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UMA REVISÃO ABRANGENTE DAS TENDÊNCIAS DE PESQUISA GLOBAL SOBRE PRODUÇÃO DE BIOHIDROGÊNIO EM BIOREATORES: UM CAMPO EM DESENVOLVIMENTO

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Trabalho de conclusão de curso apresentado ao curso de Engenharia de Energias da Universidade da Integração Internacional da Lusofonia Afro-Brasileira como requisito parcial à obtenção do título de Engenheiro de Energia.

Orientador: Prof. Dr. José Cleiton Sousa dos Santos.

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_____

Me. Francisco Simão Neto
Universidade Federal do Ceará

Aos meus pais, Lúcia e Fernando.

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A todos, meu muito obrigado.

“Long story short

I survived.”

Taylor Swift (evermore)

RESUMO

A produção de biohidrogênio a partir de fontes renováveis é um campo de pesquisa em expansão que oferece uma alternativa de energia limpa. O uso de biorreatores para produzir biohidrogênio a partir de substratos orgânicos apresenta promissoras possibilidades para atender à crescente demanda global por energia sustentável, sendo que a seleção de micro-organismos, condições de cultivo e o design do biorreator desempenham papéis cruciais na produção eficiente. Além disso, o uso de resíduos agrícolas e industriais como matérias-primas pode ajudar a reduzir as emissões de gases de efeito estufa. Essas condições controladas proporcionadas pelos biorreatores garantem uma produção consistente e escalável, resultando em um aumento significativo nos investimentos em tecnologias de biorreatores. A utilização de análise bibliométrica, combinada com visualizações utilizando o VOSviewer ou o CiteSpace, permite explorar padrões de pesquisa e tendências no campo da produção de biohidrogênio em biorreatores. O estudo identificou um crescimento significativo nas publicações nessa área, com a China inicialmente sendo o país mais produtivo, mas a Índia acompanhando ao longo do tempo. A análise do índice H e de citações revelou a dominação da China em ambas as métricas, enquanto a Índia e a Coreia do Sul também fizeram contribuições significativas. Agências de financiamento na China e no Brasil foram importantes contribuintes, e revistas específicas como "International Journal of Hydrogen Energy," "Bioresource Technology," e "Renewable Energy" desempenharam um papel crucial na publicação de estudos relevantes. Análises de coautoria e cocitação identificaram pesquisadores-chave e suas colaborações, destacando a importância de certas áreas de pesquisa. Além disso, a análise de palavras-chave revelou um foco na fermentação escura e indicou direções emergentes de pesquisa, como "Enterobacter aerogenes" e "biomassa lignocelulósica". Essas descobertas abrangem tendências globais na geração de biohidrogênio em biorreatores, enfatizando o aumento nos estudos, com a China liderando em publicações e citações, proporcionando insights valiosos para futuros avanços na produção de biohidrogênio e na transição para fontes de energia mais limpas.

Palavras-chave: Biohidrogênio; Bioreator; Produção; Bibliometria avançada.

ABSTRACT

The production of biohydrogen from renewable sources is an expanding research field of that offers a clean energy alternative. The use of bioreactors to produce biohydrogen from organic substrates holds promise in meeting the increasing global demand for sustainable energy, with factors such as microorganism selection, cultivation conditions, and bioreactor design playing crucial roles in efficient production. Additionally, the use of agricultural and industrial waste as raw materials can help reduce greenhouse gas emissions. The controlled conditions provided by bioreactors ensure consistent and scalable production, leading to increased investment in bioreactor technologies. Utilizing Bibliometric analysis, combined with visualizations using VOSviewer or CiteSpace, allows to explore research patterns and trends in the field of biohydrogen production in bioreactors. The study found significant growth in publications in this area, with China initially being the most productive country, but India catching up over time. The H-index and citation analysis revealed China's dominance in both metrics, while India and South Korea also made significant contributions. Funding agencies in China and Brazil were major contributors, and specific journals like "International Journal of Hydrogen Energy," "Bioresource Technology," and "Renewable Energy" played a crucial role in publishing relevant studies. Coauthorship and cocitation analyses identified key researchers and their collaborations, highlighting the importance of certain research areas. Furthermore, keywords analysis revealed a focus on dark fermentation and indicated emerging research directions such as "Enterobacter aerogenes" and "lignocellulosic biomass." These findings encompass global trends in biohydrogen generation in bioreactors, emphasizing the increase in studies, with China leading in publications and citations, providing valuable insights for future advancements in biohydrogen production and the transition to cleaner energy sources.

Keywords: Biohydrogen; Bioreactor; Production; Advanced bibliometrics.

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SUMÁRIO

1. INTRODUCTION

Biohydrogen is a gas biologically produced by microorganisms such as bacteria or algae, stands as a renewable energy source. Derived from organic materials like agricultural waste, it represents a clean alternative to fossil fuels. However, its large-scale production faces technological and economic challenges that need to be overcome for widespread viability (Liu et al., 2014). It's production from renewable sources is a rapidly expanding research area due to its importance as an alternative source of clean energy (Łukajtis et al., 2018a; Singh; Sharma, 2012). With the increasing global demand for sustainable and renewable energy sources, their production in bioreactors has been considered a promising option to meet this need (Łukajtis et al., 2018b). This method involves the use of microorganisms capable of producing hydrogen from organic substrates (Ghimire et al., 2015; Singh; Sharma, 2012).

Among the important factors for the production of biohydrogen are: the selection of adequate microorganisms, the control of the cultivation conditions and the design of the bioreactor (Sirohi et al., 2022). The use of agricultural and/or industrial waste as raw material can help reduce greenhouse gas emissions (Khan et al., 2016; Show; Lee; Chang, 2011).

This process requires specific conditions, such as temperature, pH and nutrient concentration (Eryildiz; Lukitawesa; Taherzadeh, 2020). The use of bioreactors allows controlling these conditions, ensuring a more efficient and consistent production, in addition to being attractive due to its industrial-scale production capacity, considering that investment in bioreactor technologies for the production of biohydrogen has grown exponentially in the last decade (Singh; Sharma, 2012; Zhang et al., 2018). There are different types of bioreactors used for this purpose, including fixed bed bioreactors, activated sludge bioreactors and membrane bioreactors (Park et al., 2017).

As a way of verifying this growth, advanced bibliometric analysis was applied, which is a useful tool to evaluate the scientific production in a given area, allowing to identify trends and gaps in the literature (Simao Neto et al., 2023; Sivaranjani et al., 2023). This research method can be applied to evaluate the production of biohydrogen in bioreactors, allowing to understand its current state and direct future investigations (Nogueira et al., 2023).

An advanced bibliometric analysis can help identify which microorganisms have been most studied, as well as which culture conditions have been most used in the literature. Also, what types of bioreactors have been used and what are the current trends in their designs (Sales et al., 2023; Venkata Mohan et al., 2010). It can also highlight which are the main scientific journals that publish articles related to the production of biohydrogen in bioreactors,

as well as which are the countries and institutions that contribute the most to research in this area (Arimi et al., 2015; Rodrigues et al., 2023). Helping to understand the geographic distribution and investigating potential scientific collaborations (Sivarajani et al., 2023).

Thus, the present study aims to outline the structure of knowledge on the production of biohydrogen in bioreactors. So far, bibliometric analysis studies addressing the production of biohydrogen by bioreactors are scarce in the literature. In this way, the bibliometric analysis is produced by analyzing the keywords together with the bibliographic review portals as the main units of analysis to answer the following research questions (QPs):

• RQ1. How has scientific production on the production of biohydrogen by bioreactors developed over time?

• RQ2. What are the main research points (keywords) within the literature on biohydrogen production by bioreactors?

• RQ3. What are the main raw materials in biohydrogen production by bioreactors?

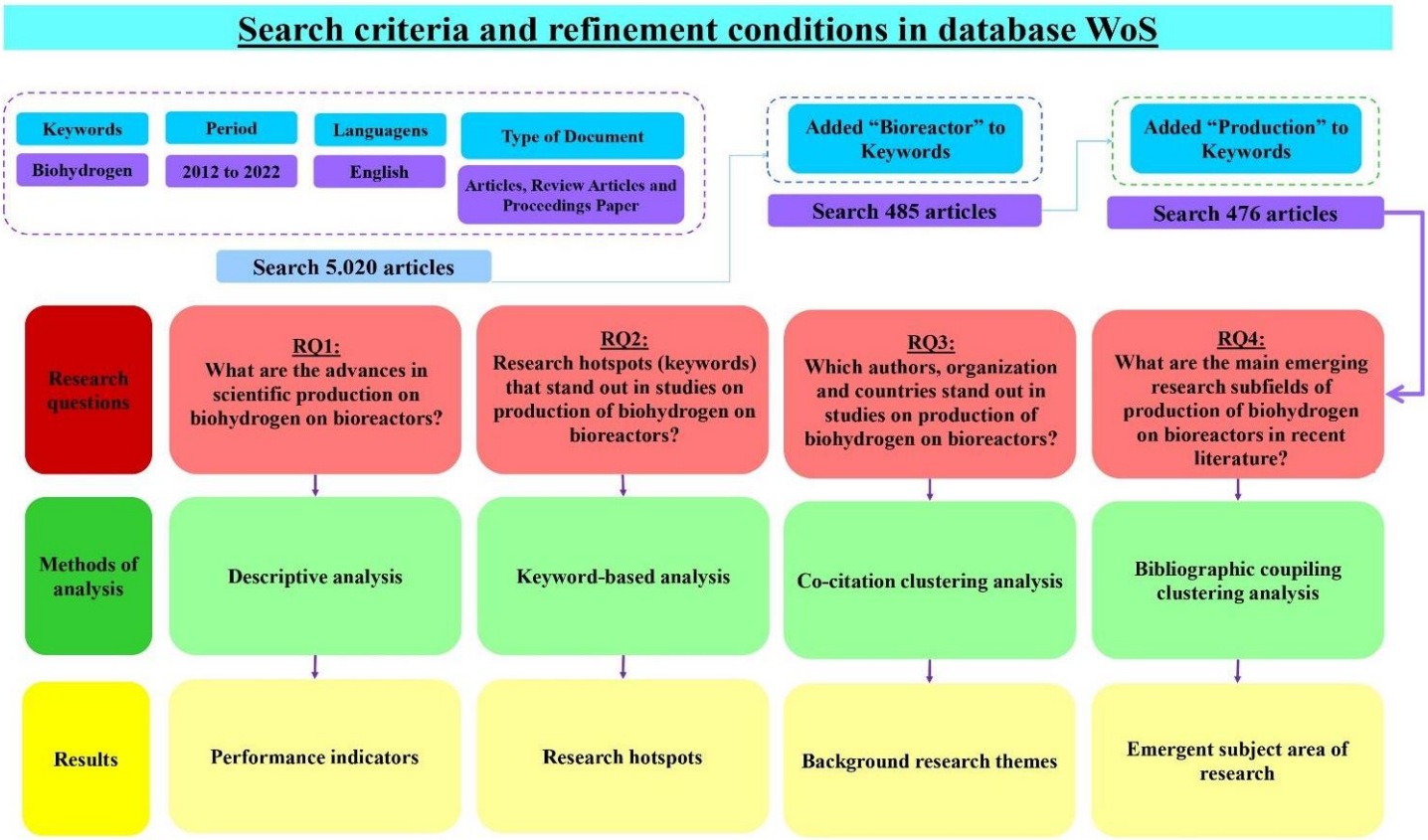
• RQ4. What are the main research groups on biohydrogen production by bioreactors?

