile, the CLWS process is an emerging hydrogen generation technology via redox cycling. Historically, the chemical looping process for the generation of hydrogen was introduced as the “steam-iron” process (Voitic and Hacker, 2016).

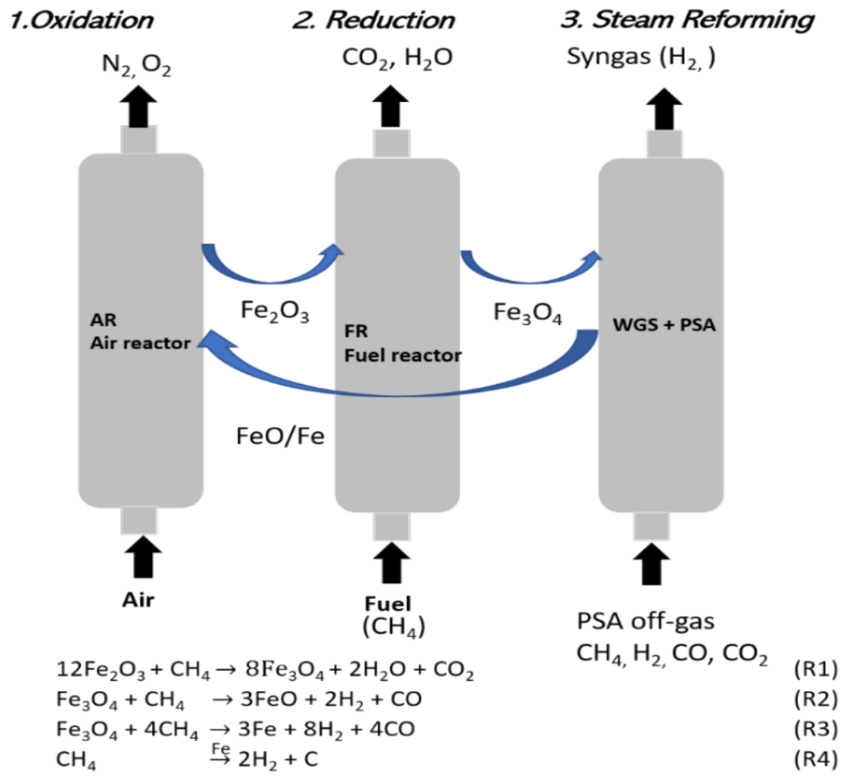

Figure 2 Schematic of the methane CLR step using Fe as the oxygen carrier (Zornoza *et al*., 2022)

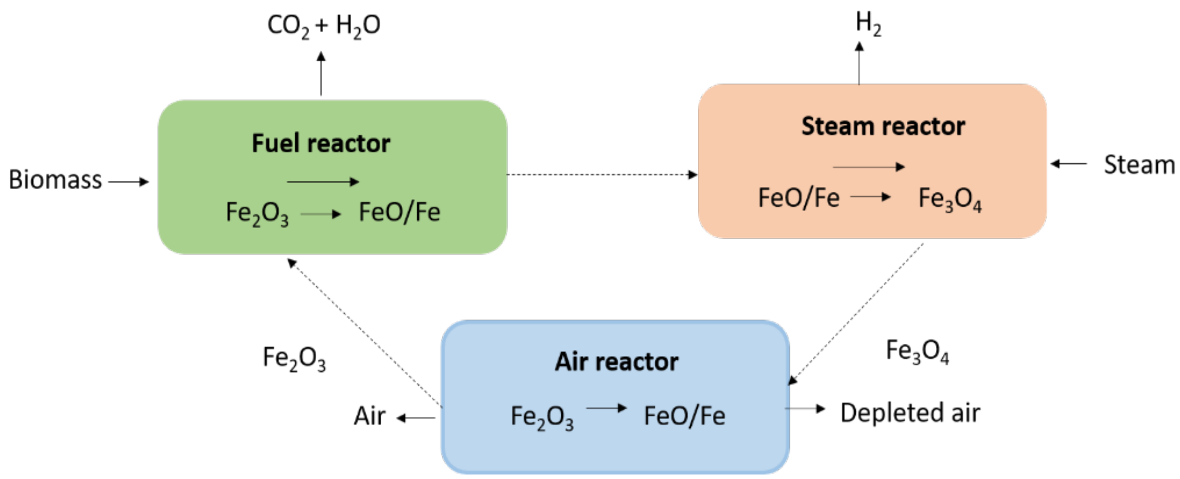

Figure 3. Diagram of steps for hydrogen production from biomass through chemical looping formation (Xiao *et al*., 2014)

In general, the CLWS technology process is illustrated in **Figure 4**. CLWS process primarily consists of reduction and oxidation steps with a metal oxide serving as the oxygen carrier, and it provides a potentially viable option for carbon-free hydrogen generation in conjunction with carbonaceous fuel conversion (Fan and Li, 2010). The oxygen carrier donates lattice oxygen for the conversion of fuel to chemicals or heat during the reduction step. The oxygen-depleted oxygen carrier is then re-oxidized by water steam to produce hydrogen in the oxidation step. In some cases, water-oxidized oxygen carriers may still require air oxidation (Protasova and Snijkers, 2016). Because of their high oxygen storage capacity (OSC), superior redox activity, and ease of availability, Fe_2O_3-based metal oxides are the most promising oxygen carriers in the CLWS process. Iron oxides are even being investigated for use in chemical looping hydrogen production (Voitic and Hacker, 2016).

