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Review Article

Sustainability and challenges in hydrogen production: An advanced bibliometric analysis

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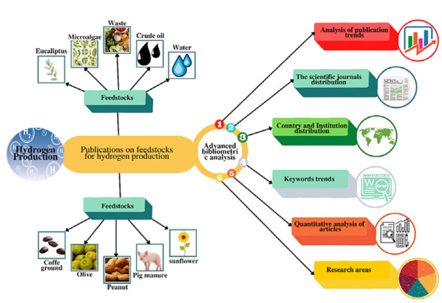
HIGHLIGHTS

- Research on hydrogen production is assessed via the bibliometric method.
- Presentation of the growing interest in research on hydrogen production.
- Microsoft Excell, VOSviewer, and CiteSpace are employed to analyze 10,655 publications.
- Comprehensive research guidelines are given for hydrogen researchers and producers.
- Analysis of the most used and least used raw material for hydrogen production.

GRAPHICAL ABSTRACT



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ABSTRACT

Hydrogen has a high and diversified amount of feedstocks, methods, and improvement processes for its production. In recent years, studies on hydrogen production have been growing and diversifying to a greater extent. Hydrogen production can be based on renewable feedstocks such as biomass or fossil fuels such as petroleum. An analysis of 10,655 publications from the Web of Science Core Collection database (2010–2022) was performed using VOSviewer, CiteSpace and Microsoft excel. The top three organizations that had the highest number of publications in the field of hydrogen production included the Chinese Academy Of Sciences, Ontario Tech University and Xi An Jiaotong University. The journal with the largest number of publications is the International Journal Of Hydrogen Energy. In addition to organizations and journals, the most promising authors and literature in this field of research were analyzed. Through cluster analysis, it was found that two constant search fields were Photocatalytic hydrogen production and Fermentative hydrogen production. Future studies should focus on process design, continuous photo-hydrogen production and looping steam. This bibliometric study focused on illustrating the overview of hydrogen production research, conducting a systematic survey of current research, which could be used by industry professionals and researchers interested in this area.

Contents

Introduction

Hydrogen is the most abundant component with numerous chemical substances present in the universe. It is essential as a fuel and for several chemical processes, such as hydrocracking, hydrogenation, and hydrotreatment [1]. The amount of substances arranged in nature that contain hydrogen is vast, highlighting the water that can be seawater, rain, well, or river water. In addition to water, hydrogen can be obtained from fossil hydrocarbons, hydrogen sulfide, biomass, and other substances. The forms of energy for hydrogen extraction from the substances mentioned above can be divided into four groups: electrical, thermal, biochemical, and photonics [2].

Hydrogen has numerous uses, and it is mainly applied as a chemical substance, such as in the improvement and desulfurization of conventional oil (in oil refineries) and production chemicals (ammonia, methanol, and pharmaceuticals), and also applied as a fuel [2]. Several methods of producing hydrogen have accentuated greenhouse gas emissions. Annually, 70 million tons of H_2 were produced from 75% natural gas and 23% coal which causes most production to have an emission of greenhouse gas emissions [3].

In recent years attention has been given to the effects of global warming and issues related to energy supply have grown worldwide. The abnormal state of the climate was linked to the increase in the concentration of greenhouse gases. Reducing these greenhouse gas emissions is the primary concern when dealing with climate anomalies [4]. Given this scenario, obtaining energy from renewable sources has become an essential ally in the face of global warming, so obtaining hydrogen through "green routes" has drawn the attention of several scholars interested in research on clean energy production.

Research on hydrogen production dates back to the early 1950s. However, still not concerned with production methods or environmental pollution, the oldest research dealt with low temperatures in hydrogen production [5]. The increase in hydrogen production research has grown significantly in recent years, from over 500 to 1000 publications per year from 2010 to 2021 year respectively (Fig. 1). The increase in interest in the area of hydrogen production is notable. Although the search for the title "Hydrogen Production" resulted in 1251 publications in 2021, adding keywords ("Bibliometr*' OR "Bibliometric Analysis" OR "Bibliometric map" OR "Scientometric*" OR "Research Trends" AND "Hydrogen Production") on the Web of Science resulted in only 1 publication [6], when searching all fields for the exact keywords, 61 results were obtained, the first of which was published in 2005 [7].

In this study, a bibliometric analysis was performed to evaluate 10,655 publications from the Web of Science (WoS) database, from the year 2010–2022, to understand the development processes and the future perspective of hydrogen production research. Bibliometrics evaluates studies from different parts of the world, institutions, and authors based on the total number of citations, publications, impact factor, and several other parameters. It plays an essential role in illustrating the history of a particular area or subject, predicting the future of this area, and improving communication between researchers [8].

Methodology

Data source

The Web of Science (WoS) database (https://www.webofscience.com) was used to carry out the bibliometric analyzes of this article, as it is considered a high-quality tool and the most useful for generating citation data for scientific research [8]. Initially, "Hydrogen Production" was used in the title field. The period was set from the year 2010–2022 to focus on the most recent advances in research. In addition, English was chosen as the language, and the document types were refined to "articles", "review articles", and "proceedings papers". After the refinement, 10,655 publications were obtained for the bibliographic analysis, starting the downloads on February 2, 2022. The search frame of the search criteria is shown in Fig. 2.

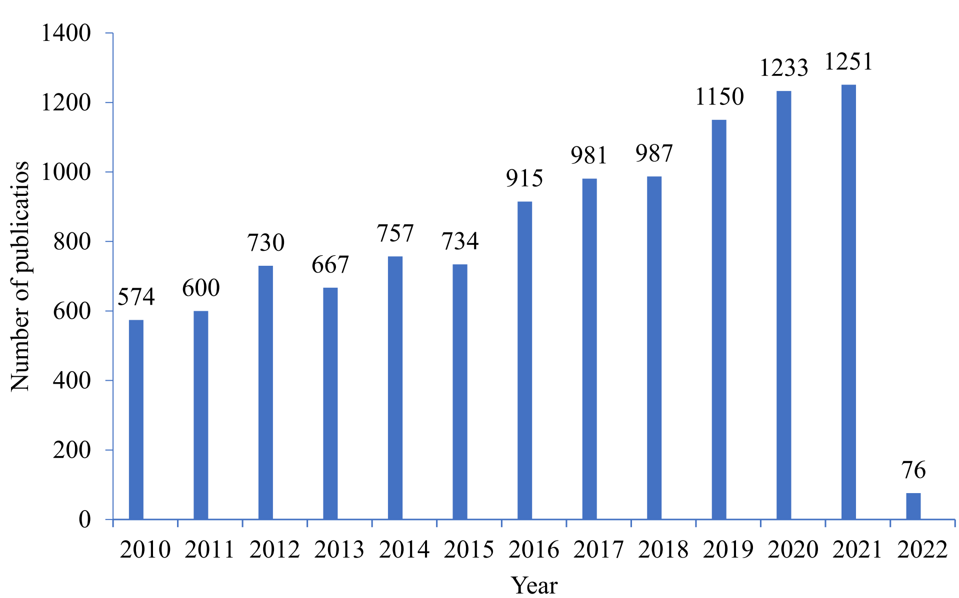

Fig. 1 – Yearly publications related to hydrogen production research from 2010 to 2022.