2. METODOLOGY

2.1 Data Source

The Web of Science - Core Collection was used as the main data source. The Web of Science - Core Collection (https://www-periodicoscapes-gov-br.ezl.periodicos.capes.gov.br/index.php) encompasses a considerable amount of high-level literature in a variety of fields of science, including the biohydrogen production areas in bioreactors. It ranks as one of the most highly regarded databases for the bibliometric analysis of scientific papers (Mourao; Martinho, 2020). Furthermore, Sciencedirect (https://www.sciencedirect.com) was also consulted to corroborate the results achieved with the Web of Science - Core Collection, in addition to being used as a source of additional material. Sciencedirect, developed by Elsevier, is a comprehensive database of scientific abstracts and citations reviewed by scientists working in the field addressed, containing thousands of titles from international publishers and is also available for bibliometric analysis (Bodnariuk; Melentiev, 2019).

Figure 1. Representation of the study methodology in the PRISMA structure.



Source: Author (2023).

2.2 Data Collection

Data collection was carried out on the Web of Science website, consisting of the following steps: in the first step, some parameters were defined, such as the types of work required, namely articles, review articles and conference articles. Then, the language of the publications was defined, where the chosen one was “English”. Finally, the period in which the works were published was defined, corresponding to the years 2012 – 2022. In the second stage, the keywords were searched, starting with the word “Biohydrogen” in all fields, which resulted in 5,020 results. Then another search field was added for the second word, “Bioreactor”, also in all fields, resulting in 485 results. Finally, the last word was searched in all fields, “Production”, resulting in 476 articles.

2.3 Data Extraction

The files obtained were imported into Microsoft Excel software to be processed afterwards. The selection of literature and the analysis and extraction of data from the chosen articles were carried out. This database provides information on the annual number of publications, frequency of citation, countries of origin, authors, journals, institutions and funding agencies. In addition, the impact factor (IF) and categories (Q1, Q2, Q3 and Q4) of journals are available for access in the Journal Citation Report (JCR) 2019 (available at: http://thomsonreuters.com/journal- citation reports/), a reference standard applied to classify journal performance. The H-index was also another important indicator to determine the scientific production and academic status of a researcher and the productivity and impact of a country, institution or journal.

2.4 Data Visualization and Analysis

The Java VOS viewer program (downloaded from http://vosviewer.com) is a software tool used to build scientific literature visualization networks, which encompass researchers, journals, research organizations or countries and can be connected by co-authoring, citation, cocitation and co-occurrence analysis. Co-authorship analysis is a reliable resolution to define similar connections between items through the number of co-authored documents. The citation analysis of items is elaborated based on the number of times they cited each other. The co-citation and co-occurrence analyze explain the relationship between the items, respectively, based on the number of times they are referenced together and the number of works in which they occur together. In the present study, this software was used to analyze country/region citations, institutional citations, author co-authorship and co-citation, journal co-citation and keyword co-occurrence.

In the network graphs produced by the VOS viewer, each node features different information, such as countries/regions, institutions, journals or keywords. They were given different colors according to different taxonomies or times of occurrence. In general, node size was determined by the calculated betweenness centrality of each parameter, with larger nodes representing a higher level of centrality. The links between the nodes indicated correlation between the parameters, and their thickness represents their strength. Total link strength (TLS) was used to quantitatively assess them.

Another scientific research software used was CiteSpace V, which made it possible to carry out the institution and author co-authorship analysis, journal co-citation, a double map overlay of journals, and reference co-citation analysis. In the representation charts prepared, each point symbolizes the research category under analysis, and its magnitude is directly proportional to the number of incidences or references. The connections between the dots represent the strength of collaborations, cross-references or joint occurrences. The hue of each point indicates the temporal distribution. Clusters formed by adjacent points correspond to correlated subjects, and the transfer of knowledge between clusters can be observed by the variation in tonality.

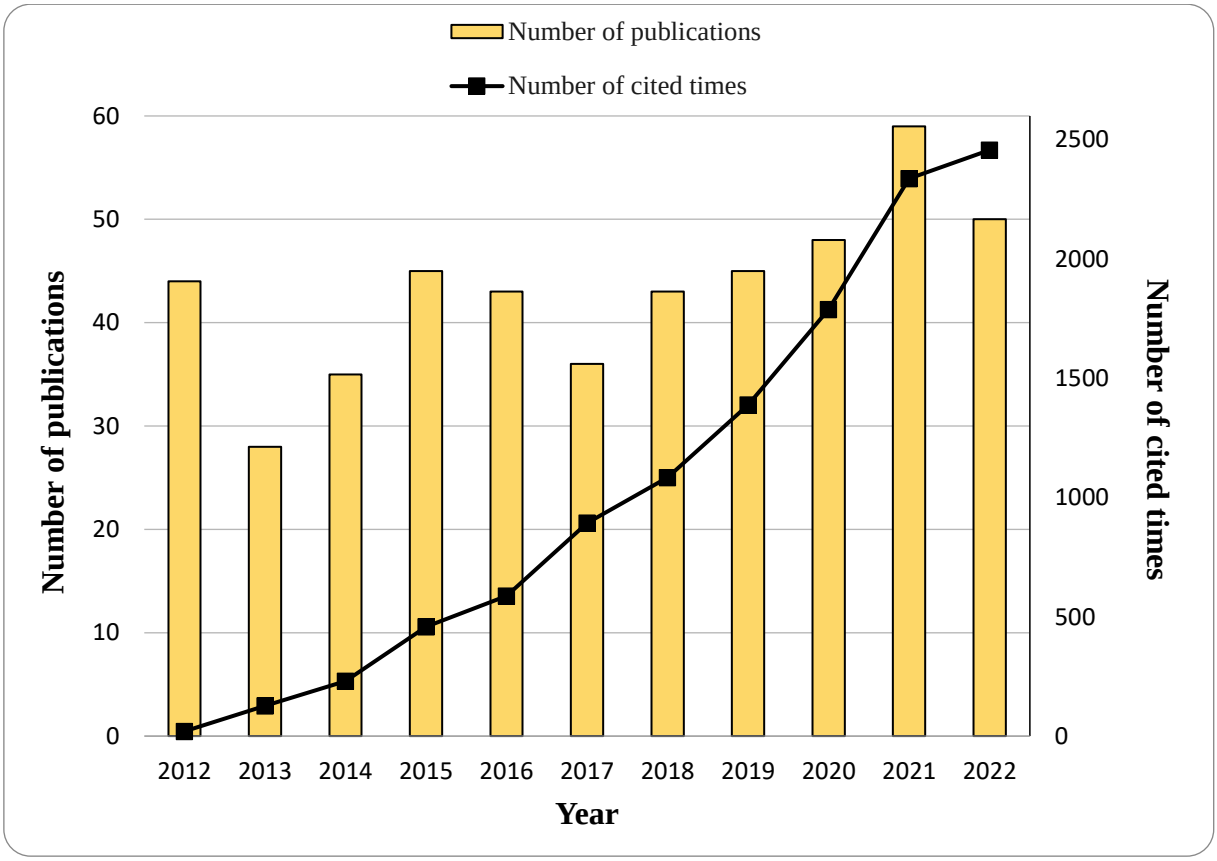
Different parameter settings in the VOS viewer or CiteSpace will produce different effects on the analysis of the visual representation. Some of the main VOS viewer software configuration options have been detailed in the "Results" section. The CiteSpace software parameter settings were as follows: time range (from 2010 to 2022), years per range (one or two years), term source (title, abstract, author keywords, and additional keywords), type of point (select one parameter at a time, such as institution, author, cited author, reference or keyword), selection criteria (top 50), exclusions (minimum tree expansion and removal of networks per range) and representation visual (grouping view or time zone view).

3. RESULTS

3.1 Trend of Global Publications and Citations

A total of 476 WoSCC publications were obtained, of which 383 articles, 78 review articles and 53 proceeding papers, met the inclusion criteria in the period from 2012 to 2022 (Figure 1). As shown in Figure 2, global research on production of biohydrogen on bioreactors has shown a steady increase over the past 10 years. The number of publications grew from 40 (2012) to 476 (2022), with almost 43% of them (202) being published in the last four years. All publications received a total of 11,372 citations, resulting in an average of 23 citations per article. As 2012 serves as the initial reference year, there were no citations of works published in that year. The recording of citations for publications from 2012 commenced in the following year.

Figure 2. Global trend of annual publications and citations related to production of biohydrogen in bioreactors from 2012 to 2022.

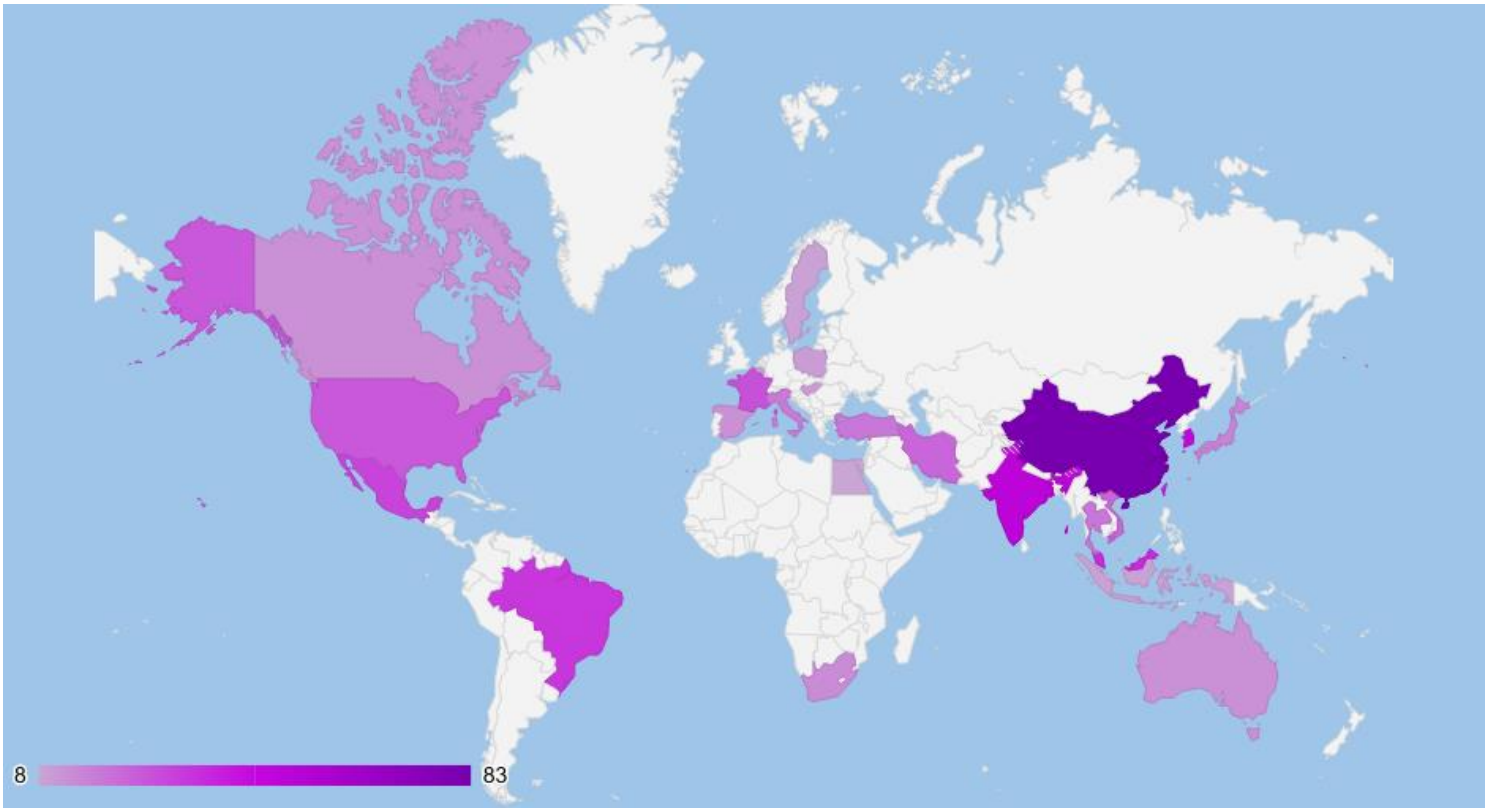


Source: Author (2023).