Based on **Figure 4**, a three-step chemical looping can be generalized by relying on the ability of iron oxides oxygen carriers to transport oxygen between the three reactors, namely the fuel reactor (FR), steam reactor (SR), and air reactor (AR), as following Qiu *et al.* (2018):

1. Reduction step (CO used as fuels):

   $3Fe_2O_3 + CO \leftrightarrow 2Fe_3O_4 + CO_2$ $\Delta H_{1173\ K}$ = -41.04 kJ/mol (R1)

   $Fe_3O_4 + CO \leftrightarrow 3FeO + CO_2$ $\Delta H_{1173\ K}$ = 12.98 kJ/mol (R2)

   $FeO + CO \leftrightarrow Fe + CO_2$ $\Delta H_{1173\ K}$ = -16.29 kJ/mol (R3)

2. Steam oxidation

   $3FeO + H_2O \leftrightarrow Fe_3O_4 + H_2$ $\Delta H_{1173\ K}$ = -46.12 kJ/mol (R4)

   $3Fe + 4H_2O \leftrightarrow Fe_3O_4 + 4H_2$ $\Delta H_{1173\ K}$ = -96.64 kJ/mol (R5)

3. Air oxidization

   $4Fe_3O_4 + O_2 \leftrightarrow 6Fe_2O_3 + CO_2$ $\Delta H_{1173\ K}$ = -481.70 kJ/mol (R6)

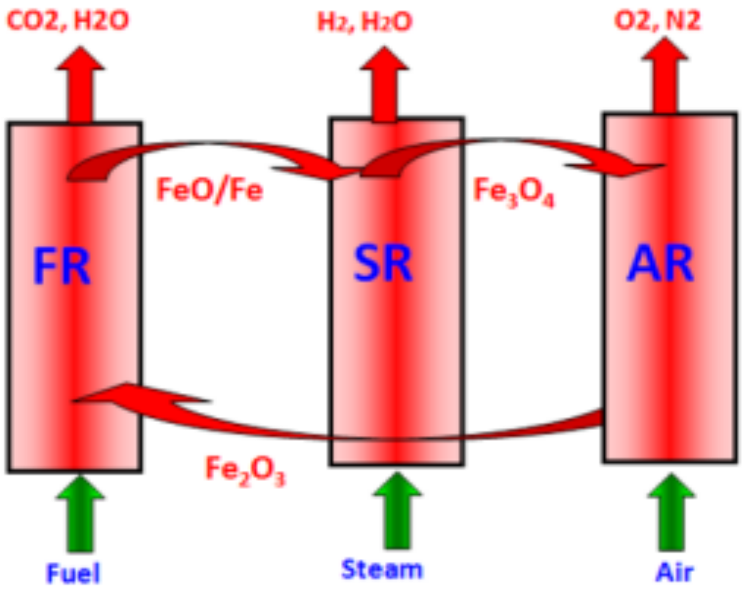

Figure 4. Illustration of chemical looping water-splitting technology (Qiu *et al*., 2018)

4. Method

Figure 5 is an illustration of the bibliometric analysis steps related to the topic of metal oxide redox reactions for energy storage (hydrogen production) systems which are explained in detail as follows:

1. Step 1: Harvesting Data

Harvesting data is the first step for trend analysis in research. At this stage, published research documents (articles) related to certain topics are collected using the Scopus database through the Scopus.com website. Research documents were collected using the keywords "iron," AND "hydrogen," AND "energy," AND "oxide" which are determined from the last ten years (2014-2023). After various published research documents have been collected, the search for suitable research documents is filtered based on the type of document in the form of journals. The number of research documents that have been successfully harvested related to metal oxide redox reactions for energy storage systems is as many as 1980 documents. Finally, the collected research document data is stored in (*.csv) format. Thus, it can be analyzed with Microsoft Excel software and (*.ris). Next, visualization analysis can be carried out with VOSviewer software.

2. Step 2: Screening Data

The research documents gathered during stage 1 cannot be analyzed directly. As a result, data filtering is required. At this stage, data screening was performed by paying close attention to the article title and the year of publication. Articles with irrelevant titles and missing publication years were eliminated. The cleansed data was then transferred to a Microsoft Excel file for additional examination with bibliometric tools.

3. Step 3: Data Analysis and Visualization

Selected documents that had been cleaned and saved in Microsoft Excel were converted to *.ris format. The data was then accessed and visualized. The trend analysis was carried out using bibliometric analysis software (VOSViewer). VOSviewer is a computer program developed for building and viewing bibliometric maps. VOSViewer offers a text mining function that can be used to build and visualize correlations in article or publication excerpts (Al Husaeni and Nandiyanto, 2022, Van and Waltman, 2010, Shen and Wang, 2020). In this study, VOSviewer is used as a tool that can visualize the results of the analysis. The terms in the VOSviewer network mapping visualization were filtered at this stage. The source database was used to map the article data. Three types of data mapping visualizations were employed: network, density, and overlay. More details on data analysis and visualization with VOSviewer software can be found elsewhere (Al Husaeni and Nandiyanto, 2022). Apart from using Ms.Excel in processing and analyzing data, we also use the results of the analysis provided directly by the official Scopus website (Scopus.com).