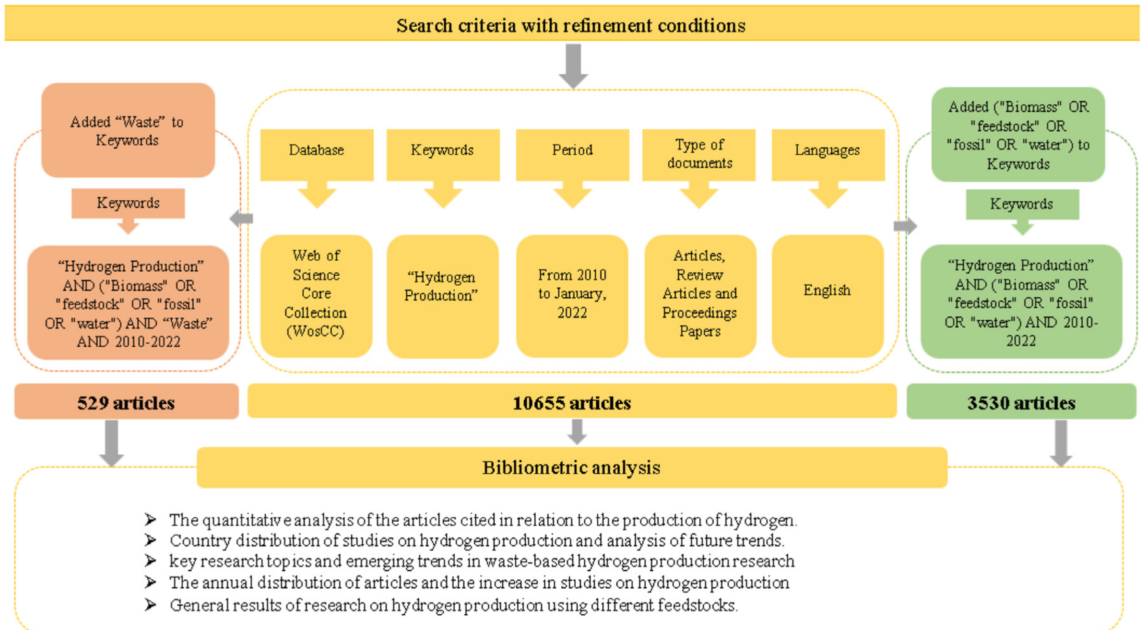

Fig. 2 – The research framework of the search criteria.

Data analysis

The VOSviewer software (version 1.6.17) [www.vosviewer.com/], is a freely available computer program developed to assist in the visualization and construction of bibliometric maps [9]. It was used to analyze the data obtained in WoS, allowing the construction of maps of journals, countries, institutions, and authors based on co-citation data and keyword maps based on co-occurrence data. They were allowed to understand the organization of clusters in this field. Standard Microsoft Excel spreadsheets (Microsoft Office Professional Plus, 2019) were also used for data analysis and cataloging. Another software used was CiteSpace. With this program, it was possible to predict and identify possible future research sub-areas in this area through clusters and keywords [10].

Results and discussion

Bibliometric analysis

Quantitative analysis of publication trends

After searching through the Web of Science, 14,728 publications were found published from January 1950 to January 2022. The first article publishes in January 1950 [5], in which Ipatieff, Monroe, and Fischer described the conversion of methane and steam into hydrogen, carbon dioxide, and carbon monoxide with temperatures ranging from 470° to 790 °C in various catalysis. From the year 50s to the 70s, only 15 publications were registered, illustrating an almost zero interest in hydrogen production, with less than one publication per year. The scenario began to change in the mid-70s, when the number of publications in 1975 reached 18 papers, with research related to thermochemical cycles and electrolysis for hydrogen production being the main focus that year. In the first 34 years, the interest in the area increased significantly, with the average number of publications exceeding 113 per year. This increase is also related to the 1st World Hydrogen Energy Conference in March 1976 and subsequent editions [11]. From the year 2010–2022, the average number of publications increased to more than 719 articles per year. This increase is necessarily linked to growing concerns about environmental conditions and increasing demand for energy, resulting in the demand for renewable energy sources [12].

The scientific journals distribution

In total, 1345 different journals allocate the selected publications, totalling an average of 7.9 to 0.66 articles per journal per year. These numbers show tremendous scientific interest in the area of hydrogen production. The various scientific groups researching the subject illustrate that hydrogen production is researched from many different points of view, producing various scientific articles. The 12 prominent scientific journals are illustrated in Table 1, according to the number of publications in the researched area. Making a quantitative analysis of the publications of these 12 journals, it is observed that they concentrate approximately 43% of the total identified publications. The "International Journal of Hydrogen Energy" is the first on the list, with 2892 publications, equivalent to more than 27% of the total publications analyzed, reaching 75,723 citations. Despite the highlight in the total number of publications and citations, this journal currently has the third-lowest impact factor in the list of the top 12 journals. This is because the impact factor of a given year depends on the number of citations and the number of items. Citable in the last two years. The journal "Bioresource Technology" is in second place with 257 publications, 9179 citations, and an impact factor of 9.64. This value is lower than the impact factor of the journal "Applied Catalysis B Environmental", which occupies the third position., this journal has the highest impact factor on the list, with a value of 19.5, with many publications equal to 241 and 13,259 citations.

Table 1 – Top 12 productive mainstream journals in WCO-based hydrogen production research from 2010 to 2022.

RANK	JOURNAL TITLE	TPs	Pr (%)	CPJ	TC	ACPY	C	IF	ANMP	AC
1	INTERNATIONAL JOURNAL OF HYDROGEN ENERGY	2892	27.142	26,18	75723	5408,79	UK	5,81	241	26,2
2	BIORESOURCE TECHNOLOGY	257	2.412	35,71	9179	706,08	NL	9,64	21	35,7
3	APPLIED CATALYSIS B ENVIRONMENTAL	241	2.262	55,01	13259	1019,92	NL	19,5	20	55,0
4	ENERGY CONVERSION AND MANAGEMENT	155	1.455	29,09	4510	346,92	UK	9,7	13	29,1
5	JOURNAL OF MATERIALS CHEMISTRY A	151	1.417	47,76	7212	721,2	UK	12,73	13	47,8
6	RSC ADVANCES	141	1.323	18,46	2603	236,64	UK	3,36	12	18,5
7	CHEMICAL ENGINEERING JOURNAL	137	1.286	27,45	3761	313,42	CH	13,27	11	27,5
8	ENERGY	124	1.164	22,73	2819	216,85	UK	7,14	10	22,7
9	APPLIED SURFACE SCIENCE	114	1.070	25,26	2880	261,82	NL	6,7	10	25,3
10	INTERNATIONAL JOURNAL OF ENERGY RESEARCH	110	1.032	15,99	1759	135,31	UK	5,16	9	16,0
11	CATALYSIS TODAY	106	0.995	23,47	2488	191,38	NL	6,76	9	23,5
12	APPLIED ENERGY	105	0.985	29,83	3133	261,08	UK	9,74	9	29,8

Note: TPs = Total Publications; Pr(%) = Proportion; CPJ = Citation Per Journal; TC = Total Citation; ACPY = Average Citations Per Year; C = Country; IF = Impact Factor in 2020; ANMP = Average number of published manuscripts per year since 2010; AC = Average Citation = TC/TPs. NL = Netherlands; UK = United Kingdom; CH = Switzerland.

Table 2 – The 12 most productive countries in the field of hydrogen production.

RANK	COUNTRY	TPs	Pr (%)	TC	CPC	ACPY	H-index
1	CHINA	3773	35.411	109167	28,93374	7797,64	124
2	USA	984	9.235	41651	42,32825	3203,92	94
3	SOUTH KOREA	698	6.551	15913	22,79799	1224,08	58
4	CANADA	594	5.575	18028	30,35017	1386,77	62
5	JAPAN	591	5.547	18289	30,94585	1406,85	65
6	INDIA	568	5.331	13871	24,42077	1067	56
7	SPAIN	411	3.857	13583	33,04866	1044,85	60
8	TURKEY	392	3.679	8052	20,54082	619,38	45
9	ITALY	379	3.557	10671	28,15567	820,85	52
10	IRAN	365	3.426	7482	20,49863	575,54	45
11	TAIWAN	346	3.247	9299	26,87572	715,31	48
12	GERMANY	323	3.031	12102	37,46749	930,92	56

Note: TPs: Total Publications; Pr(%): Proportion; CPC: Citation Per Country; TC: Total Citation; ACPY: Average Citations Per Year.

Country and institution distribution

Those informed by the authors in the field of affiliation were considered the country and institution of origin of the works. The 12 most productive countries house 88.45% of the total publications out of the 104 countries, as shown in Table 2, which illustrates the vast interest in the area. The most significant number of publications is concentrated in China (3773 publications, about 35.4% of the total), followed by USA (984 publications, about 9.2% of the total) and South Korea (698 publications, about 6.5% of the total).

The countries mentioned above had the highest number of publications. However, the USA had the highest average number of citations, followed by Spain, Japan, and Canada, despite the proximity of the average values of the latter two. Fig. 3 shows the distribution of publications by country according to the period and area of research, with greater emphasis on the 25 countries that presented at least 5 publications and 3000 citations.

Fig. 4 presents a network map of collaborative links between the analyzed scientific groups. Analyzing Fig. 4, China and the USA are the most collaborative countries in the field. It is easy to understand the interest of these two powers in the Hydrogen area due to the search for clean and renewable sources of energy and the bet on electric vehicles, and the decarbonization of transport.