3.2 Contributions of Countries/Regions

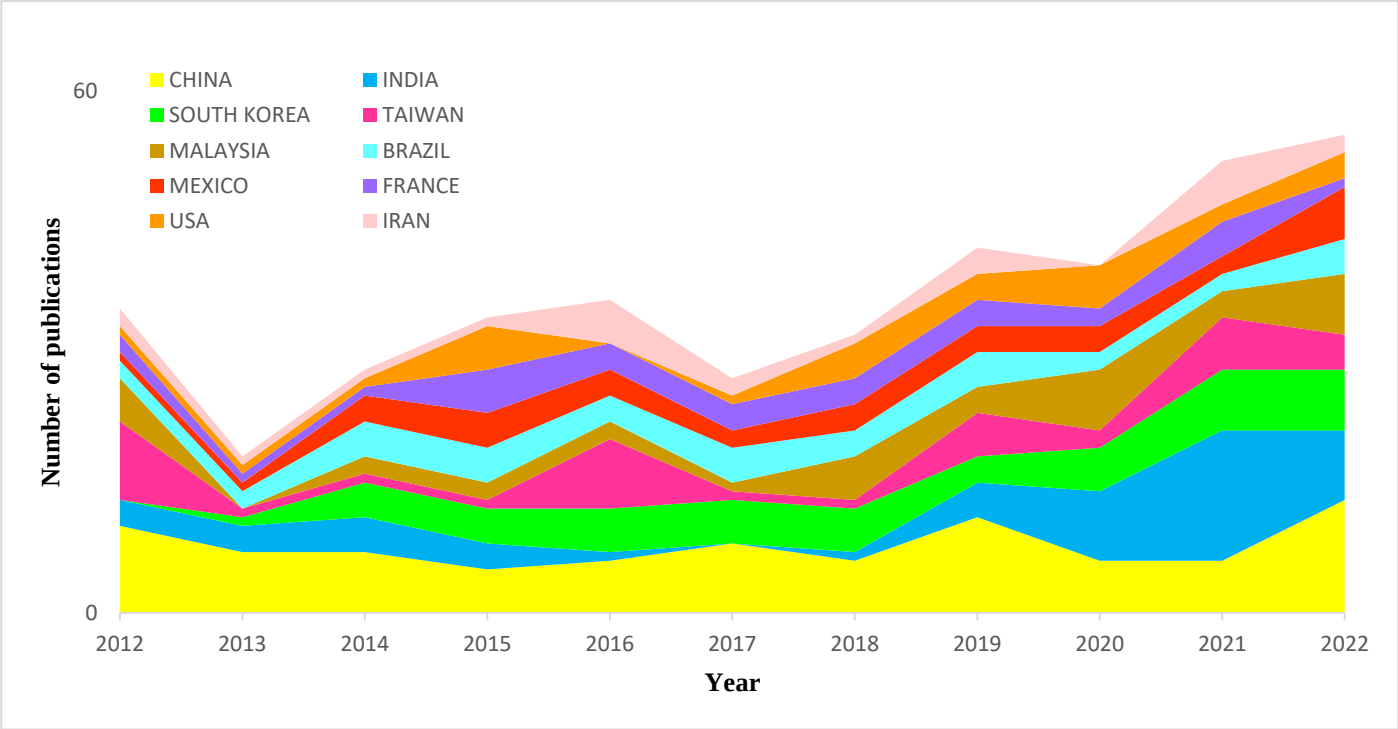
The distribution of published articles was visualized on a global map. The colors on the map indicate different levels of density (Figure 3). Figure 4 presents a significant trend in the annual publications of the main countries between 2012 and 2022. In total, 25 countries/regions participated in the publications. China led in productivity, with 83 articles published (17,43%), followed by India with 50 articles (10,50%) Figure 5. As shown in Figure 6 and Figure 7, China the achieved the highest number of citations (463 times) and an H-index of 25, outperforming other countries/regions and taking the top spot globally. China, India, and South Korea excel in biohydrogen research due to large populations, rapid economic growth, and a focus on sustainable energy to meet increasing demand. Substantial investments in research and development, supported by favorable government policies and robust research infrastructure, contribute to their prominence in publishing on this topic.

Figure 3. World map displaying the global distribution of production of biohydrogen in bioreactors.



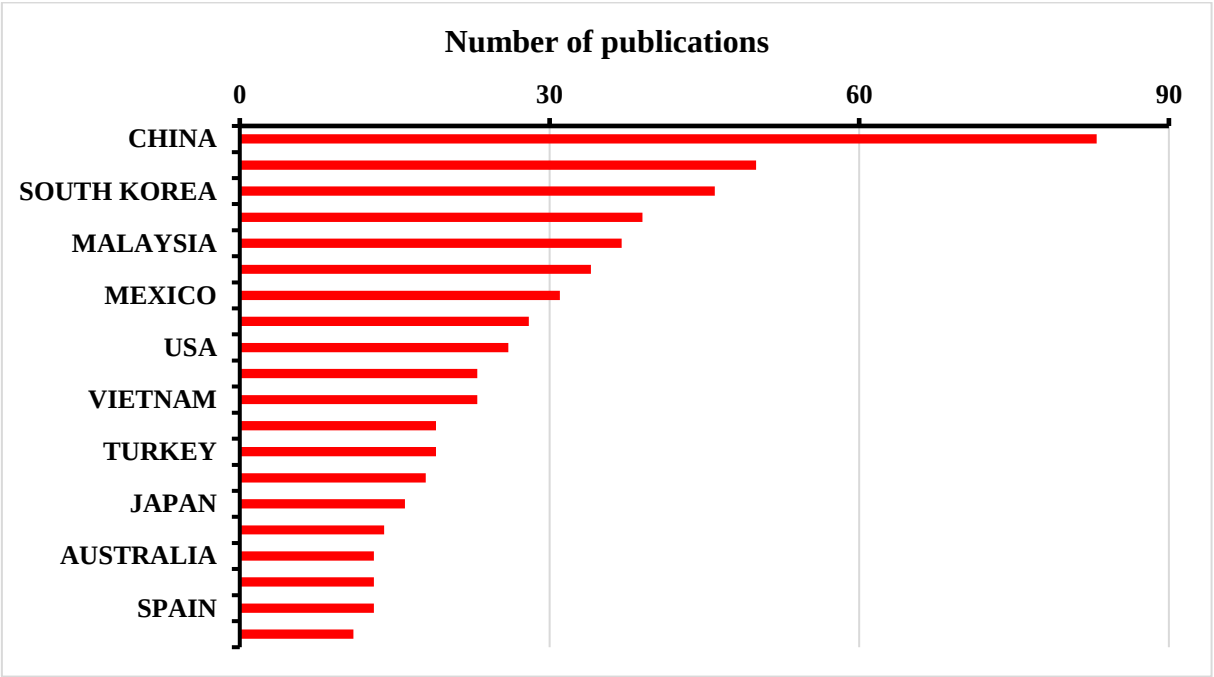
Source: Author (2023).

Figure 4. Growth trends in the publication quantity of the top 10 countries/regions in production of biohydrogen in bioreactors research from 2012 to 2022.



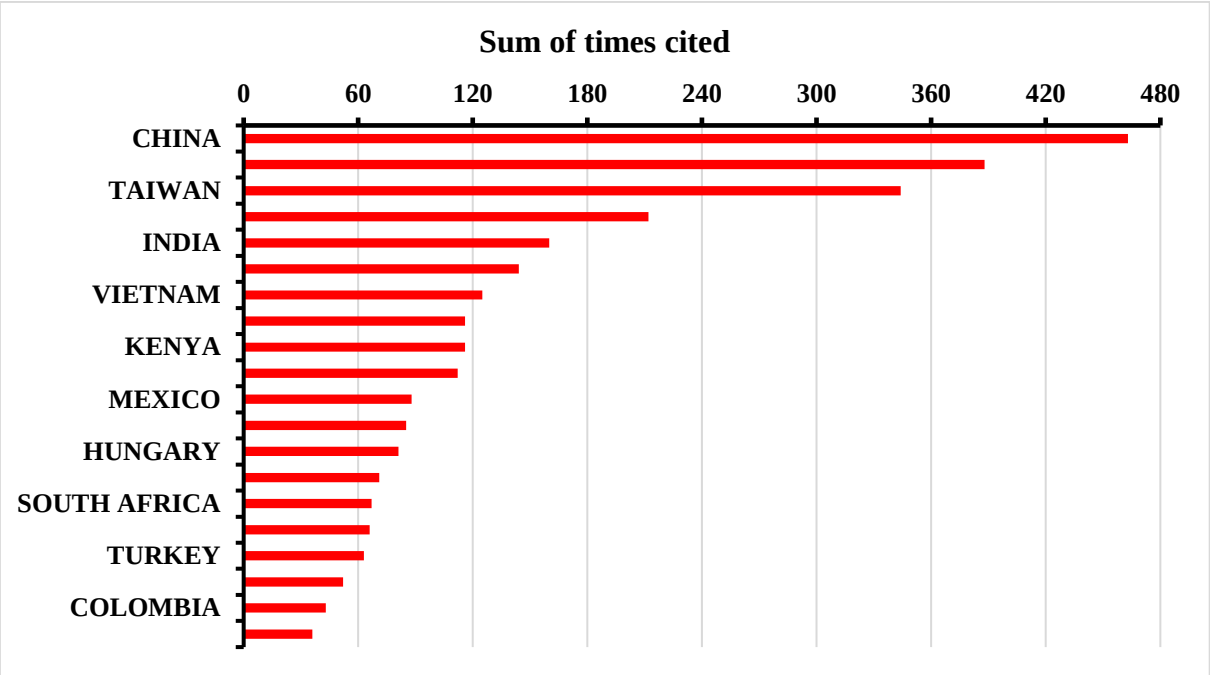
Source: Author (2023)

Figure 5. Total number of publications of top 20 countries in this field.



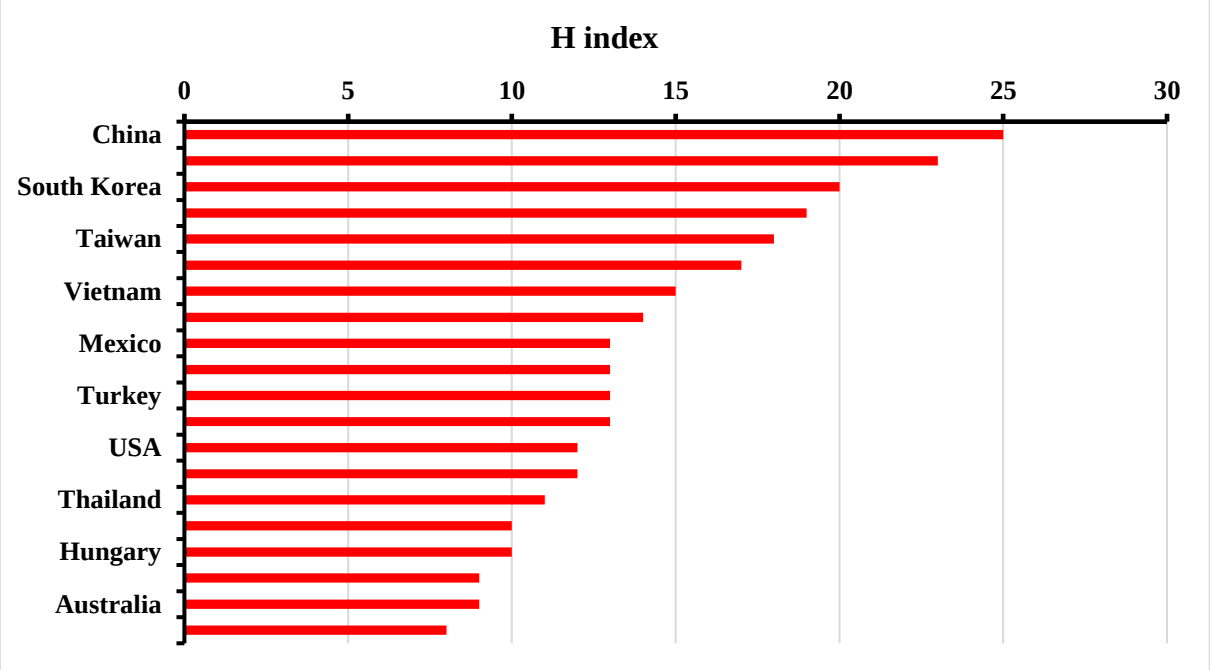
Source: Author (2023).