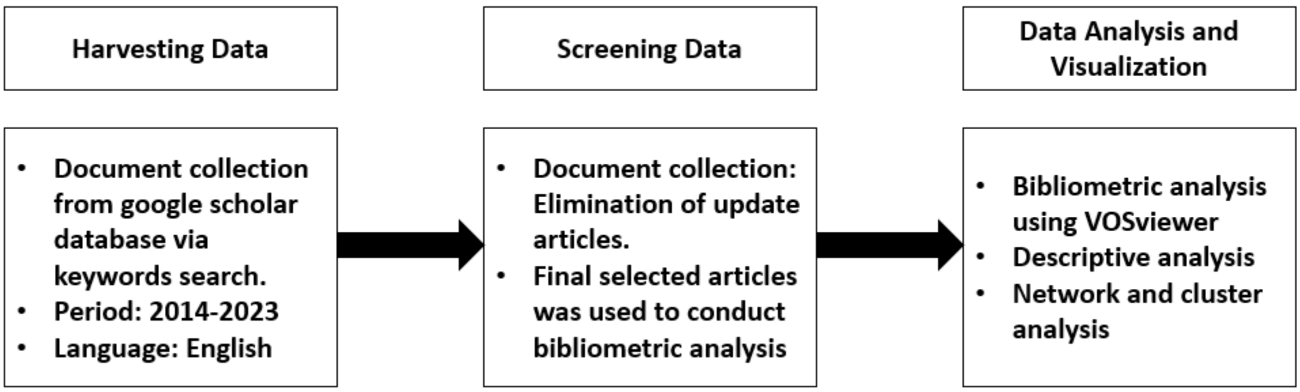

Figure 5. Step by step for conducting bibliometric analysis.

5. Results and Discussion

5.1 Development of publications on "iron", "hydrogen", "energy", and "oxide" per year (2014-2023)

The development of the number of published articles on the topic "iron," "hydrogen," "energy," and "oxides" can be seen in **Table 1** and **Figure 6**. Based on **Figure 6**, from 2014 to 2016, research on "iron," "hydrogen," "energy," and "oxides" fluctuated; namely, in 2014, the number of publications was 103, increasing in the following year, namely in 2015 to 107 documents. However, in 2016 this decreased again by 1 document to 106. Nevertheless, in 2016–2022, research on "iron," "hydrogen," "energy," and "oxides" experienced a significant increase; namely, there were 106 documents in 2016, 118 documents in 2017, 207 documents in 2018, 222 documents in 2019, 284 documents in 2020, 338 documents in 2021, and 332 documents in 2022. Whereas in 2023, the date of data collection was July 10, 2023, the number of publications regarding "iron," "hydrogen," "energy," and "oxides" is 169

documents. Based on these results, research on "iron," "hydrogen," "energy," and "oxides" is still in great demand by researchers for research. Even though it will decrease in 2023, this will not have much effect because this research was conducted in July 2023. Thus, there is still a possibility that in August-December, the number of publications regarding "iron," "hydrogen," "energy," and "oxides" will decrease.

Table 1. Development of the publication with keywords "iron," "hydrogen," "energy," and "oxides" from 2014-2023

Year	Documents
2023	169
2022	332
2021	338
2020	284
2019	222
2018	207
2017	118
2016	106
2015	107
2014	103

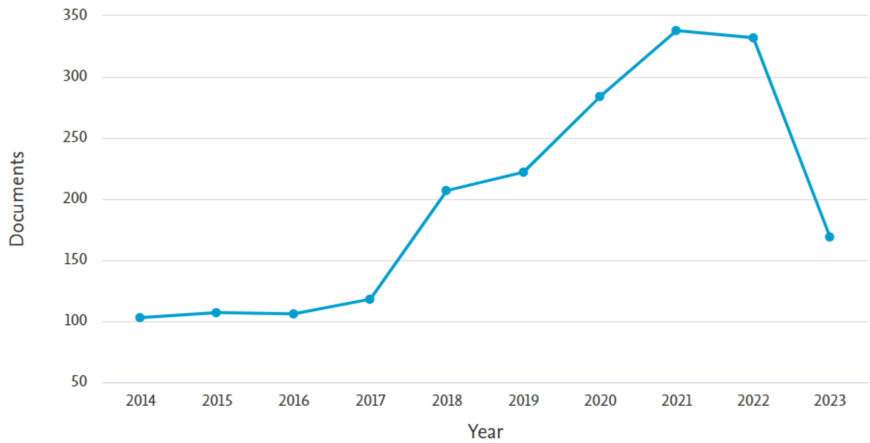

Figure 6. Development of the publication with keywords "iron", "hydrogen", "energy", and "oxide" from 2014-2023

5.2 Ten articles with the highest number of citations

In addition to the development of publications per year, this research also examines articles with the highest number of citations. Of the 1986 documents found, ten documents have the highest number of citations, namely > 300 or even nearly 400. The first position with 998 citations was occupied by an article written by Wang *et al.* (2015) entitled "Bifunctional non-noble metal oxide nanoparticle electrocatalysts through lithium-induced conversion for overall water splitting." Then, there are articles written by Song *et al.* (2018) entitled "Transition metal oxides as electrocatalysts for the oxygen evolution reaction in alkaline solutions: An application-inspired renaissance" that has a total of 911 citations, and article entitled "High-performance bifunctional porous non-noble metal phosphide catalyst for overall water splitting" (Yu *et al.*, 2018) that has a total of 755 citations. A detailed list of publications with the highest number of citations is shown in **Table 2**.

Table 2. Ten articles with the highest number of citations.

No	Article title	Citations	Ref.
1	Bifunctional non-noble metal oxide nanoparticle electrocatalysts through lithium-induced conversion for overall water splitting	998	Wang *et al.* (2015)
2	Transition Metal Oxides as Electrocatalysts for the Oxygen Evolution Reaction in Alkaline Solutions: An Application-Inspired Renaissance	911	Song *et al.* (2018)
3	The highly active and stable hybrid catalyst of cobalt-doped FeS2 nanosheets-carbon nanotubes for hydrogen evolution reaction	746	Yu *et al.* (2018)
4	Unification of catalytic water oxidation and oxygen reduction reactions: Amorphous beat crystalline cobalt iron oxides	506	Wang *et al.* (2015)
5	The adaptive synergy between catechol and lysine promotes wet adhesion by surface salt displacement	487	Indra *et al.* (2014)
6	New BiVO4 Dual Photoanodes with Enriched Oxygen Vacancies for Efficient Solar-Driven Water Splitting	411	Maier *et al.* (2015)
7	Removal of pharmaceuticals from water by homo/heterogonous Fenton-type processes – A review	407	Wang *et al.* (2018)
8	Iron-doped nickel oxide nanocrystals as highly efficient electrocatalysts for alkaline water splitting	405	Mirzaei *et al.* (2017)
	Iron-doped nickel oxide nanocrystals as highly efficient electrocatalysts for alkaline water splitting	405	Fominykh *et al.* (2015)
	Electronic Structure Tuning in Ni3FeN/r-GO Aerogel toward Bifunctional Electrocatalyst for Overall Water Splitting	398	Yang *et al.* (2018)