The analysis showed that 4089 institutions from 104 countries were responsible for the published works. These data illustrate the high level of interest in this area in many parts of the world. Despite being 104 countries in total, the 12 most productive countries in the area are home to more than 80% of the total publications analyzed in this article, highlighting countries such as China, the USA, and South Korea, probably because they are countries that are in the same front of decarbonization. Although there are a large number of institutions interested in the area, 1902 institutions (about 46.5% of the total number of institutions) have only one publication in the area, illustrating a very high rate of institutional dispersion, illustrating that only about 53.5% of all institutions conduct research consistently in this area. Nevertheless, analyzing the relative importance of institutional research can be tricky. For example, the Wuhan University of Technology (China), the National Center for Nanoscience (China), and Technology and the Chinese Academy of Sciences (China) published together an article that currently has 1978 citations and ranks first among 12 articles cited in the area [13], illustrating the great importance of co-authorship between institutions, on the other hand, Hanbat National University

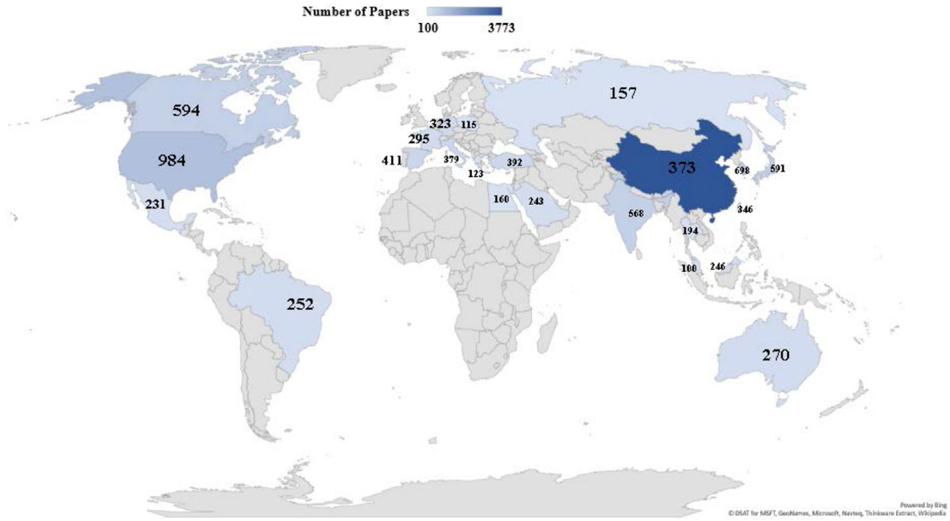

Fig. 3 – Distribution of publications by country, with greater emphasis on the 25 countries that presented at least 5 publications and 3000 citations.

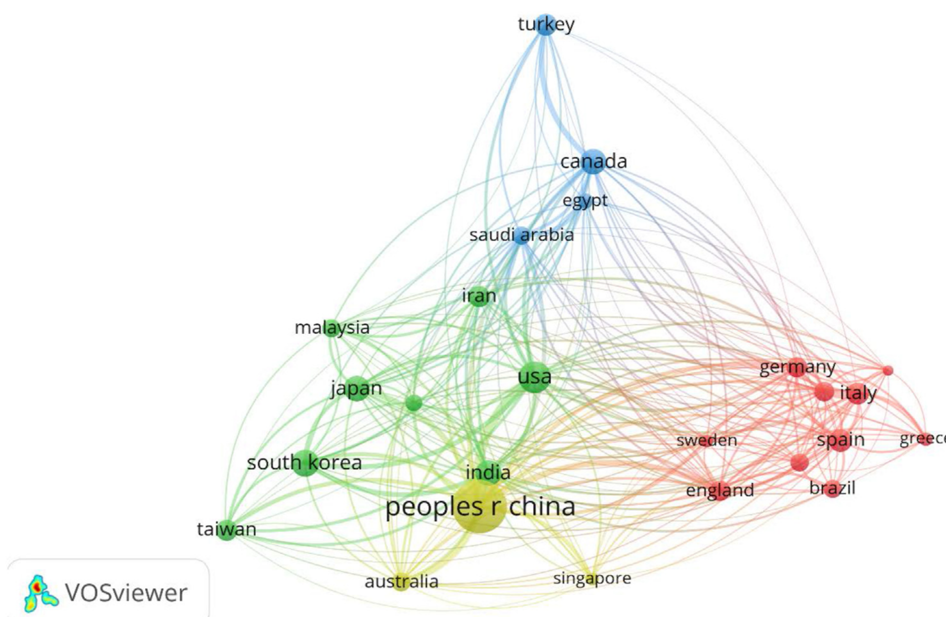

Fig. 4 – Country/regional collaboration network in hydrogen production from WCO research.

(South Korea), National Renewable Energy Laboratory (USA), and Kyungpook National University (South Korea) published together an article that has only 1 citation [14], illustrating that institutional co-authorship is not the only determining factor for the relevance of a publication, but also the quality of the scientific research built, this statement can be confirmed with the analysis of the case from the University of Western Australia (Australia), which published an article that has 1763 citations and is among the 12 most cited articles in the area [15]. Additional network maps were also built on understanding better the interconnection between the most influential institutions, illustrated in Fig. 5. For this, institutions that have at least 2400 citations accumulated by the total number of publications in the period under analysis were selected, having identified 23 institutions (0.56% of the total number of institutions), including the Chinese Academy Of Sciences, the Harbin Institute Of Technology and the Xi An Jiaotong University.

Twenty-three thousand nine hundred eighty-six authors were identified for the total number of published works (about 2.2 authors per article). These data also reinforce the high dispersion of researchers in the area. By selecting only authors with at least 20 publications and 800 citations, 27 authors were obtained. Among them, Dincer I stands out, with the most significant number of publications in the area (234 documents) and 8416 citations. To better understand the collaboration between authors, we have a collaborative network map shown in Fig. 6. Authors with previously determined

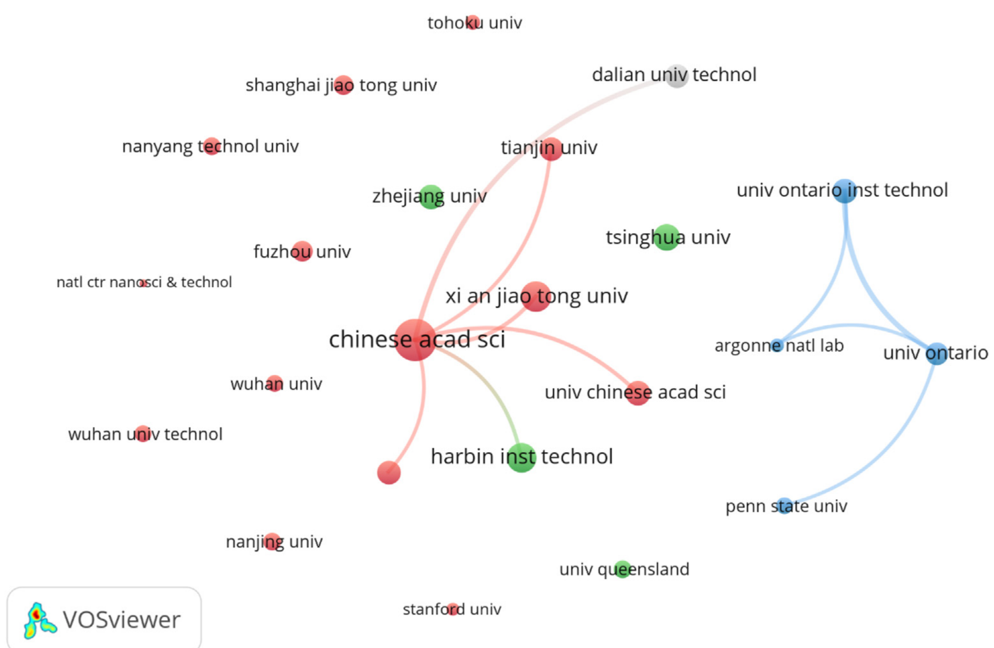

Fig. 5 – Network visualization map based on the collaboration among the organizations.

publications and citations do not only collaborate with authors who have numbers of publications and citations close to their own. It is expected that the groups obtained in this map are small. However, curiosity is that authors form small groups from the same country. The collaboration of only two groups from different countries reinforced the idea that a relevant part of the collaborations is carried out only in the institution's interior in which the researchers are linked.