Figure 6. Sum of total citations of top 20 countries in this field.



Source: Author (2023).

Figure 7. H-index of top 20 countries in this field.

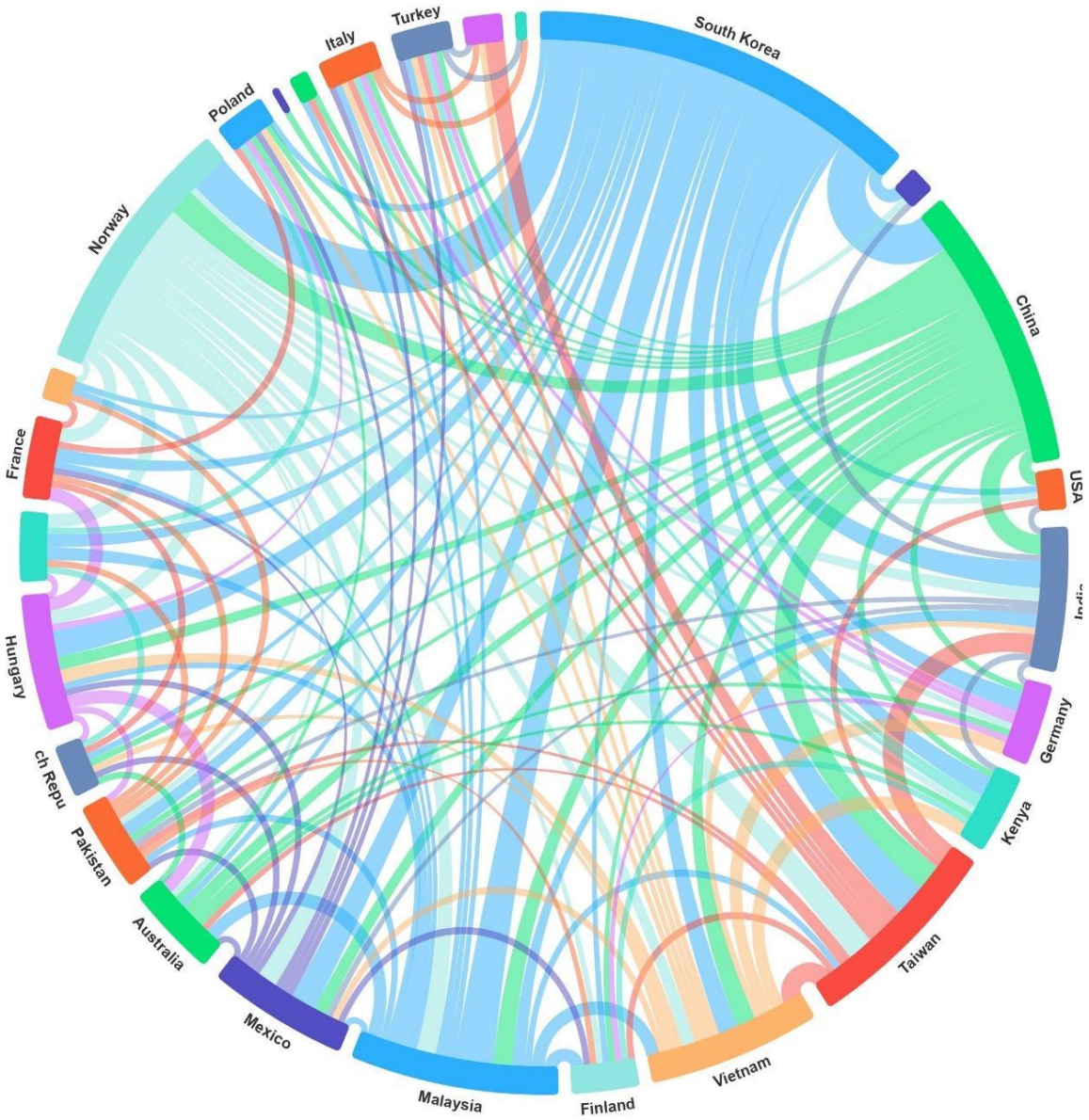


Source: Author (2023).

With regard to cross-country/region co-authorship analysis, South Korea has emerged as a center of production of biohydrogen on bioreactors research, maintaining close collaboration with China, Malaysia and Norway (Figure 8), The thickness of the line reflects

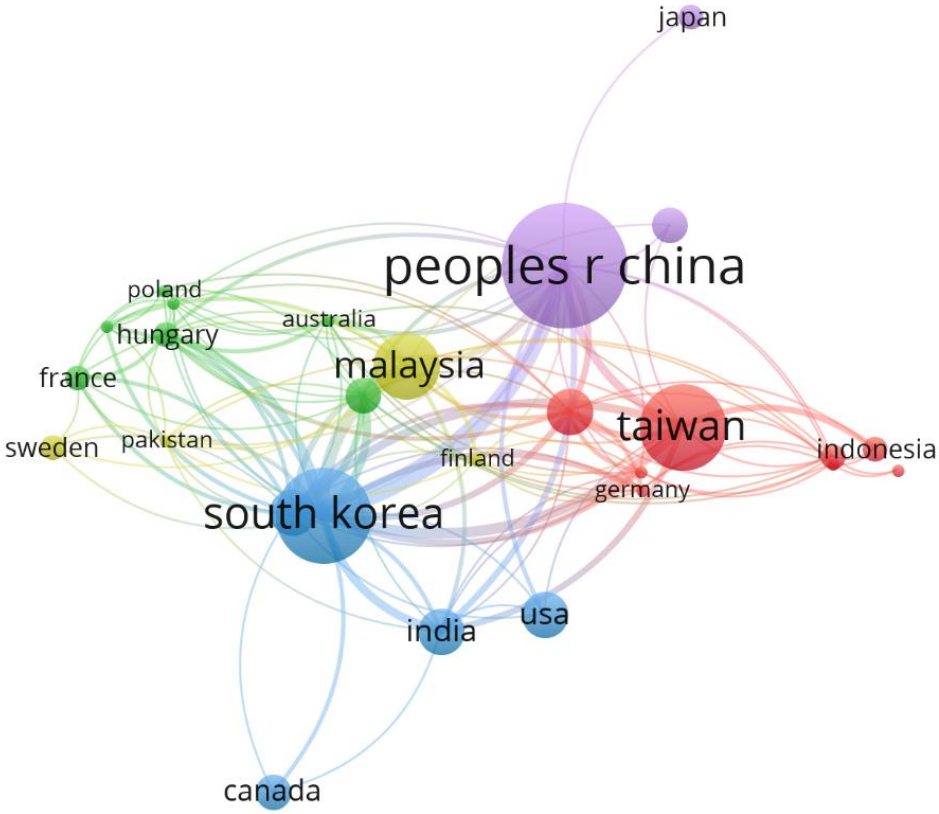
the frequency of the cooperation. Publications from 33 countries were selected, with a minimum number of documents per country above 1, and analyzed using the VOS viewer (Figure 9). Each node represents a country/region, and node size indicates the number of publications. The connection between the nodes represents a citation relationship, and the thickness of the lines indicates citation strength (weights on the TLS). The resulting network map showed 27 nodes and 133 connections. The three countries with the highest Total Size Index (TLS) were the South Korea (TLS = 58), China (TLS = 41) and Norway (TLS = 38).

Figure 8. Distribution and international cooperation of countries/regions that are involved in production of biohydrogen on bioreactors.



Source: Author (2023).

Figure 9. Citation map of countries/regions on production of biohydrogen on bioreactors research generated by the VOS viewer.



Source: Author (2023).

3.3 Contributions of Institutions

A total number of 200 organizations collaborated in studies on biohydrogen generation in bioreactor experiments. Feng Chia University led in terms of contribution, with 24 published papers, followed by Centre National de la Recherche Scientifique and Universidade de São Paulo, with 19 and 18 articles respectively. Table 1 presents the top 10 influential institutions and the number of publications from each of them.

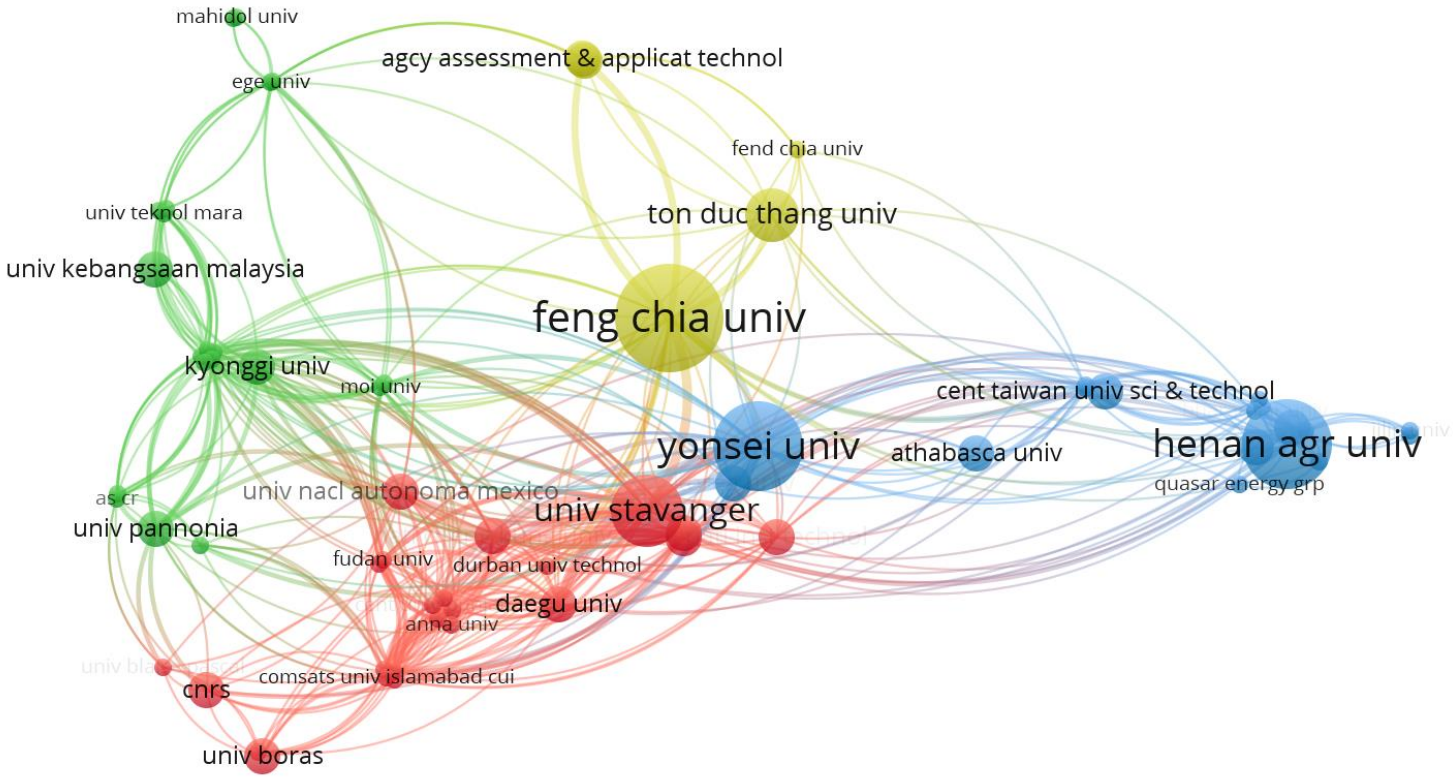
Table 1. Top 10 institutes that collaborated in studies on production of biohydrogen on bioreactors in publications

Rank	Instituitions	Countries/regions	Count
1	Feng Chia University	China	24
2	Centre Entre National de la Recherche Scientifique CNRS	France	19
3	Universidade de São Paulo	Brazil	18
4	Yonsei University	South Korea	18
5	Universidad Nacional Autonoma de Mexico	Mexico	16
6	Council of Scientific Industrial Research CSIR India	India	15
7	Ton Duc Thang University	Vietnam	14
8	Henan Agricultural University	China	13
9	Chongqing University	China	12
10	CSIR Indian Institute of Chemical Technology IICT	India	11

Source: Author (2023).