The number of citations of an article indicates that the article made has been recognized and used as a source (reference) for other articles. In addition, the citation also indicates that the articles written are widely used by other researchers to strengthen their assumptions (Brooks, 1985). The function of the citation is to verify the data obtained. Thus, that is made can be accounted for and has accountability (Robinson-García *et al*., 2016).

5.3 The ten authors with the greatest number of publications

Table 3 and **Figure 7** show ten authors who frequently research "iron," "hydrogen," "energy," and "oxides." This calculation was taken from Scopus-indexed articles published in 2014–2023. Based on **Figure 7**, Najafpour, M.M. is a frequent research writer with a total of eight publications (over the past ten years). In second place were Salavati-Niasari, M. and Sohn, H. Y., with seven documents each. The next are Ismail, M. and Sazelee, N.A., with six documents each. Then, Xu, J., Abbas, M., Ali, N.A., Barreca, D., and Cao, D. had five documents each during the given period.

Table 3. Ten authors with the greatest number of publications

Authors	Documents
Najafpour, M.M.	8
Salavati-Niasari, M.	7
Sohn, H.Y.	7
Ismail, M.	6
Sazelee, N.A.	6
Xu, J.	5
Abbas, M.	5
Ali, N.A.	5
Barreca, D.	5
Cao, D.	5

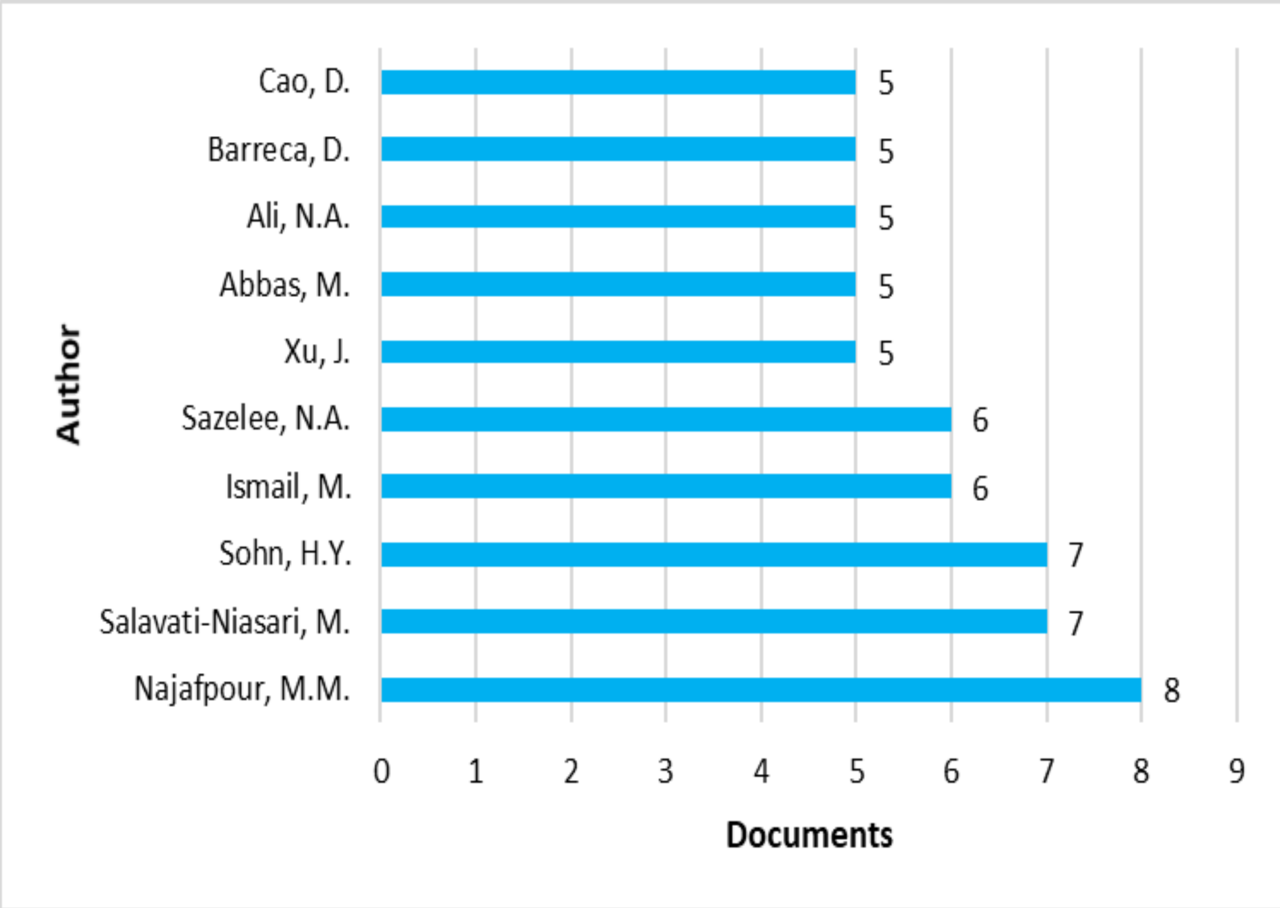

Figure 7. Ten authors with the greatest number of publications

5.4 Ten countries and affiliations in the world with the highest number of publications

The journal that publishes a lot of research on “iron,” "hydrogen," "energy," and "oxides" is in China, with a total of 843 publications. The detailed list can be seen in **Table 4** and **Figure 8**. Based on **Table 4**, China is a country that publishes many articles examining the research topics of "iron," "hydrogen," "energy," and "oxides." Besides China, there are other countries such as the United States, with a total of 241 documents, India with a total of 180 documents, Iran (123 documents), South Korea (122 documents), Germany (100 documents), Australia (80 documents), Japan (66 documents), United Kingdom (58 documents), and Spain (55 documents).