Quantitative analysis of cited articles

One of the leading indicators of the relevance of a publication is citation [16]. Table 3 presents the most cited publications in the period under analysis. First in the ranking of the most cited articles is an article that reports on hydrogen production by water separation using graphene nanosheets as photocatalysts [13]. It is important to note that the seven authors of this article are from the same country (China). The second most cited publication is a literature review on the state of

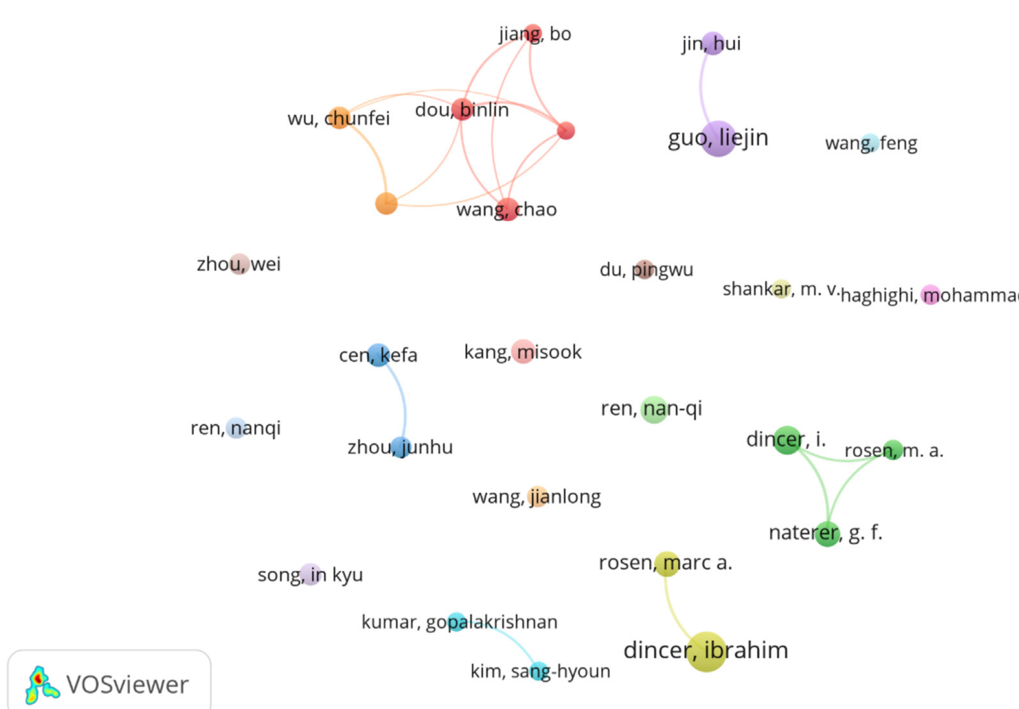

Fig. 6 – Network visualization map based on the collaboration among the authors.

Table 3 – Top 12 works of literature based on citations from 2010 to 2022.

CITATIONS	YEAR	AUTHOR	TITLE	SOURCE	COUNTRY
1978	2011	Li	Highly Efficient Visible-Light-Driven Photocatalytic Hydrogen Production of CdS-Cluster-Decorated Graphene Nanosheets	JOURNAL OF THE AMERICAN CHEMICAL SOCIETY	China
1763	2010	Zeng	Recent progress in alkaline water electrolysis for hydrogen production and applications	PROGRESS IN ENERGY AND COMBUSTION SCIENCE	Australia
1028	2011	Merki	Amorphous molybdenum sulfide films as catalysts for electrochemical hydrogen production in water	CHEMICAL SCIENCE	Switzerland
998	2010	Zuo	Self-Doped Ti3+ Enhanced Photocatalyst for Hydrogen Production under Visible Light	JOURNAL OF THE AMERICAN CHEMICAL SOCIETY	USA
986	2015	Wu	Porous molybdenum carbide nano-octahedrons synthesized via confined carburization in metal-organic frameworks for efficient hydrogen production	NATURE COMMUNICATIONS	Singapore
956	2017	Ran	Ti3C2 MXene co-catalyst on metal sulfide photo-absorbers for enhanced visible-light photocatalytic hydrogen production	NATURE COMMUNICATIONS	Australia
949	2010	Yu	Hydrogen Production by Photocatalytic Water Splitting over Pt/TiO2 Nanosheets with Exposed (001) Facets	JOURNAL OF PHYSICAL CHEMISTRY C	China
946	2011	Murdoch	The effect of gold loading and particle size on photocatalytic hydrogen production from ethanol over Au/TiO2 nanoparticles	NATURE CHEMISTRY	Scotland
932	2015	Dincer	Review and evaluation of hydrogen production methods for better sustainability	INTERNATIONAL JOURNAL OF HYDROGEN ENERGY	Canada
830	2016	Hosseini	Hydrogen production from renewable and sustainable energy resources: Promising green energy carrier for clean development	RENEWABLE & SUSTAINABLE ENERGY REVIEWS	Malaysia
827	2010	Chen	Accelerating materials development for photoelectrochemical hydrogen production: Standards for methods, definitions, and reporting protocols	JOURNAL OF MATERIALS RESEARCH	USA
823	2011	Tedsree	Hydrogen production from formic acid decomposition at room temperature using an Ag–Pd core-shell nanocatalyst	NATURE NANOTECHNOLOGY	England

Note: Author and country listing in this table refer to the first author (Surname only) and country in each article.

technology and knowledge of hydrogen production by water electrolysis, pointing out the points that need to be improved [15]. This review had two authors from the same country (Australia) and obtained 1763 citations. The third most cited article obtained 1028 citations; its four authors are from the same country (Switzerland). This article discusses using the electrochemical method's use of molybdenum sulfide films as catalysts for hydrogen production.

It is important to note that there is no direct relationship between the most cited publications (Table 3) and the most cited journals (Table 1), as only the International Journal Of Hydrogen Energy and Journal of Materials Research appear on the two lists and are in different positions. It is also possible to observe the predominance of works related to photocatalytic hydrogen production [13,15,17–20], illustrating a particular interest in this type of material by the scientific community, probably because it is considered promising. One of the characteristics that the most cited articles present is the publication period. Most of the most cited articles were published more than 10 years ago, although an article from 2017 occupies the sixth position in the list of the twelve most cited articles [17], indicating that the interest in works related to the production of photocatalytic hydrogen remains high.

Research areas

The analyzed articles on hydrogen production are grouped into a total of 67 research areas in the Web of Science database, many articles are included in more than one research area, so there are more than 30 research areas with less than 10 articles on hydrogen production. Fig. 7 presents the 6 main areas of research, which house 84% of published articles. About, 6351 articles were registered in the " Chemistry " research area, becoming the most common research area, involving photosynthetic and photocatalytic processes for hydrogen production. Then, the research area “Energy fuels”, with 5356 records, involving research on hydrogen production from petroleum hydrocarbons; “Electrochemistry”, with 3173 records, involving photovoltaic devices and analysis of the electrochemical production of hydrogen; and “Engineering” with 2461 records, involving technological research for hydrogen production. The variety of research areas shows us several actors in the hydrogen production knowledge chain.

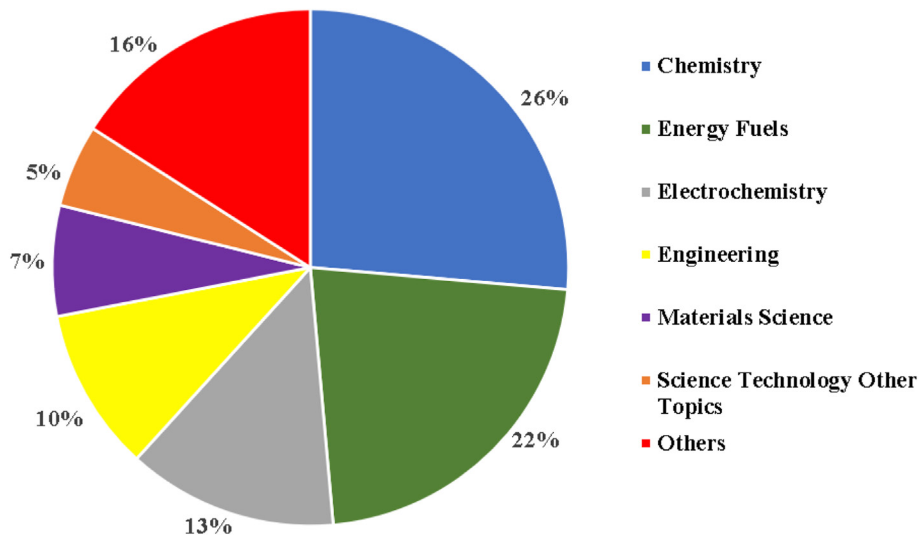

Fig. 7 – Research area distributions in the field of hydrogen production research.