Regarding the institutions citation analysis shown in Figure 10, only those with a minimum of 1 publication were included. The network map consisted of 65 nodes and 480 links. The top three institutions with the highest TLS (Total Link Strength) were the UNIVERSITETET I STAVANGER (TLS = 62), the YONSEI UNIVERSITY (TLS = 50), and the FENG CHIA UNIVERSITY (TLS = 45).

Figure 10. Mapping of the citation analysis among 65 identified institutions on production of biohydrogen on bioreactors research based on the VOS viewer.



Source: Author (2023).

3.4 Contributions of Funding Agencies

Table 2 lists the top 10 global funding organizations that have provided funding for bioreactor research for biohydrogen production. Of those mentioned, 3 are from Brazil and 3 are from China. First place went to the National Natural Science Foundation of China (NSFC), which supported a total of 48 studies. In second place, we have the Consejo Nacional De Ciencia Y Tecnologia Conacyt from Mexico, with 20 supported studies, followed by the European Commission in third place, with a support of 18 studies.

Table 2. Top 10 related funding agencies.

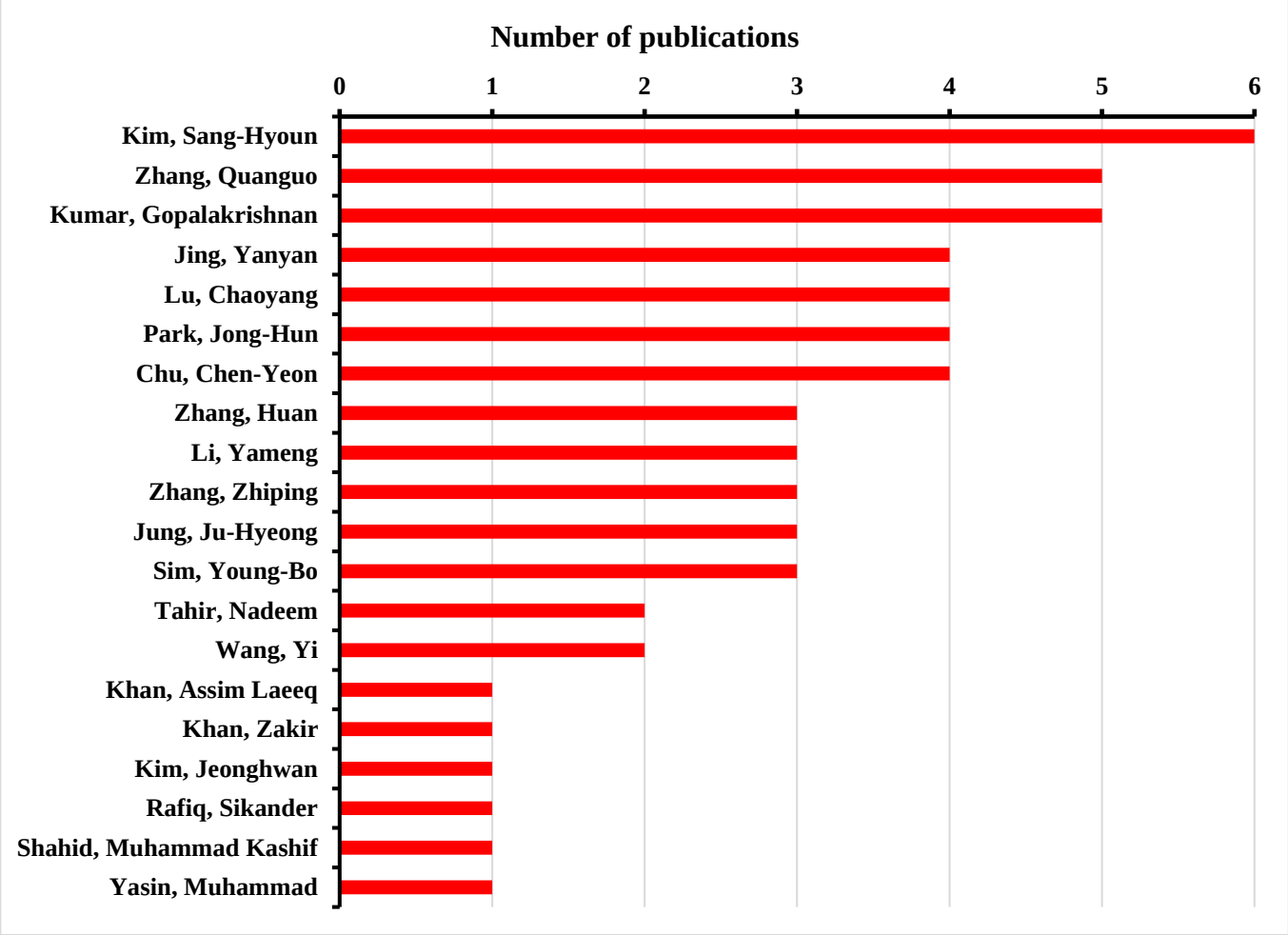
Funding Agencies	Countries/region	Count	Percentage
National Natural Science Foundation Of China Nsfc	China	48	10,08
Consejo Nacional De Ciencia Y Tecnologia Conacyt	Mexico	20	4,2
European Commission	European Union	18	9
Fundação De Amparo A Pesquisa Do Estado De Sao Paulo Fapesp	Brazil	17	3,5
Ministry Of Science And Technology Taiwan	Taiwan	16	3,3
Conselho Nacional De Desenvolvimento Cientifico E Tecnológico Cnpq	Brazil	15	3,1
Coordenação De Aperfeiçoamento De Pessoal De Nível Superior Capes	Brazil	11	2,3
National High Technology Research And Development Program Of China	China	11	2,3
Department Of Biotechnology Dbt India	India	10	2,1
Fundamental Research Funds For The Central Universities	China	10	2,1

Source: Author (2023).

3.5 Contributions of Authors

Figure 11 shows the 20 most prolific authors in terms of publications. Of the top 20 authors identified in WoSCC, their 57 publications represented 12% of all literature in the field in question. De Kim, Sang-Hyoun from the South Korea was the most prominent author, having published 6 articles, followed by Zhang, Quanguo (China) and Kumar and Gopalakrishnan (India) with 5 articles, and Jing, Yanyan (China), Lu, Chaoyang (China), Park, Jong-Hun (South Korea) and Chu, Chen-Yeon (China) with 4 articles.

Figure 11. Top 20 most productive authors based on the number of publications.



Source: Author (2023).

3.6 Journal Analysis

A total of 133 journals have recently emerged in this research area. The top 10 active journals have published 269 papers on biohydrogen production in bioreactors, representing 56.16% of the total 479 publications (as shown in Table 3). The INTERNATIONAL JOURNAL OF HYDROGEN ENERGY had the highest number of published papers (131), accounting for 27.35% of the publications. In second place is BIORESOURCE TECHNOLOGY with 65 publications. The journal RENEWABLE & SUSTAINABLE ENERGY REVIEWS has the highest impact factor, with a value of 16.799, followed by CHEMICAL ENGINEERING JOURNAL (16.744) and BIORESOURCE TECHNOLOGY (11.889). According to the JCR 2019 criteria, the top 10 active journals were classified as Q1 in 6 cases, Q2 in 2 cases, and Q3 in 2 cases.

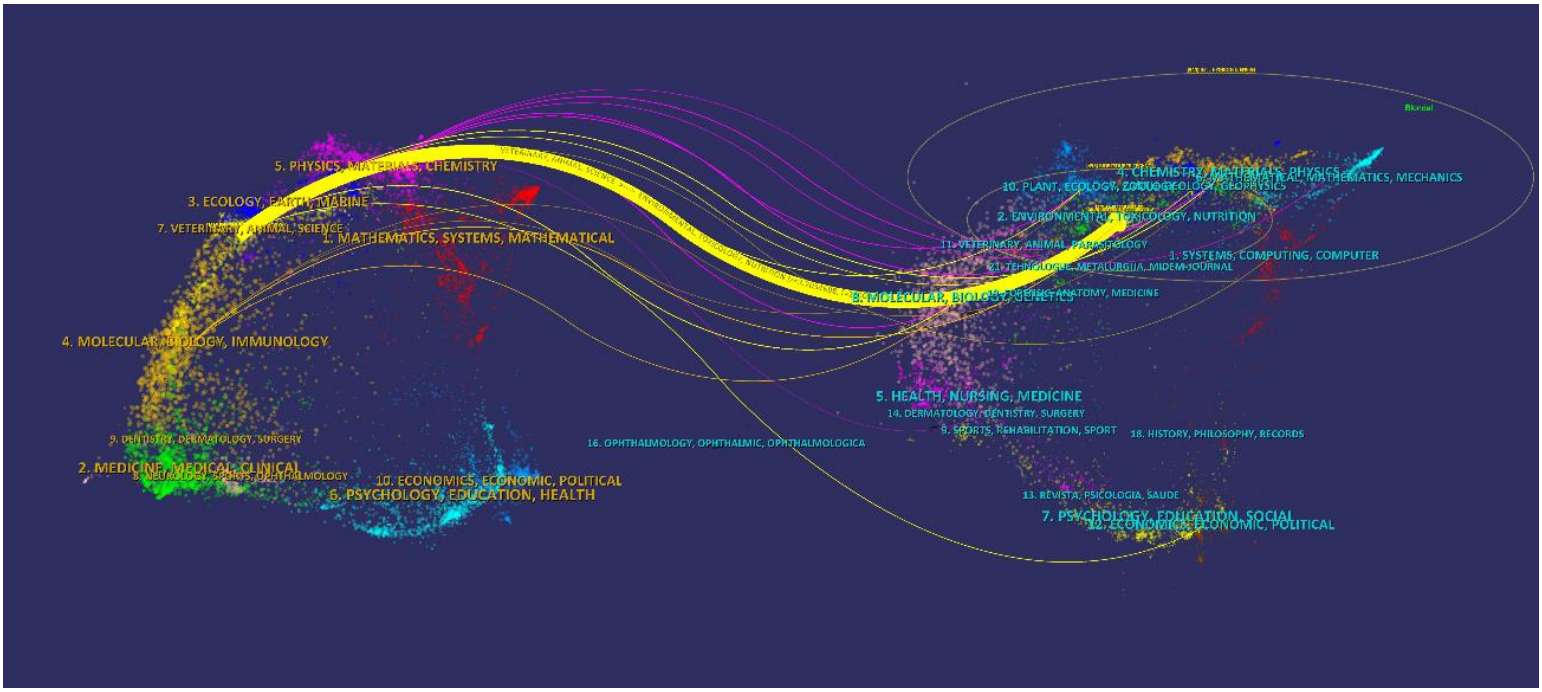
Table 3. Top 10 journals in the field research ranked by publication number.