This statement is also reinforced by the existence of the Ministry of Education of China as an affiliate with the greatest number of publications regarding “iron,” “hydrogen,” “energy,” and “oxides.” The Ministry of Education of China, in the last ten years (2014–2023), published 147 articles (see **Table 5**). Apart from the Ministry of Education of China, there are several other affiliations such as the Chinese Academy of Sciences (109 documents), the University of Chinese Academy of Sciences (42 documents), Beijing University of Science and Technology (31 documents), University of Science and Technology of China (29 documents), Tsinghua University (28 documents), CNRS Center National de la Recherche Scientifique (25 documents), King Saud University (25 documents), Northeastern University (23 documents), and Tianjin University (22 documents). Based on **Figure 8**, the affiliates that are included in the ten affiliates with the highest number of publications are mostly from China. The results in **Figure 8** can strengthen the findings in **Figure 9.**

Table 4. Top ten countries in the World with the highest number of publications

Country/Territory	Documents
China	843
United States	241
India	180
Iran	123
South Korea	122
Germany	100
Australia	80
Japan	66
United Kingdom	58
Spain	55

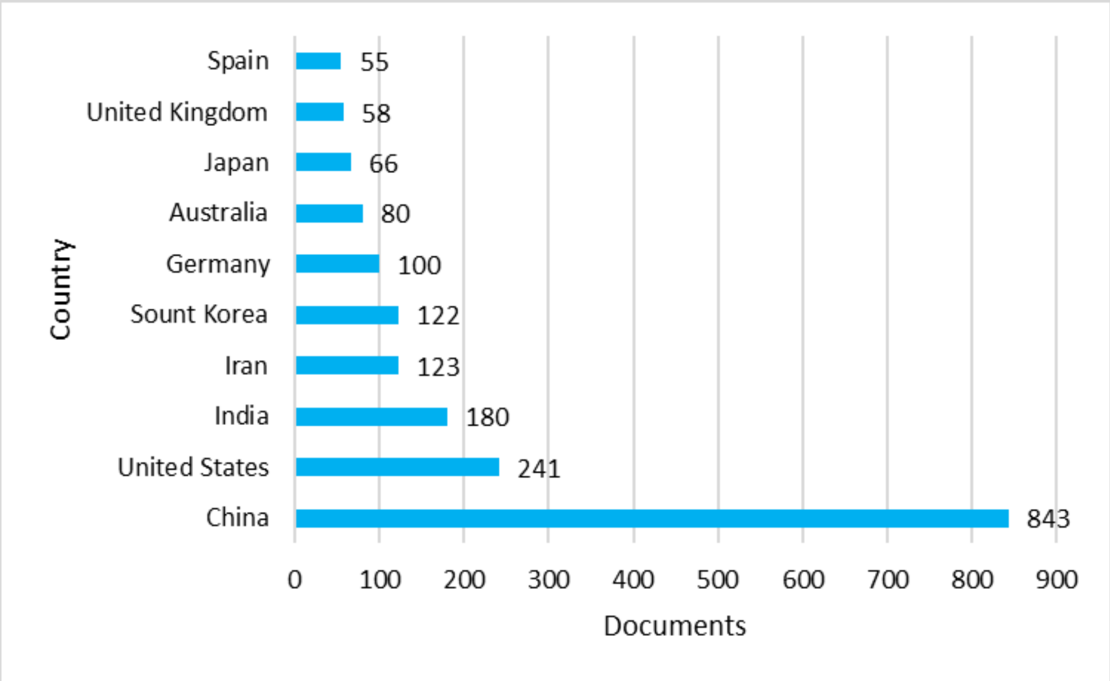

Figure 8. Top ten countries in the World with the highest number of publications

Table 5. Ten authors with the greatest number of publications

Affiliation	Documents
Ministry of Education of China	147
Chinese Academy of Sciences	109
University of Chinese Academy of Sciences	42
University of Science and Technology Beijing	31
University of Science and Technology of China	29
Tsinghua University	28
CNRS Centre National de la Recherche Scientfique	25
King Saud University	25
Northeastern University	23
Tianjin University	22