Feedstocks for hydrogen production

Classification of feedstocks

There is a wide variety of feedstocks for hydrogen production. However, they can be classified into 2 categories illustrated in Fig. 8, fossil fuels and renewable resources (water, biomass). Fig. 8 presents some feedstocks used in hydrogen production, and it is possible to observe which category each feedstock belongs. It is essential to highlight that some biomass feedstocks for bioenergy production are cultivated on a large scale in monoculture plantations. This ends up impacting society and the environment, such as increased competition for natural and agricultural land, the negative impact on biodiversity, the influence on food prices, and the worsening of water scarcity [21]. Therefore, using more sustainable and less competitive biomass such as household food residues, crop residues, livestock manure, and aquatic biomass is becoming more attractive. Feedstocks from the renewable resources category can be found in various locations worldwide. For edible feedstocks, despite the high competitiveness, some examples can be cited, such as rice straw, rice shell, wheat stalk, peanut shell, corn stalk, corn cob, and sorghum stalk [22]. In the case of inedible feedstocks and aquatic biomass, some examples can be cited, such as green waste (conforming mainly by grass, leaves, and fresh pruning originating from gardens and parks), wood sawdust, *Chlorella* sp., *Spirogyra* sp., *Pistia stratiotes*, *Keratococcus*, *Oscillatoria*, *Microcystis wesenbergii*, *Microcystis aeruginosaare*, *Arthrospira platensis*, *Eichhornia crassipes*, *Scenedesmus obliquus*, *Chlorella vulgaris* and *Spartina anglica* [23].

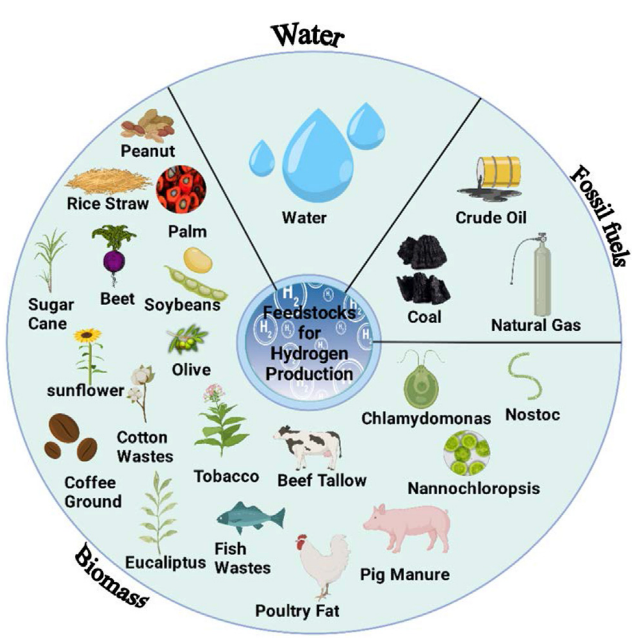

Fig. 8 – List of various feedstocks used in hydrogen production. The picture is divided into three parts: edible oils, inedible oils, microbial oils, and animal fats.

Among the feedstocks observed, feedstocks from water and biomass are the most relevant among the 3530 publications located in the database, and 2867 publications were found with the keyword "Water" and 823 publications with the keyword "Biomass". The keyword "fossil" was cited in only 25 publications, and the least cited keyword was "feedstock," with 11 citations. It is important to note that the refinement criteria used in this case were the same as the initial search, but adding the logical operator "AND" and using the following search terms in the keyword plus field: ("Biomass" OR "feedstock" OR "fossil" OR "Water"). Some publications that have water as the main object of study are listed in Table 3, which lists the 12 most cited articles, with one of these publications ranking first among the most cited articles. For the case of using biomass as a keyword, the most cited publication for this case is also in the list of most cited articles, occupying the ninth position, this article analyzes the methods of hydrogen production aiming at an improvement in sustainability and the authors focus on the environmental, technical, financial and social aspects of 19 different methods of hydrogen production, making a comparative evaluation [24]. This publication obtained 932 citations in the analyzed period.

Microalgae

The search for "Microalgae" as a feedstock for hydrogen production presents few studies, illustrating a low level of research interest. However, the few publications analyzed have numerous advantages in using microalgae as a feedstock for hydrogen production. Microalgae can produce hydrogen directly from renewable energy sources. Another characteristic of microalgae is that they act at ambient pressure and temperature, are carbon neutral, and do not need intermediate electrical bases. In addition, microalgae also have advantages over terrestrial biomasses, such as the ability to grow in environments not favourable for terrestrial biomasses, higher growth rate, more efficient nutrient acquisition, and solar energy conversion [25]. Due to the ease of producing lipids in large quantities and short periods, the potential for conversion into biofuels such as bio-oil, biohydrogen, biodiesel, and biogas is high [26]. Various microalgae are genetically endowed with hydrogenase for hydrogen production, and some strains can be highlighted, such as *Chlorella fusca*, *Chlamydomonas reinhardtii*, *Scenedesmus obliquus, Platymonas subcordiformis, Chlorococcum littorale*, among others [27].

Fig. 9 illustrates the relationship between some feedstocks used in hydrogen production present in the keyword plus of the 3530 documents analyzed. It is possible to observe from the graph that water and waste, as mentioned earlier, occupy prominent positions in the publications. Microalgae are the feedstocks with the lowest number of articles among those analyzed, as interest in these feedstocks is still growing and perhaps will gain more prominence in the scientific literature. Hydrogen production using microalgae is surrounded by challenges that can be overcome if interest in these feedstocks increases. The main obstacles in hydrogen production are the low biomass concentration in the microalgae culture, the high amount of water in the microalgae biomass, which requires higher energy consumption for the drying process, and the oxygen sensitivity to hydrogenase. On the other hand, the issue of biohydrogen production having little recognition on a commercial scale and the existence of limiting factors in the production of hydrogens, such as high production costs, and difficulties in transport and storage, also affect research on it [28].

Waste

The search for the keyword "Waste" presents a reasonable number of publications about the other keywords searched, 529 documents were identified, but due to the diversity of residues that can be used, it is possible to specify the type of residue during the searches. Some studies used tea residues to obtain hydrogen-rich gas, and one used tea residues from Turkey, one of the world's largest producers of tea plants. This study analyzes the effect of the ratio of catalyst, temperature, and reaction time. The authors obtained a maximum H2 yield of 3.55 mol H_2/kg of tea residue at a temperature of 850 °C and a reaction lasting 15 min [29].

Another study focused on banana waste, a plentiful source in Indonesia, ranking it among the top 10 banana-producing countries. In harvesting, residues such as leaves, stems, and banana peels are left in large quantities, as the banana tree

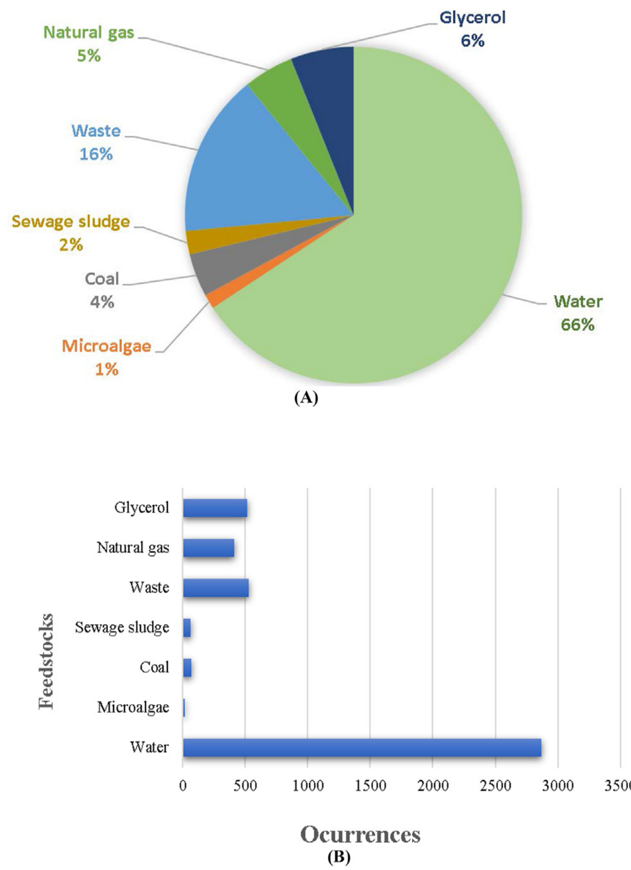

Fig. 9 – Hydrogen production feedstocks: (A) Ratio showing the percentage of articles on specific feedstocks; and (B) Number of occurrences mentioning different feedstocks in the titles of their respective articles.

cannot be harvested again. Taking advantage of the high cellulose content in the banana pseudostem, researchers have also used other banana components to compare the gas production rates of the pseudostem [30].