Rank	Journal title	Country	Count	Percentage (%)	IF (2021)	Quartile in category (2021)	H-index
1	International Journal of Hydrogen Energy	England	131	27,35	7.139	Q2	33
2	Bioresource Technology	Netherlands	65	13,57	11.889	Q1	28
3	Renewable Energy	England	15	3,13	8.634	Q1	12
4	Chemical Engineering Journal	Switzerland	12	2,51	16.744	Q1	7
5	Journal of Cleaner Production	USA	12	2,51	11.072	Q1	9
6	Bioprocess and Biosystems Engineering	Germany	8	1,67	3.434	Q2	4
7	Renewable & Sustainable Energy Reviews	USA	8	1,67	16.799	Q1	8
8	Energies	Switzerland	7	1,46	3.252	Q3	4
9	Science of the Total Environment	Netherlands	6	1,25	10.754	Q1	5
10	Applied Biochemistry and Biotechnology	USA	5	1,04	3.094	Q3	4

Source: Author (2023).

Figure 12 illustrates a graph that combines two representative maps of publications related to research on biohydrogen production in bioreactors. In general, the presence of a single central flow of references was identified in the current map. The published studies primarily focus on journals from three specific fields: i) veterinary medicine, animal science; ii) physics, materials, chemistry; and iii) molecular biology, immunology. In turn, the most cited publications predominantly originated from journals in the areas of i) environment, toxicology, nutrition; ii) physics, materials, chemistry; and iii) plant, ecology, zoology.

Figure 12. A dual-map overlay was generated using CiteSpace to visualize journals focused on production of biohydrogen on bioreactor.



Source: Author (2023).

The labels on the maps indicate the different research subjects addressed by these journals. Citing journals are located on the left side, while the right side represents the cited journals. Color-coded lines denote distinct reference paths, originating from the citing map and terminating at the cited map. The line widths are adjusted proportionally based on the frequency of citations using a z-score scale.

3.7 Reference Analysis

Table 4 lists the basic information of the articles that were the 10 most cited. These highly cited studies were published between 2012 and 2020, where two of these studies were published in 2012 and the rest divided between 2015 and 2020. The most cited article was written by Ghimire et al. (2015) with 560 citations and an average of 62 citations per year. The article written by Singh et al. (2012) ranked second with 293 citations and 24 citations per year. It is worth mentioning that the most cited article surpasses the second in almost 50% the number of citations, reinforcing its relevance on the subject. The third position was occupied by Puyol et al. (2017) with 292 citations and an annual average of 41 citations.

Table 4. Top 10 articles on biohydrogen production in bioreactors with the most citations.

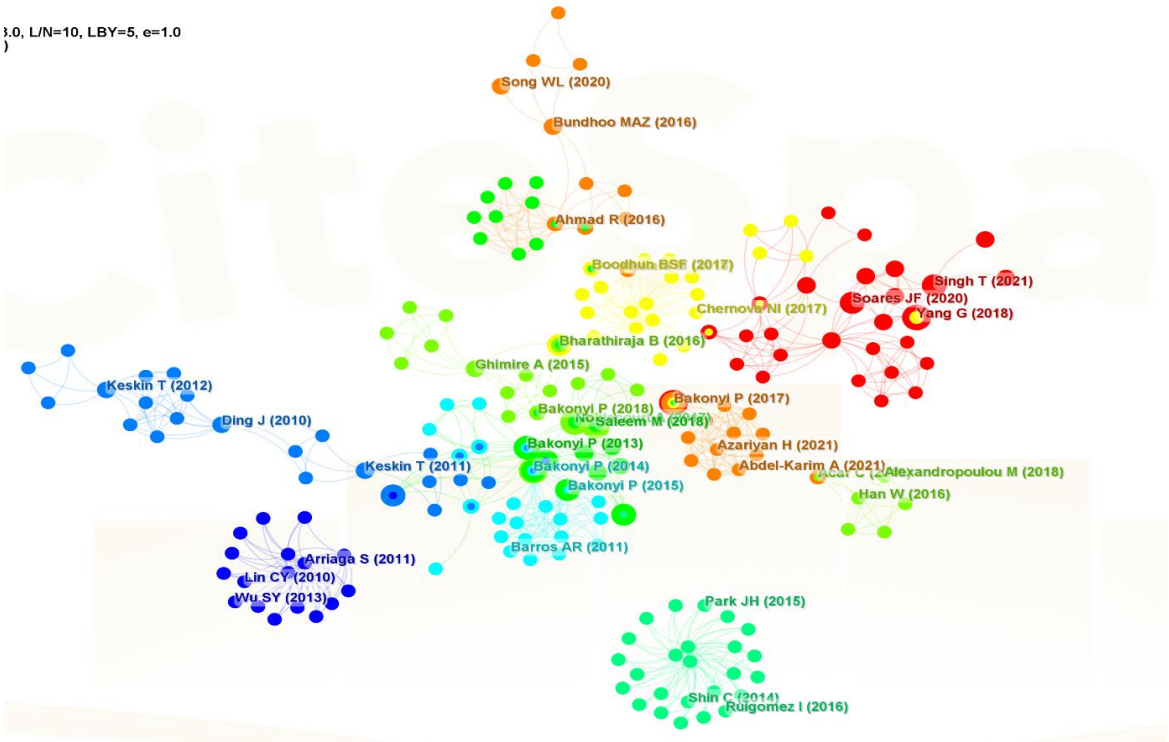
Rank	Title	Journal	First Author	Year	Citations	References
1	A review on dark fermentative biohydrogen production from organic biomass: Process parameters and use of by-products	Applied Energy	Ghimire, A	2015	560	(Ghimire et al., 2015)
2	Development of suitable photobioreactor for algae production - A review	Renewable & Sustainable Energy Reviews	Singh, R	2012	293	(Singh; Sharma, 2012)
3	Resource Recovery from Wastewater by Biological Technologies: Opportunities, Challenges, and Prospects	Frontiers In Microbiology	Puyol, D	2017	292	(Puyol et al., 2017)
4	Hydrogen production from biomass using dark fermentation	Renewable & Sustainable Energy Reviews	Lukajtis, R	2018	241	(Łukajtis et al., 2018b)
5	Bioengineering of anaerobic digestion for volatile fatty acids, hydrogen or methane production: A critical review	Bioengineered	Wainaina, S	2019	234	(Wainaina et al., 2019)
6	Biohydrogen production: Current perspectives and the way forward	International Journal Of Hydrogen Energy	Show, K	2012	212	(Show et al., 2012)
7	Optimization of process parameters for production of volatile fatty acid, biohydrogen and methane from anaerobic digestion	Bioresource Technology	Khan, M	2016	178	(Khan et al., 2016)
8	A critical review on issues and overcoming strategies for the enhancement of dark fermentative hydrogen production in continuous systems	International Journal Of Hydrogen Energy	Sivagurunathan, P	2016	166	(Sivagurunathan et al., 2016)
9	Recent achievements in enhancing anaerobic digestion with carbon-based functional materials	Bioresource Technology	Zhang, J	2018	131	(Zhang et al., 2018)
10	Algae as green energy reserve: Technological outlook on biofuel production	Chemosphere	Anto, S	2020	124	(Anto et al., 2020)

Source: Author (2023).

The reference cocitation relationship was visualized in a cocitation network (Figure 13). As shown in Figure 13, the cocitation network consists of 270 nodes and can be grouped into 11 main subclusters. The Q-value of modularity is a measure for assessing the importance of community structure. The maximum value of Q equal to or greater than 0.3 indicates a significant community structure. In this study, the Q modularity was 0.8104, indicating that the network groupings were reasonable. The silhouette value of clusters #0 to #14 was greater than 0.8, indicating the good homogeneity of the clusters. Figure 14 also shows the timeline view of

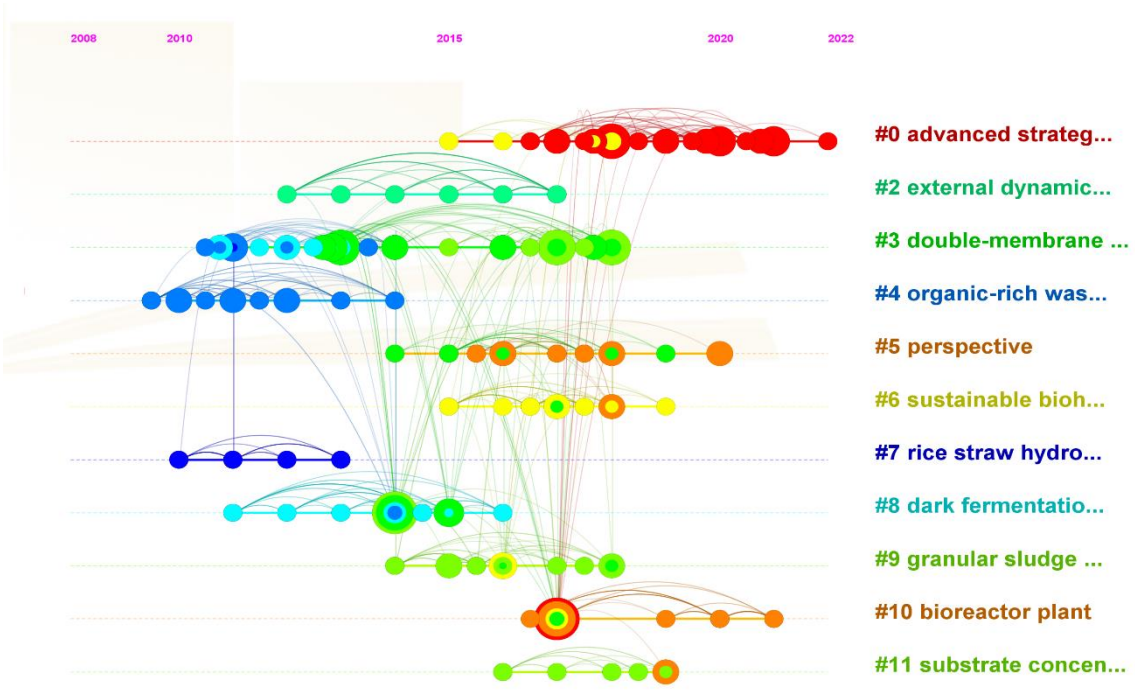
the reference co-citation clusters, which may reflect the temporal characteristics of research hotspots in this field. The largest cluster was “advanced strategies” (#0), followed by “external dynamics” (#1) and “double-membrane” (#2). The development of cluster 4 (organic-rich waste) and cluster 7 (rice straw hydrogen) occurred earlier, suggesting that early considerations focused on waste materials. Cluster 0 (advanced strategies) and cluster 10 (bioreactor plant) are current research hot spots, which indicates that more concerns are shifting towards possible applications of new means of production based on bioreactors. In Figure 14, clusters are arranged vertically in descending order according to their size. Eleven major clusters are labeled and color-coded on the right. The time evolution is shown with different colored lines. The nodes on the lines indicate the cited references and the links indicate the references cited together. The density of nodes in different time periods can reflect the dynamic changes of the corresponding clusters on the time axis.

Figure 13. Cluster view of cocitation reference.



Source: Author (2023).

Figure 14. Timeline of cocitation reference.