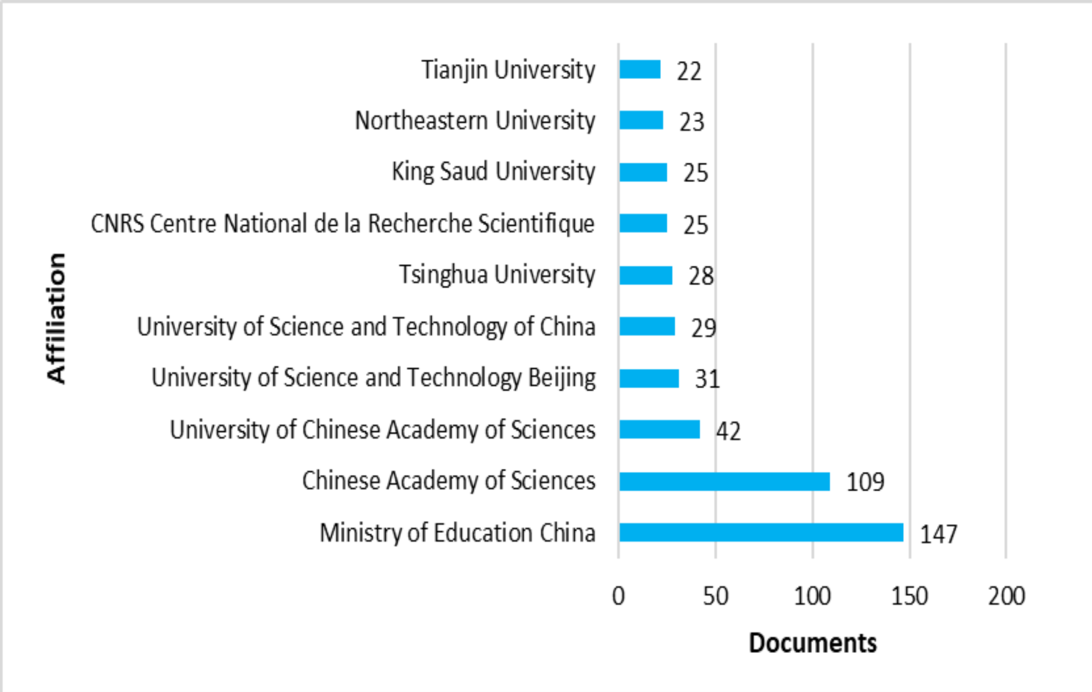

Figure 9. Top ten affiliates in the World with the greatest number of publications

5.5 Analysis of VOSviewer mapping result data

To delve deeper into the term's analysis and the potential links between them, a term cluster map was created. The cluster map included 248 terms that had been published in 2014–2023 from Scopus-indexed article data. The results of mapping the 248 terms obtained three types of visualization, namely network, density, and overlay, as shown in **Figures 10, 11,** and **12**. From the VOSviewer results, six clusters were found which were differentiated by color, namely red, green, blue, yellow, purple, and orange. The results of the six clusters illustrate the relationship between various types of topics (See **Table 6**).

Table 6. Cluster of VOSviewer results.

Cluster	Total items	Color	Items
1	68	Red	Alumina, anaerobic digestion, apparent activation energy, atmospheric pressure, bed reactor, CaO, carbon deposition, carbon dioxide, carbon monoxide, chemical, chemical looping comb, chemical reaction, CLC, clean energy, CO_2, CO_2 capture, CO_2 emission, context, deactivation, electricity, energy demand, energy efficiency, feedstock, feo, fuel, green hydrogen, greenhouse gas emission, hydrogen production, heat, high purity hydrogen, higher temperature, hydrocarbon, hydrocarbon atmosphere, hydrogen gas, hydrogen production, hydrogen reduction, hydrogen sulfide, hydrogen yield, iron ore, iron oxide reduction, lattice oxygen, mass, metallic iron, oxygen carrier, physical property, pore, pretreatment, progress, pure hydrogen, reactor, redox, redox cycle, reductant, reduction reaction, reduction step, reduction temperature, relation, renewable energy, renewable energy source, review, solid solution, stage, steel, steel industry, stream.
2	62	Green	Binding, catalyst dosage, chemical oxygen demand, chromium, co-precipitation, complexion, contaminant, degradation efficacy, electron microscopy, electrostatic interaction, elemental analysis, energy dispersive spectrum, experimental

			data, external magnet, external magnetic field, Fe_2O_4 np, graphical, H_2O_2, heavy metal, high level, hydrogel, hydrogen bond, hydrogen bonding, immobilization, ion exchange, ionic strength, iron, iron oxide nanoparticle, kcal mol, magnesium, magnetic field, magnetic nanoparticle, magnetic property, magnetic separation, magnetite nanoparticle, metal ion, mineralization, molecular oxygen, nanocatalyst, oxidant, parameter, physiochemical properties, ply, polymer, precipitation, reaction time, removal, reusability, sample magnetometer, sample magnetometry, selective oxidation, sensitivity, significant increase, thermal stability, thermodynamic study, thermogravimetric analysis, titanium, valent iron, variable, zeta potential,
3	47	Blue	Active site, alkaline medium, bifunctional electrocatalyst, cell voltage, $CoFe_2O_4$, current density, double hydroxide, efficient electrocatalyst, electrocatalysis, electrocatalysis, electrocatalytic activity, electrocatalytic perform, electrocatalytic water splitting, electrochemical water splitting, electrolyzer, electronic structure, energy conversion, excellent stability, fe site, high activity, high electrical conductivity, hydrogen evaluation reaction, hydrogen fuel, low overpotential, low Tafel slope, metal-organic framework, nanosheet, ni fe, nickel, nickel foam, nife2o4, noble metal, overall water splitting, overpotential, oxygen evaluation, oxygen evolution reaction, perovskite oxide, platinum, promising candidate, reduce graphene oxide, stable electrocatalyst, strong interaction, transition metal, transition metal oxide, water electrolysis.
4	42	Yellow	Band gap, band gap energy, bandgap, charge transfer, cocatalyst, conduction band, density functional theory (DFT) calculation, doping, effective strategy, electronic property, energy conversion efficacy, engineering, environmental issue, high potential, hydrogen energy, hydrogen evolution, lafeo3, nanostructure, optical property, oxygen vacancy, photoanode, photocatalysis, photocatalytic activity, photocatalytic performance, photocatalytic water splitting, photocathode, photocurrent, photoluminescence, promising approach, promising strategy, rational design, reversible hydrogen electron, semiconductor, solar water splitting, thin film, visible light, visible irradiation water oxidation water splitting, water splitting reaction
5	27	Purple	Abundance, battery, cathode, chemical energy, conductivity, effectivity, effective way, electrical conductivity, electrochemical performance, electrode, electrode material, electrolysis, electrolyte, energy density, energy storage, graphene, high energy, high energy density, high performance, maximum power density, oxidation reaction, oxygen reduction, oxygen reduction reaction, peak power density, power density, solid oxide electrolysis, supercapacitor
6	7	Orange	Calculation, density functional theory, energy barrier, Fe atom, hydrogen adsorption, hydrogen atom, oxygen atom.