Some studies address hydrogen production from crop, food, and livestock residues. These residues have a high abundance. In the case of Central Europe, 0.7 billion tonnes of agricultural and forestry waste were generated between 1998 and 2001. Food waste has become a relevant research topic for hydrogen production since one of the most severe environmental problems in the world has been food waste. It is estimated that over a billion tons of food waste are generated per year, about 33% of the annual global food production [31].

For this reason, one of the leading global challenges has been the disposal and use of food waste. However, some challenges must be overcome to use these residues in hydrogen production [32]. Some challenges can be cited, such as the stability of food waste due to the variation of composition with the season and culture of the country, the sorting of waste which is a severe problem in developing countries, the accumulation of volatile fatty acids and acidification of the system. For these last two challenges, the mixture of food waste and organic fractions of urban solid waste was presented as a proposed solution [33,34].

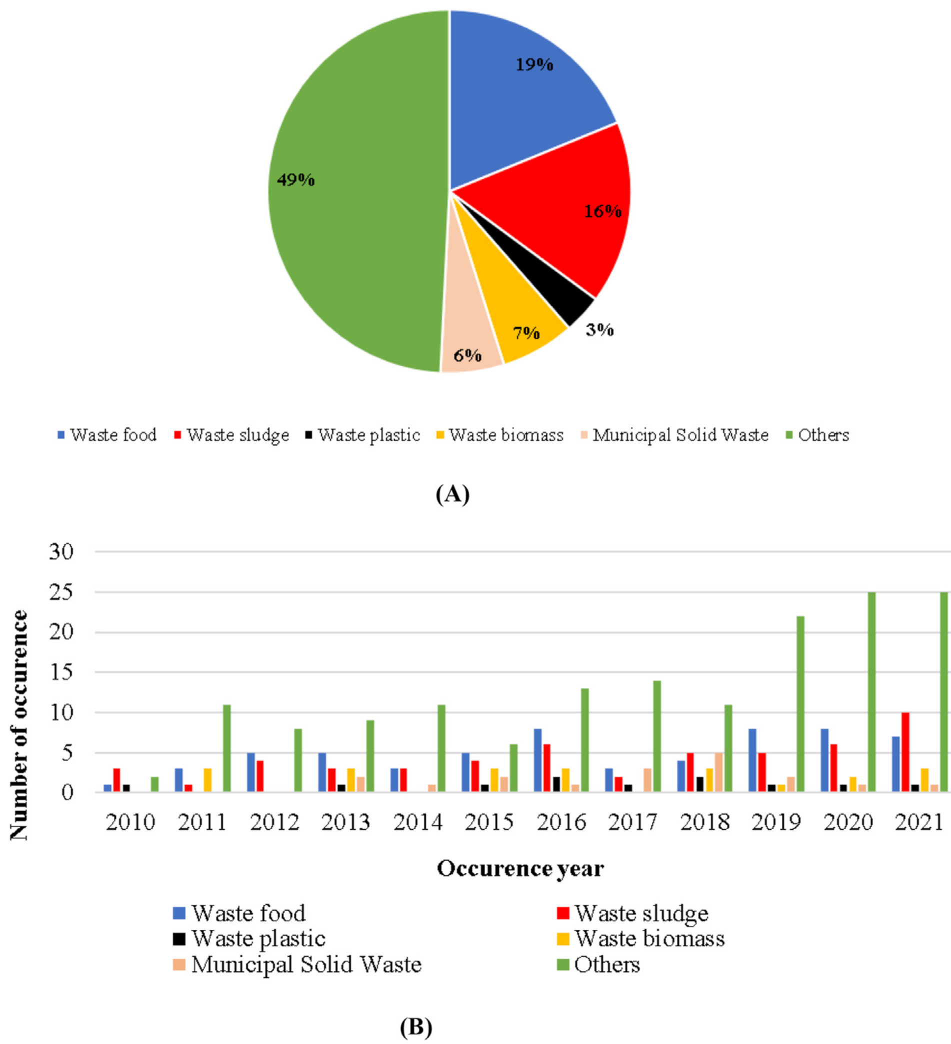

Fig. 10 – Hydrogen production from waste: (A) total number of papers; and (B) evolution over the years.

Studies on using activated sludge from waste produced in large quantities during biological wastewater treatment have also increased a lot, with 60% of the total operating costs of wastewater treatment plants being spent on sludge treatment and disposal. The high levels of proteins and carbohydrates call attention to their use as substrates for hydrogen production. Due to the low hydrogen yield of activated sludge dark fermentation, researchers have focused on optimizing sludge pretreatment methods, operating conditions, or sludge composition [33]. For example, a study was carried out to analyze the effect of polyhydroxyalkanoates, a polymer, on the production of dark fermentative hydrogen from activated residue sludge. The authors observed a direct relationship between the content of Polyhydroxyalkanoates and the volume of hydrogen produced and an inverse relationship between the content of Polyhydroxyalkanoates and the fermentation time of the residue [34].

Fig. 10 shows the growth of publications related to the use of residues for the production of hydrogen in the last 10 years. In addition to the residues previously reported, several other residues represent more than 40% of articles published on the subject, and some articles as residues of newspaper [35] and aluminium waste [36] can be cited as examples.

Water

The flammable nature of hydrogen gas, which, when burned, produces water, was discovered by Henry Cavendish in 1766. About 150 years ago, Frenchman Jules Verne predicted that hydrogen would be introduced from water as a renewable energy source instead of fuel. fossil [37]. Currently, hydrogen production using water is a reality, and it can be produced by several methods and using several different sources.

Fig. 11 presents some methods used in publications regarding hydrogen production using water, and the research interest in these methods in the last 10 years. The method that stands out is the photocatalytic method. In this method, the materials that act as photocatalysts absorb photons from the visible light spectrum causing the valence electrons to be excited and jump to the conduction band, leaving holes in the valence band. These photo-induced electrons and holes are brought to the catalyst's surface and participate in the reduction and oxidation of the adsorbed water molecules [38].

The production of hydrogen by electrolysis of water is also a method with an appropriate amount of research. The most straightforward water electrolysis unit consists of a cathode