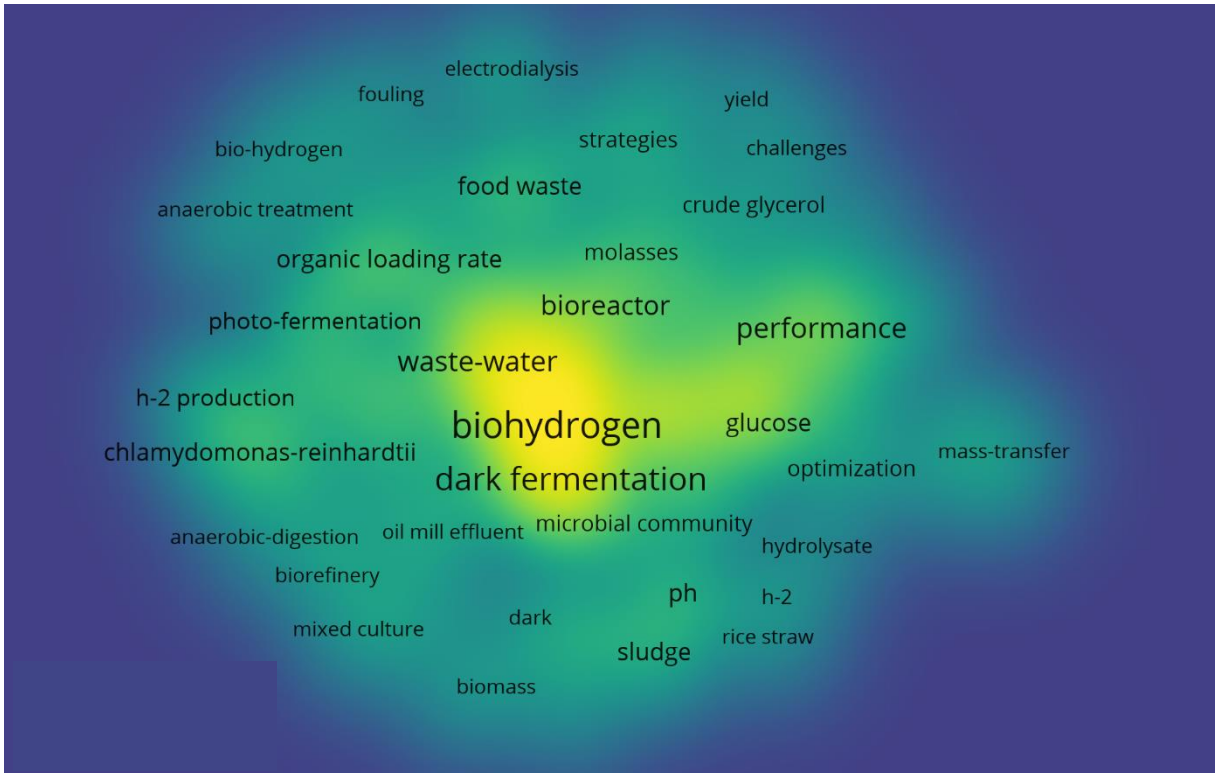


Source: Author (2023).

3.8 Keyword Analysis

The objective of keyword co-occurrence analysis is to identify emerging trends and relevant topics, making it a fundamental approach for tracking scientific progress. Using VOSviewer, a density map of the most frequent keywords was created. The results revealed the presence of 371 keywords across 476 articles, with 88 of them appearing at least twice (Figure 15). Among these, the top 20 WoSCC keywords in terms of frequency are listed in Table 5. "Biohydrogen" and "hydrogen production by fermentation" were the most frequent keywords, with 25 and 21 occurrences, respectively, aligning with the theme of our research. Other keywords were related to input waste, such as "wastewater," "waste," and "food waste," while others addressed biological processes like "dark fermentation," "fermentation," and "photofermentation."

Figure 15. Density map of keywords generated by the VOS viewer showing the hotspot on blue hydrogen research.



Source: Author (2023).

Table 5. Top 20 keywords in terms of frequency.

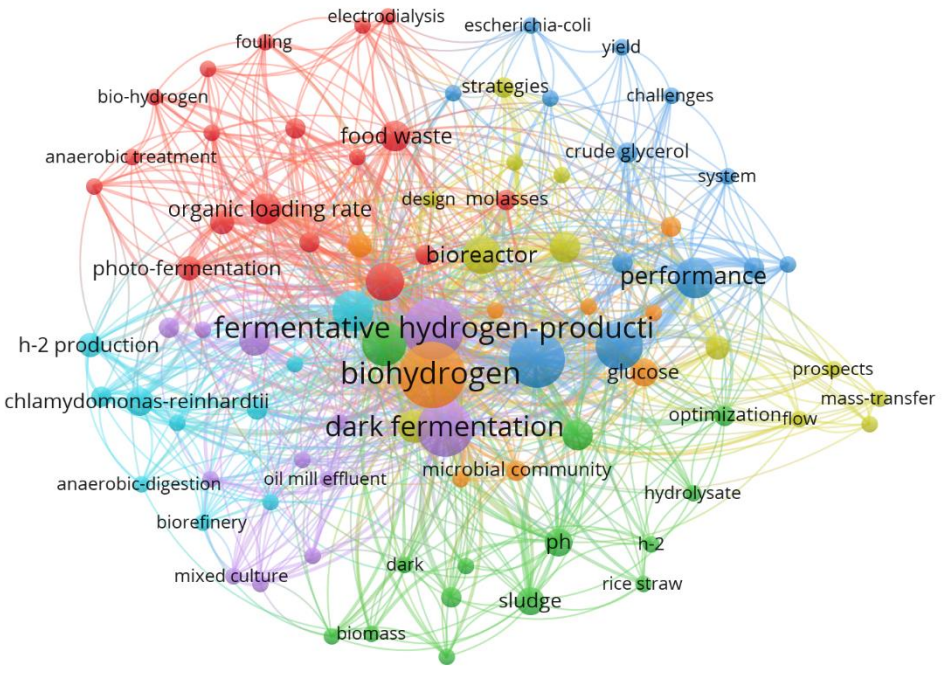
Rank	Keyword	Occurrences	TLS	Rank	Keyword	Occurrences	TLS
1	Biohydrogen	25	82	**11**	Reactor	6	31
2	Fermentation hydrogen production	21	83	**12**	Waste	6	27
3	Dark fermentation	18	65	**13**	Membrane bioreactor	6	27
4	Biohydrogen production	18	58	**14**	Food waste	6	27
5	Hydrogen production	13	44	**15**	Organic loading rate	6	26
6	Fermentation	12	46	**16**	Ph	5	25
7	Performance	10	41	**17**	*Chlamydomonas reinhardtii*	5	24
8	Waste-water	10	38	**18**	Glucose	5	19
9	Hydraulic retention time	9	38	**19**	Sludge	5	18
10	Bioreactor	9	38	**20**	Photo fermentation	4	26

TLS: total link strength.

Source: Author (2023).

As illustrated in Figure 16, all identified keywords were grouped into seven categories: "study of hydraulic retention time," "study of biohydrogen production," "study of bioreactor," "study of fermentation," "study of wastewater," "study of fermentative hydrogen production," and "study of biohydrogen production." These groupings represent the most prominent topics in biohydrogen production research in bioreactors thus far. For the "study of hydraulic retention time" group, the main keywords included "organic loading rate," "food waste," "photofermentation," and "dark fermentation." In the "study of fermentation" group, frequently used keywords were "pH," "sludge," and "residues." In the "study of biohydrogen production" group, the highlighted keywords were "biohydrogen production," "hydrogen production," and "performance." In the "study of bioreactor" group, the main keywords were "bioreactor," "bio-hydrogen production," and "reactor." The "study of fermentative hydrogen production" group featured primary keywords such as "fermentative hydrogen production," "dark fermentation," and "membrane bioreactor." In the "study of wastewater" group, frequently used keywords were "wastewater" and "H2 production." In the last group, "study of biohydrogen," the most commonly used words were "biohydrogen," "wastewater treatment," and "glucose."

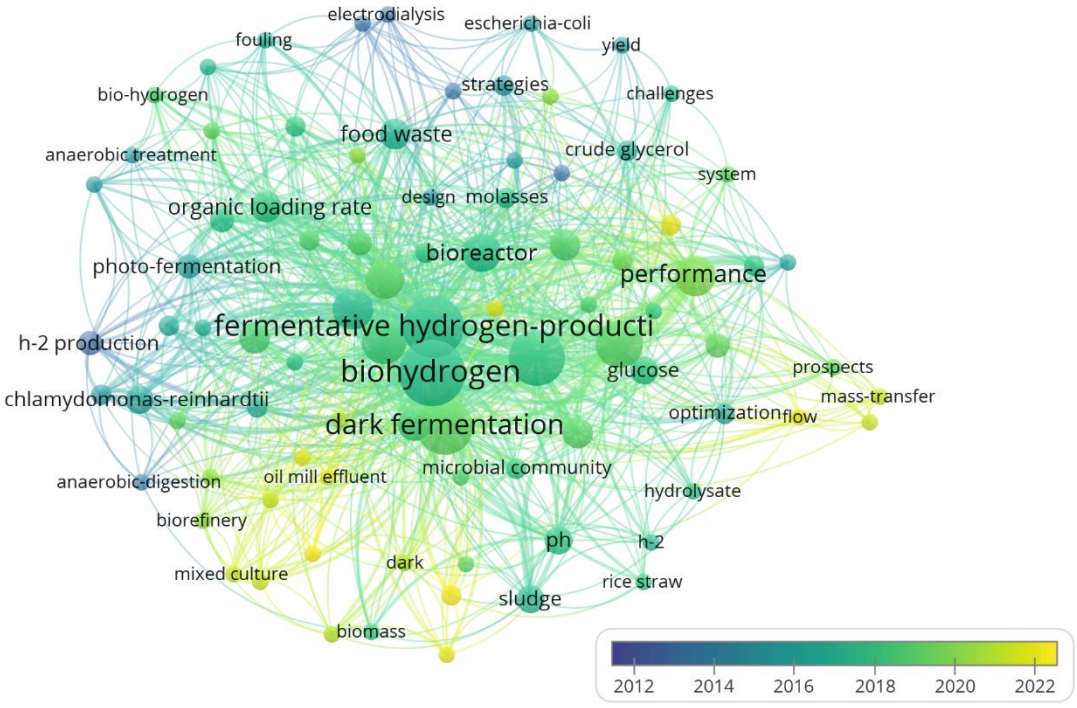
Figure 16. Keyword cooccurrence analysis on blue hydrogen research.



Source: Author (2023).

As demonstrated in the overlapping visualization map, different colors were assigned to each keyword based on the Average Appearing Year (AAY) (Figure 17). In early 2016, the focus of this field was primarily on "wastewater studies" and "hydraulic retention time." Keywords related to the "fermentation study" had the lowest AAY of all, indicating that research in this direction has received considerable attention and focus recently. On the other hand, the keywords "Enterobacter-aerogenes" and "lignocellulosic biomass" had a relatively recent AAY of 2022.00, suggesting that these keywords may become prominent points of research in this field in the coming years.

Figure 17. Overlay visualization of the cooccurrence analysis.



Source: Author (2023).

3.9 Bibliometric analysis of the production of biohydrogen in bioreactors

Unlike systematic reviews, bibliometric analysis is currently an effective tool to summarize the current state and predict future trends of progress in the relevant field of research (Chen et al., 2017). The visualization map generated using VOSviewer or CiteSpace visualizers is based on information science, computer science, scientometrics, and applied mathematics,

displaying the development process and structural relationships of knowledge in a specific area (Ding; Yang, 2022). Therefore, through bibliometric and visual analysis, we investigate research patterns related to production of biohydrogen in bioreactors, identifying key publications, contributing countries, authors, funding sources, research directions, and topics covered, as well as evaluating the contribution of different countries and institutions.

The research revealed that the field of biohydrogen production in bioreactors underwent considerable growth and there was an increase in the number of publications during the study period from 2012 to 2022. A total of 476 articles were examined, cited 11.572 times, using WoSCC. Of the 25 countries involved in publishing studies in this field, China stood out as the most productive country. Initially, there was a large discrepancy between China and other countries, but over the years this difference gradually diminished as the number of publications in India increased. The total number of publications in India was second only to China, indicating a growing interest of Indians researchers in this area. Therefore, it is accurate to predict that in the coming years more publications on biohydrogen production in bioreactors will be available due to a growing interest.