Figure 10 is a network visualization that illustrates the cluster in each of the terms used. The terms visualized in this study are marked with colored circles. To see the frequency of keywords in the abstract marked with the size of the circle. As shown in **Figure 10**, it can be seen that each cluster has a large circle, namely hydrogen production (Cluster 1), electron microscopy (Cluster 2), electrocatalyst

(Cluster 3), water separation (Cluster 4), electrodes (Cluster 5), and computation (Cluster 6). This shows that the term is often used. **Figure 11** is an overlay visualization that describes research trends every year. Based on **Figure 11**, the most studied terms were learned in 2019–2020. In addition, in **Figure 12**, which is the visualization density. The different sizes of the circles indicate the number of terms learned. From the results in **Figure 12**, different circle sizes were found in terms of hydrogen production, electron microscopy, electrocatalyst, water separation, electrodes, and calculations. These results support the results of network visualization, which shows that the term is widely discussed and published.

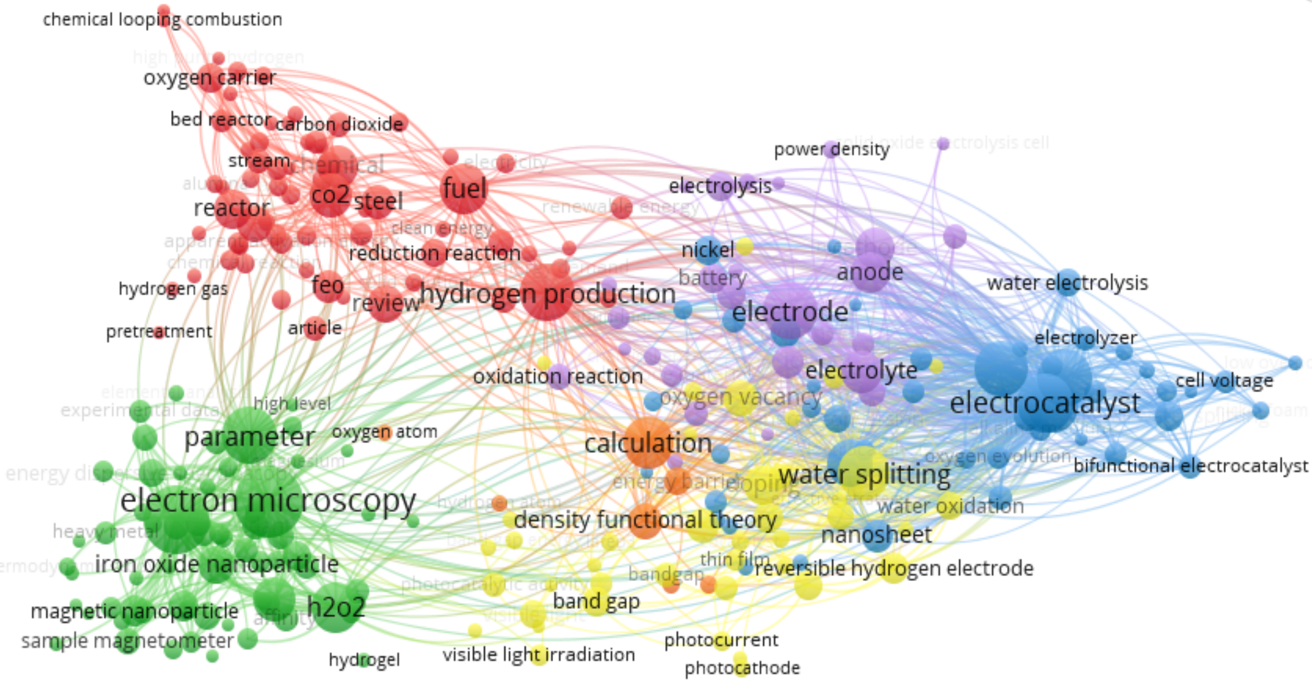

Figure 10. Network Visualization

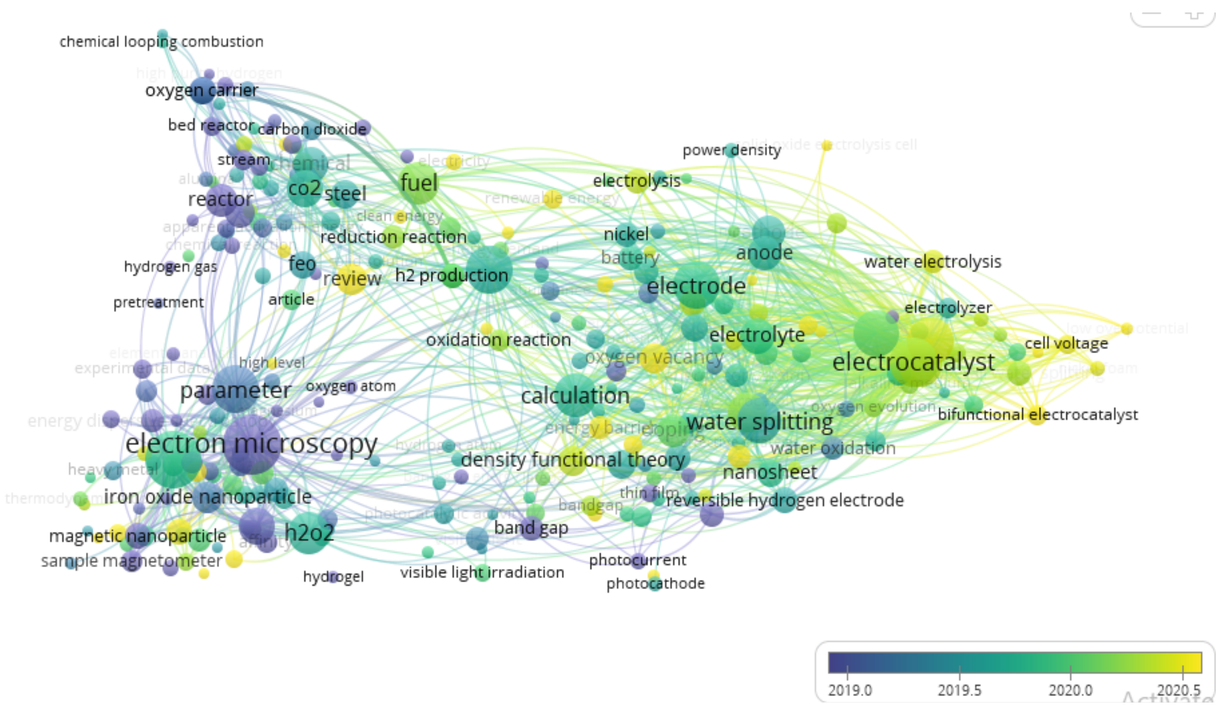

Figure 11. Overlay Visualization

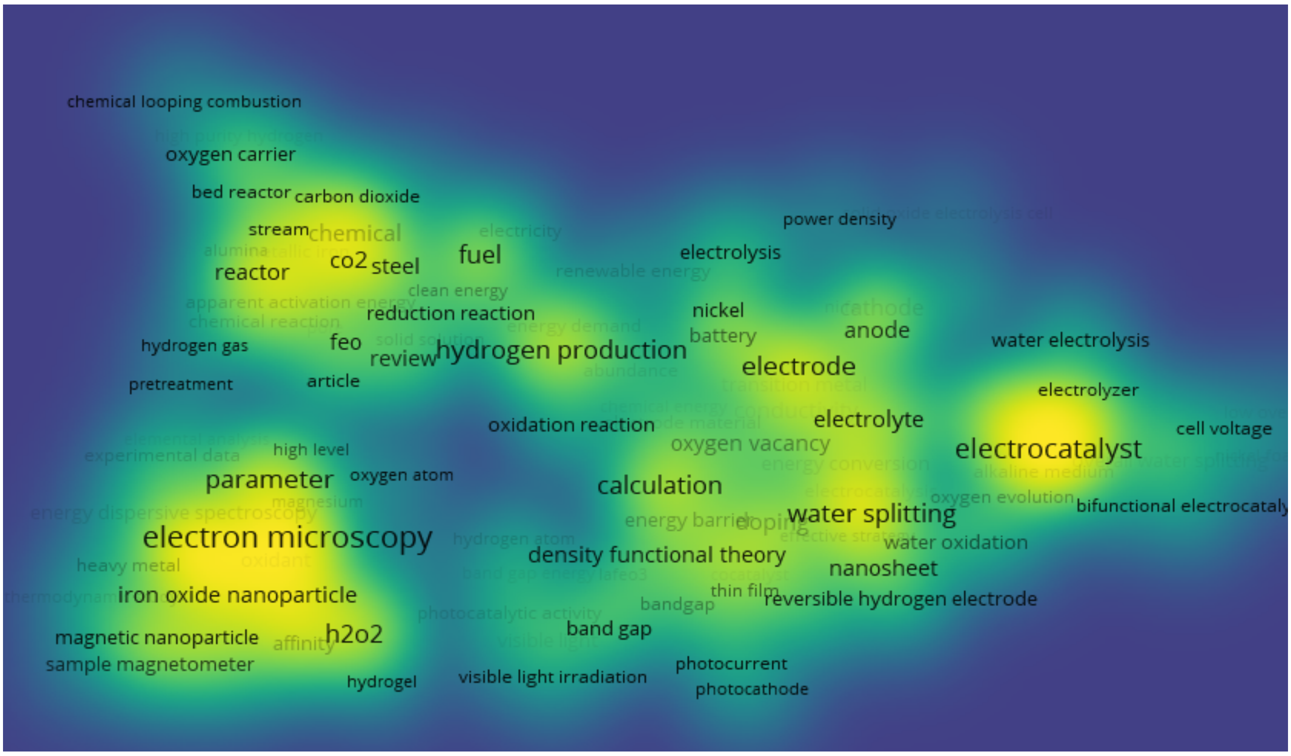

Figure 12. Density Visualization

Conclusion

The results of the bibliometric analysis show that research related to iron, hydrogen, energy, and oxide has increased in 2016–2022 (106, 118, 207, 222, 284, 338, and 332 documents, respectively), then decreased in 2023 (169 documents) and experienced fluctuations in 2014–2016 (103 documents, 107 documents, and 106 documents, respectively). Based on the results of the development of publications from 2014–2023. Research on the topic of iron, hydrogen, energy, and oxide still has high opportunities. This statement is reinforced by the results of data mapping using VOSviewer, where the term hydrogen production in cluster 1 is the most researched term. Therefore, this research is needed to find out research trends related to energy flow cycles.

In addition, China is one of the countries with the highest number of publications, namely 843 documents (from 2014 to 2023). This correlates with the affiliation that produces the most publications on the topic of iron, hydrogen, energy, and oxide, namely the Ministry of Education of China. The number of publications produced by the Ministry of Education of China from 2024–2023 is 147 documents.

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Compliance with Ethical Standards: This article does not contain any studies involving human or animal subjects.

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