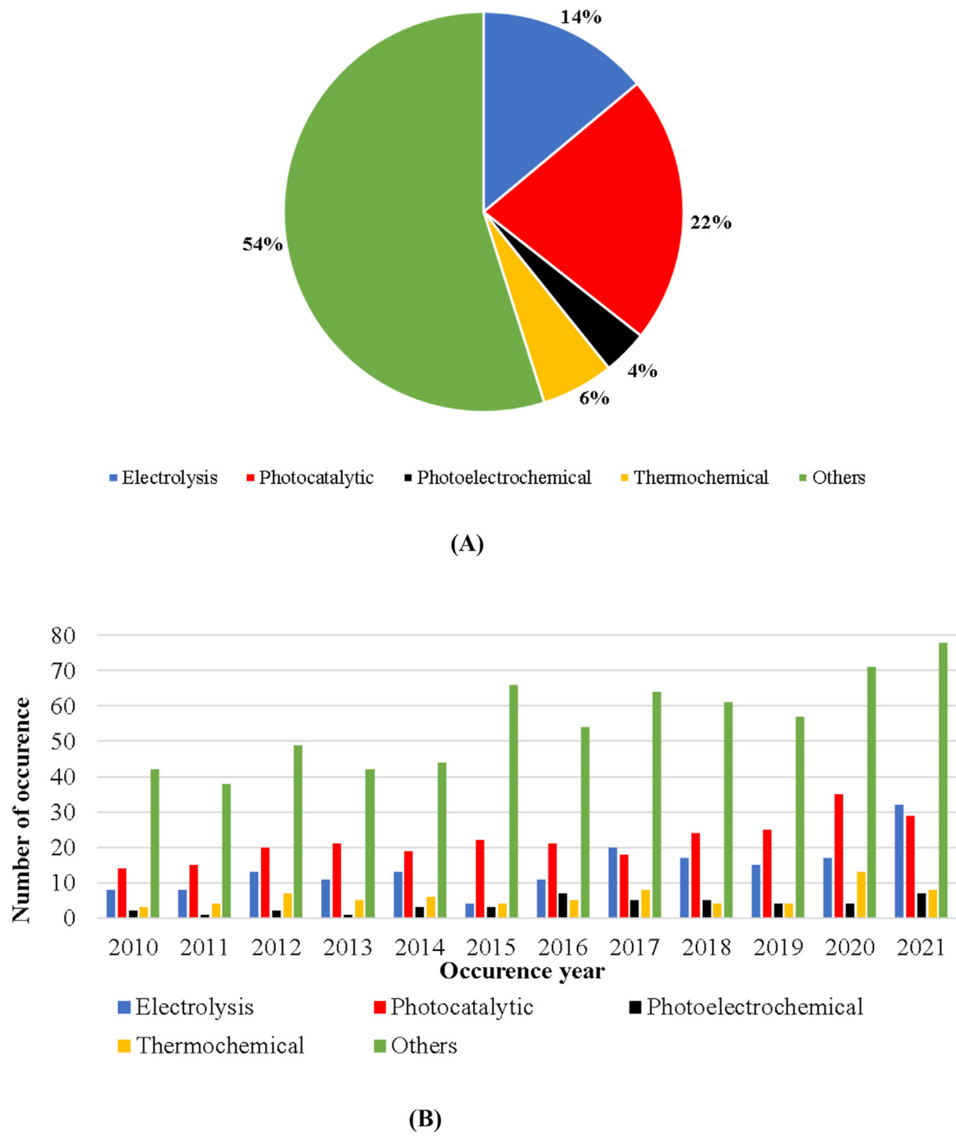

Fig. 11 – Hydrogen production from water: (A) total number of papers; and (B) evolution over the years.

and an anode immersed in a conductive electrolyte and connected by an external power supply. When a direct current is applied, in the general process, the hydrogen ions move towards the cathode, the hydroxide ions move towards the anode, and the gas acceptors are used to collect hydrogen and oxygen gases. For small production systems, the cost of electrolysis cells is the factor that determines the cost of electrolytic hydrogen. On the other hand, for large systems, the electricity cost determines the hydrogen value. Despite being a method known for about 200 years, hydrogen production still needs improvements in safety, durability, portability, energy efficiency, hydrogen release rate, operability, and one of the main points, the reduction in costs. of installation and operation. For this, many efforts are currently being made [39,40]. One of the examples is the studies to integrate renewable technologies as a source of energy in the electrolysis of water for hydrogen production [41–45]. Some researchers also investigate the influence of magnetism on the efficiency of hydrogen production by water electrolysis [46–49]. The water electrolysis method accommodates several processes, such as proton exchange membrane water electrolysis, solid oxide water electrolysis, alkaline water electrolysis, and alkaline anion exchange membrane water electrolysis [50].

Hot research topics

Quantitative analysis of frequent keywords

A better understanding of the pulse of research development, research interests, and future challenges can be obtained by researchers through keyword analysis [51]. Table 4 presents the ranking and total link strength of the 24 main keywords of this study. These keywords illustrate the most relevant issues in this field of research in the last ten years. In this field of study, the keywords hydrogen production (3009), hydrogen (1801), water(1753), performance (1342), generation (1147), and evolution (1138), stand out.

Table 4 – Quantitative analysis of 24 frequently used keywords in WCO-based hydrogen production research.

Rank	Keyword	Frequency	TLS	Rank	Keyword	Frequency	TLS
1	Hydrogen production	3009	20354	13	Photocatalysis	614	5143
2	hydrogen	1801	13303	14	Catalysts	593	4596
3	water	1753	13258	15	Oxidation	590	4717
4	performance	1342	10675	16	TiO2	582	4684
5	generation	1147	8889	17	Ethanol	547	4466
6	evolution	1138	8718	18	Catalyst	538	4253
7	biohydrogen production	1012	7650	19	Reduction	500	3998
8	h-2 production	954	7457	20	Optimization	472	3452
9	nanoparticles	899	7337	21	Degradation	462	3734
10	energy	752	5637	22	H-2 evolution	429	3581
11	methane	694	5303	23	Temperature	424	3358
12	biomass	675	5229	24	Decomposition	417	3184

Note: TLS: Total Link Strength.

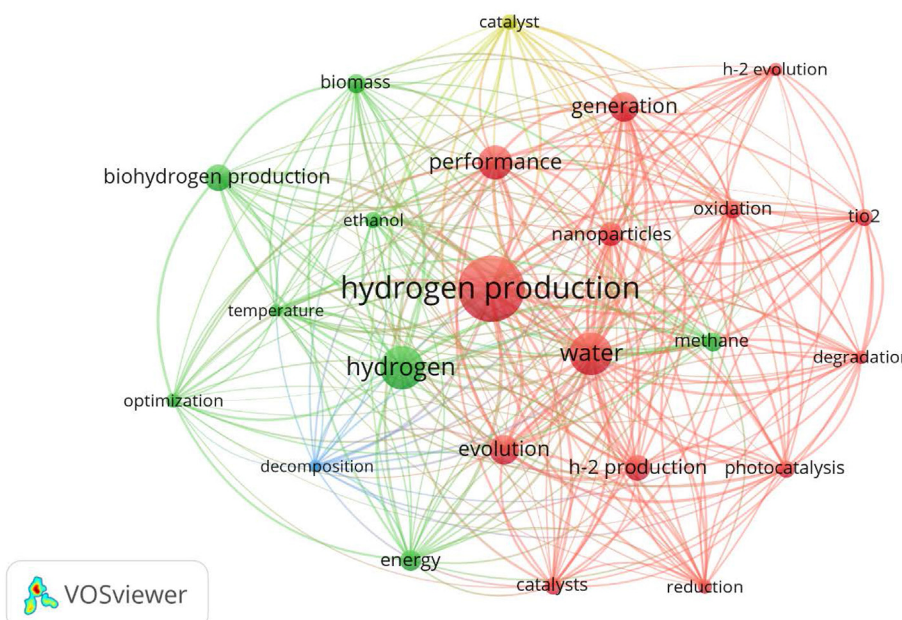

Fig. 12 – Mapping the co-citation of keywords in WCO-based hydrogen production research.

A visualization network map generated in the VOSviewer program of the 24 most important keywords with at least 400 occurrences in the database is illustrated in Fig. 12.

The network map in Fig. 12 shows that the keyword "hydrogen production" is visibly the most essential keyword used, it belongs to the red cluster that contains the keywords "photocatalysis", "performance," and "nanoparticles", indicating that there is some attention given to the use of nanoparticles in photocatalytic processes and that performance problem still constitute a technological challenge in this area. Furthermore, Fig. 12 also shows that the green cluster contains the keywords "biohydrogen production", "biomass", "Optimization" and "ethanol", indicating that the investigation of biohydrogen production has strong attention, not only in new forms of production but also in the optimization of existing processes.

Research areas

The CiteSpace software, discussed earlier in this work, was used to analyze and organize the data obtained and better understand emerging trends in the area. With this software, it is possible to visualize the development of knowledge about a specific research area [52]. From the cluster analysis, it is possible to identify more specific data for research and study topics [53]. Keywords are one of the main tools that can be used to determine future paths related to green hydrogen production and its raw materials. Table 5 shows the five primary sets of co-citation between articles related to the study topic.

Research fields

Cluster #0 has "photocatalytic hydrogen production" as its main keyword. Special attention is given to this technology as it is one of the most promising for converting clean solar

Table 5 – Top five co-citation research clusters on raw materials for hydrogen production based on the CiteSpace analysis.

CID	Label	NS	Mean	Top Five Terms	Representative Articles
#0	Photocatalytic hydrogen production	104	2015	photocatalytic hydrogen production; enhanced photocatalytic hydrogen production; hydrogen production; efficient photocatalytic hydrogen production; visible light.	(ANGELINA, ZHURENOK V, 2021) and (JIAYU, CHU, 2018)
#1	Fermentative hydrogen production	66	2014	fermentative hydrogen production; photo fermentation process; initial feedstock composition dilution; sequential dark; microbial population.	(TRAN, T GIANG, 2019) and (C, NINO-NAVARRO, 2020)
#2	Process design	63	2016	process design; process intensification; pemfc grade hydrogen production; multifunctional reactor; biomass gasification.	(BO, LIAO, 2013) and (PO –CHIH, KUO, 2018)
#3	continuous photo-hydrogen production;	59	2013	continuous photo-hydrogen production; macro-algae laminaria japônica; using anaerobic mixed bactéria; conversion efficiency; material flow analysis.	(HONGYAN, LIU, 2014) and (ELA, EROGLU, 2011)
#4	Looping steam	54	2014	looping steam; using sorption; enhanced steam; thermodynamic analysis; shale gas.	(ZAINAB, IBRAHIM S G ADIYA, 2017) and (J, SPRAGG, 2018)

Note: CID = Cluster ID, NS = Node Size.

energy into chemical energy, producing hydrogen by the direct photocatalytic splitting of water into H_2 and O_2, or more efficiently, in the presence of sacrificial reagents. The article that represents the cluster proposed a new technique to build efficient heterojunctions. For this, the researchers synthesized two groups of ternary catalysts, showing for the first time that by changing the order of platinum deposition, it is possible to obtain two types of photocatalysts. The authors further analyzed the rate of photocatalytic hydrogen production using the two types of photocatalysts [54]. Another article from this cluster proposes the fabrication of ternary heterostructures, which provide excellent visible light photocatalytic activity for hydrogen evolution without the need for any noble metal cocatalyst. The authors believe these synthesized ternary heterostructures can be used as promising noble metal-free catalysts for hydrogen production by photocatalytic water separation [55]. The third article of the cluster addresses the recycling of TiO_2 composite film for use as a photocatalyst for the production of hydrogen. The authors were able to prepare for the first time by the methods of corrosion-calcination and sol-gel spin coating. One of the authors' goals was to find easy and efficient routes to manufacture some photocatalysts that can be used in large-scale photocatalytic hydrogen production [56].

Cluster #1 is represented by the keyword “fermentative hydrogen production”. The prominence of this word probably arises because microbial fermentation processes are used in most biological developments to produce hydrogen. Organisms such as archaea, algae, and bacteria break down organic matter into carbon dioxide and hydrogen [57]. One of the outstanding works of this cluster is an investigation of the acid-thermal pretreatment of *Chlorella* sp. The authors show the effectiveness in the solubilization of *Chlorella* sp. using the acid-thermal pre-treatment, the optimal conditions for the pre-treatment being a biomass concentration of 40 g/L, 0.75% (v/v) of H_2SO_4, the temperature of 160 °C and pre-treatment time of 30 min [58]. In another article, some authors used fruit and vegetable residues and powdered cheese whey through dark fermentation, which is the process in which carbohydrate-rich substrates are anaerobically metabolized to produce hydrogen, followed by photofermentation, that occurs under anaerobic conditions. Also, in this case, photoheterotrophic bacteria use light as an energy source and metabolize organic molecules to produce H_2, biomass, and CO_2 as primary by-products. This two-stage system strategy (dark fermentation and photofermentation) has been proposed as a proposal to increase the efficiency of hydrogen production [59]. Another publication featured in this cluster deals with the use of volatile fatty acids from hydrogen production to be used as carbon sources for the cultivation of the oleaginous yeast *Cryptococcus curvatus*, after experiments the authors consider that the raw materials deficient in nitrogen are the best raw materials for this process [60].

Emerging trends

Cluster #2 presents the photohydrogen production method by continuous culture from different raw materials. One of the outstanding articles studies the saccharification efficiency of the pre-treated *Laminaria japonica* macroalgae for hydrogen production. The heat pretreatment proved to be the most promising, with the best results for increasing hydrogen production. In addition to this pretreatment, the authors performed other different pretreatments, such as acid, alkaline and ultrasonic, and made a comparison between them [61]. Another study [62] researched the production of photofermentative hydrogen from wastewater from mills, analyzing the influence of iron and molybdenum. The authors found that the addition of metal to olive mill wastewater can provide an increase in hydrogen production, biomass accumulation and removal of chemical oxygen demands. The third article of this cluster [63] presents the modification of carbon fibers activated by acidic, alkaline and neutral solutions as a proposal to improve the immobilization capacity of bacteria and the performance of hydrogen production.

Cluster #3 focuses on publications that present hydrogen production methods with chemical loop integration. This cluster's promising paper does a thorough chemical equilibrium analysis to illustrate the advantages of chemical loop integration and sorption enhancement with the conventional catalytic steam reforming method for hydrogen production. In the article, the authors use typical shale gas as raw material and analyze the effect of temperature, vapor to carbon ratio and pressure [64]. The second article of this cluster makes a thermodynamic analysis of sorption-enhanced chemical looping steam reforming for hydrogen production using bio-oil as raw material. In the article, the authors highlight the role of sorption enhancement, which can increase hydrogen yield and purity, and chemical looping, which can reduce the net energy balance of the process, but the best results are obtained when these two techniques are combined [65]. In the third article of this cluster, coal, sewage sludge, microalgae and sawdust are used as raw materials to carry out a thermodynamic analysis of hydrogen production via supercritical water gasification. The authors analyze the effects of various parameters such as temperature, pressure and feed concentration [66].

Cluster #4 emphasizes supercritical water gasification for hydrogen production. In a study, lignocellulosic biomasses (pine wood and wheat straw) were impregnated with nickel for subcritical (300 °C) and supercritical (400 and 500 °C) gasification of water, to analyze the influence of temperature, biomass ratio-water and residence time in hydrogen production. The study authors found that hydrogen production had a higher yield at higher supercritical temperatures [67]. Another publication [68] addresses the development of a new receiver/reactor for hydrogen production with biomass gasification in supercritical water. The authors used corn on the cob as raw material and managed to generate hydrogen-rich fuel gas in the device built. The authors also analyzed the effect of normal direct solar irradiation, flow rates, the concentration of raw materials and alkaline catalysts. A study on the use of some agricultural residues for hydrogen production by subcritical and supercritical catalytic gasification of water is also part of this cluster [69]. In this study, the authors used cotton and tobacco stalks as raw materials. Effects of temperature (300–600 °C) and type of catalyst (Troa, dolomite and Borax) were also analyzed.

Conclusions

In this article, a broad analysis of the literature related to hydrogen production was carried out further the emerging trends that are analyzed in the current works and the promising alternatives that can be studied in the future. This study analyzed and evaluated a set of 10,655 publications that were published between 2010 and 2022 in the WoS database with the aid of three different tools (VoSviewer, CiteSpace and Microsoft Excel). From this initial database, it was possible to create two more targeted databases of 3530 and 529 articles respectively, to understand the direction of research in this area. This research could be used by researchers interested in hydrogen production, providing relevant research directions. The study carried out involves the following relevant conclusions:

- China, the United States of America and South Korea produced the largest amount of publications among all countries/regions involved in research on hydrogen production.
- Microalgae was one of the raw materials highlighted in this work, this raw material received little attention in the literature because the number of articles that mention that this raw material is very small, despite the enormous potential and sustainability advantages that it presents. This is because it is a recent area of research and normally raw materials explored for a long time become more interesting due to the amount of information available.
- Research topics were identified from a keyword perspective. From the analysis of all keywords, the following themes stand out: hydrogen production, hydrogen, water, performance, Generation, evolution, and biohydrogen.
- The Chinese Academy Of Science is the organization at the center of the 4089 organizations involved in research on hydrogen production, having produced the most publications followed by Xi An Jiaotong University.
- As the cluster analysis illustrated, two constant search fields are Photocatalytic hydrogen production and Fermentative hydrogen production. In the future, studies should focus on Process design, continuous photo-hydrogen production and Looping steam.

Despite a large number of raw materials and known production methods, there is still a great concern on the part of researchers regarding the low yield of hydrogen that some raw materials present, the efficiency during the hydrogen production processes, the improvement of existing methods., and especially the difficulty of using some raw materials, methods or processes in the production of hydrogen on a large scale.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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