The H-index plays a crucial role in characterizing a researcher's scientific output and academic prestige. For instance, if an author has an H-index of n, it means they have n publications that have received n citations or more (Rubem; de Moura; Soares de Mello, 2015). The H-index has been widely used as the dominant metric to assess an individual's academic production. Furthermore, previous studies have considered it a valuable indicator to evaluate the productivity and impact of a country, institution, or journal (Chapman et al., 2019). Similar to the H-index, the total number of citations from a country, institution, or journal also reflects the quality and academic impact of their publications. The research revealed that the China leads in both the total number of citations and H-index. From an H-index perspective, India and South Korea also play a significant role in this field. Additionally, among the top 10 most productive institutions, China accounts for three of them and is the only developing country, while India comes in second place with two of them, demonstrating considerable progress. However, it is important to note that both Malaysia and Taiwan’s average citation rate was significantly higher than that of the South Korea and India, even considering that these countries have a higher H-index. In addition to quantity, improvements in the quality of publications are necessary. Simultaneously, research and development in biohydrogen production in bioreactors require substantial human and financial resources, with the economic foundation playing a

crucial role in supporting scientific research. Among the top 10 funding agencies, the majority of major contributors are located in China and Brazil, each one with three institutions, indicating that Brazil has been standing out in the area studied.

The journals "International Journal of Hydrogen Energy" (IF = 7.139, Q2), "Bioresource Technology" (IF = 11.889, Q1), and "Renewable Energy" (IF = 8.889, Q1) were responsible for publishing the majority of studies related to biohydrogen production in bioreactors. These scientific journals, due to their high impact scores and JCR rankings, are capable of attracting excellent articles, thereby contributing to the increased academic influence of these publications. Consequently, it is plausible to infer that the mentioned journals are more likely to publish future advancements in this field. Additionally, a dual-map overlay technique was utilized to provide a comprehensive view of scientific portfolio trends, enabling the analysis of information flow among these publications. This approach serves as a means to examine knowledge sharing and information exchange among the journals. The results highlight that the published studies predominantly focused on scientific journals in the following areas: i) veterinary, animal science; ii) physics, materials, chemistry; and iii) molecular biology, immunology. These journals primarily referenced publications in scientific journals in the following areas: i) environmental, toxicology, nutrition; ii) physics, materials, chemistry; and iii) plant, ecology, zoology.

Coauthorship analysis is a method that seeks to evaluate the relationship between items through the number of coauthored documents. In this study, this analysis was used to examine collaboration among various authors, institutions, and countries. Additionally, the Total Link Strength (TLS) indicator was employed for a quantitative assessment of the proximity of cooperation. Results with a higher TLS value indicate a greater propensity for authors, institutions, and countries to work collaboratively. In other words, a higher value is associated with a higher frequency of cooperation among these entities. The current results suggest that North Korea, as a research hub, has close collaborations with China, Malaysia, and Norway. In the context of author coauthorship analysis, Kim, Sang-Hyoun, from North Korea, was identified as the author with the highest number of publications, followed by Zhang, Quanguo, from China, and Kumar, Gopalakrishnan, from India. These researchers and their respective institutions exert significant influence in the field of emerging development in production of biohydrogen in bioreactors.

Cocitation analysis is a research method used to assess the degree of relationship between documents. In author cocitation analysis, the relevance among authors is determined by the number of times their articles are cited by the same article. This method is often employed to evaluate authors' academic influence. In the clustering map, authors' research categories can be divided into eleven groups, such as "advanced strategies" (#0), followed by "external dynamics" (#1) and "double membrane" (#2), among others. These research areas have received the most attention from scholars in this field. As a result, it can be observed that scholars were primarily focused on potential applications of new production methods based on bioreactors.

The ten most referenced studies were published between 2012 and 2020, with two of them being published in 2012. The most cited study, written by Ghimire et al. (2015), received 560 citations with an average of 62 citations per year. This article highlights dark fermentation of biomass as a promising technology for producing renewable biohydrogen. The co-citation analysis of references in the database also confirmed its central position in the network map. The study's main contribution was to provide a comprehensive analysis of anaerobic fermentation of organic biomass, highlighting its potential for biohydrogen production from various types of waste, such as agricultural, agro-industrial, and municipal organic waste. Furthermore, advancements were presented in optimizing bioreactor operational parameters, enriching the microbial community, and utilizing by-products, such as volatile fatty acids, to enhance the efficiency and technical and economic viability of the process. It was also observed that the most cited articles are older. In the co-citation network, articles with similar topics are often cited together and tend to cluster in specific locations. Figure 14 illustrates the chronological visualization of co-citation reference clusters, reflecting dynamic changes and developmental trends in corresponding clusters across different periods. The largest cluster was "advanced strategies" (#0), followed by "external dynamics" (#1) and "double-membrane" (#2). The earliest developed clusters were "organic-rich waste" (#4) and "rice straw hydrogen" (#7), while the most recent ones are "bioreactor plant" (#10) and "substrate concentration" (#11). The transition from organic waste to the use of bioreactor plants and substrate concentration demonstrates a growing understanding of factors affecting biohydrogen production and the endeavor to optimize the involved processes. These innovative approaches have the potential to drive advancements in biohydrogen production, contributing to the transition towards cleaner and renewable energy sources. These findings align with the results revealed through the analysis of two databases using VOSviewer.

In the field of bibliometrics, the analysis of frequently used keywords can provide insights into relevant categories and the development of a research theme. Based on the co-occurrence analysis of keywords using VOSviewer, all identified keywords from WoSCC were grouped into seven categories: "study of hydraulic retention time," "study of biohydrogen production," "study of bioreactor," "study of fermentation," "study of wastewater," "study of fermentative hydrogen production," and "study of biohydrogen production." These groups represent the main research directions in the field of biohydrogen production in bioreactors.

Based on the obtained data, it can be observed that the research focuses more on the dark fermentation process than on the photofermentation process. The main difference between dark fermentation and photofermentation lies in the conditions of biohydrogen production (anaerobic and lightless versus anaerobic and light) and the organisms involved (anaerobic bacteria versus photosynthetic bacteria).

Furthermore, our data showed that keywords with the latest AAY, such as "Enterobacter-aerogenes" and "lignocellulosic biomass," have the potential to become prominent research points in the coming years.

i) "Enterobacter aerogenes" is a Gram-negative bacterial species belonging to the Enterobacter genus. This bacterium is commonly found in the environment and can also be found in the gastrointestinal tract of humans and animals. It has the ability to ferment a variety of sugars, producing a range of end products including lactic acid, acetic acid, ethanoic acid, and gas (Davin-Regli; Pagés, 2015).

ii) "Lignocellulosic biomass" is a term used to describe plant-based raw material primarily composed of cellulose, hemicellulose, and lignin. It is an abundant source of renewable carbon and can be found in a variety of plant materials such as agricultural residues, straw, wood, and tree bark. Lignocellulosic biomass has attracted interest as a sustainable alternative to fossil fuels as it can be converted into biofuels, such as cellulosic ethanol, through degradation and fermentation processes. These processes require breaking the chemical bonds of cellulose and hemicellulose to release fermentable sugars and then fermenting these sugars by microorganisms such as bacteria or fungi to produce biofuels (Zheng et al., 2014).

4. STRENGTHS AND LIMITATIONS

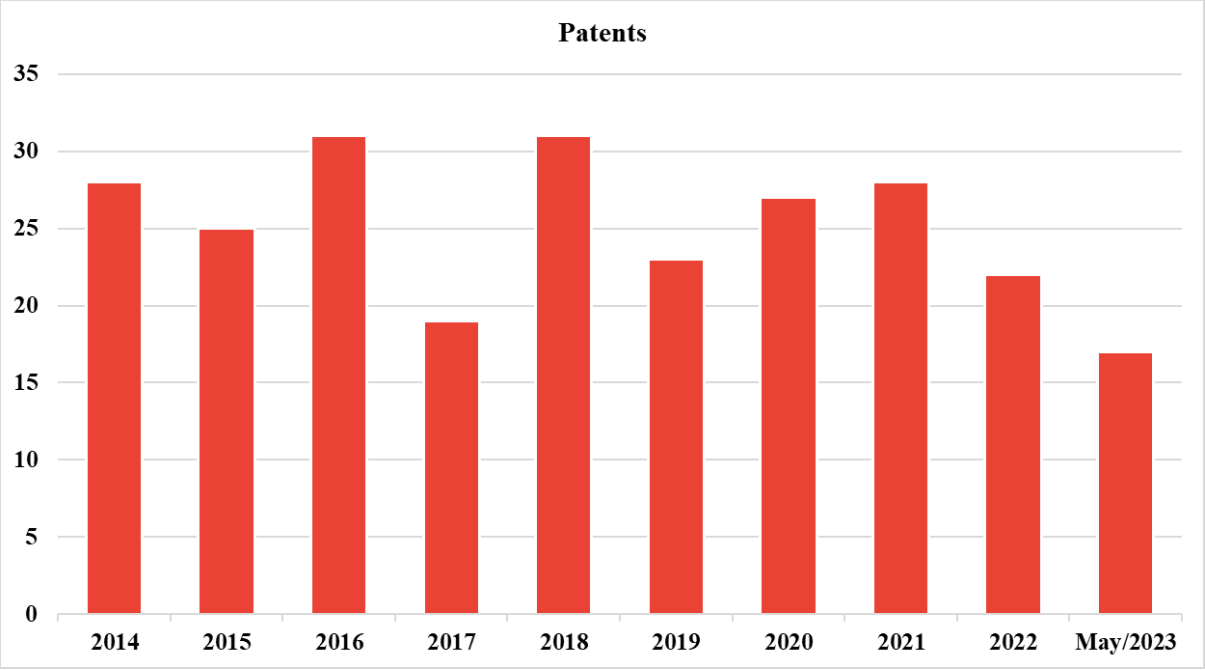
There are several significant advantages to this study. Firstly, a systematic analysis, for the first time, of global research trends in biohydrogen production on bioreactors over the past 10 years using the scientometric method. This provided researchers with a comprehensive understanding in this field and offered references on prominent research areas and future directions. Secondly, utilized two widely recognized scientometric software tools to conduct the study in parallel, allowing us to obtain more comprehensive and reliable analysis results.

Despite the mentioned advantages, it is important to note some limitations. Due to the constraints of bibliometric software, merging the two databases for analysis was challenging, resulting in the selection of WoSCC as the only search database. However, it should be emphasized that WoSCC is the most commonly used and recommended database for bibliometric analysis. The bibliometric analysis results may differ from the actual research landscape since the WoSCC database is continuously updated. Some recently published and potentially influential papers may not have been included in our study due to low citation frequency. Additionally, only English-language articles were included, potentially leading to the exclusion of important research studies published in other languages.

5. A REVIEW OF BIOHYDROGEN IN BIOREACTOR PATENTS

It is evident that the number of publications related to the production of biohydrogen in bioreactors is a topic that has been widely discussed, as can be seen from the constancy in the annual production of patents on this topic, with the years 2016 and 2018 presenting more productions. Topics such as Technological innovation, Intellectual property protection, Commercial potential and Collaboration and knowledge sharing have gained prominence in patents involving production in the subject studied. By exploring research platforms or robust patent databases, such as the United States Patent and Trademark Office (USPTO) (WORLD INTELLECTUAL PROPERTY ORGANIZATION, 2004) and the European Patent Office (EPO) (EUROPEAN PATENT OFFICE, 1991), were identified a total of 251 international patents related to the production of biohydrogen in bioreactors and to reinforce the concern with the use of recent data, the period analyzed was from 2014 to May 2023. Figure 18 below illustrates the growth in the volume of patents over the years.

Figure 18. Graph showing the number of patents per year.

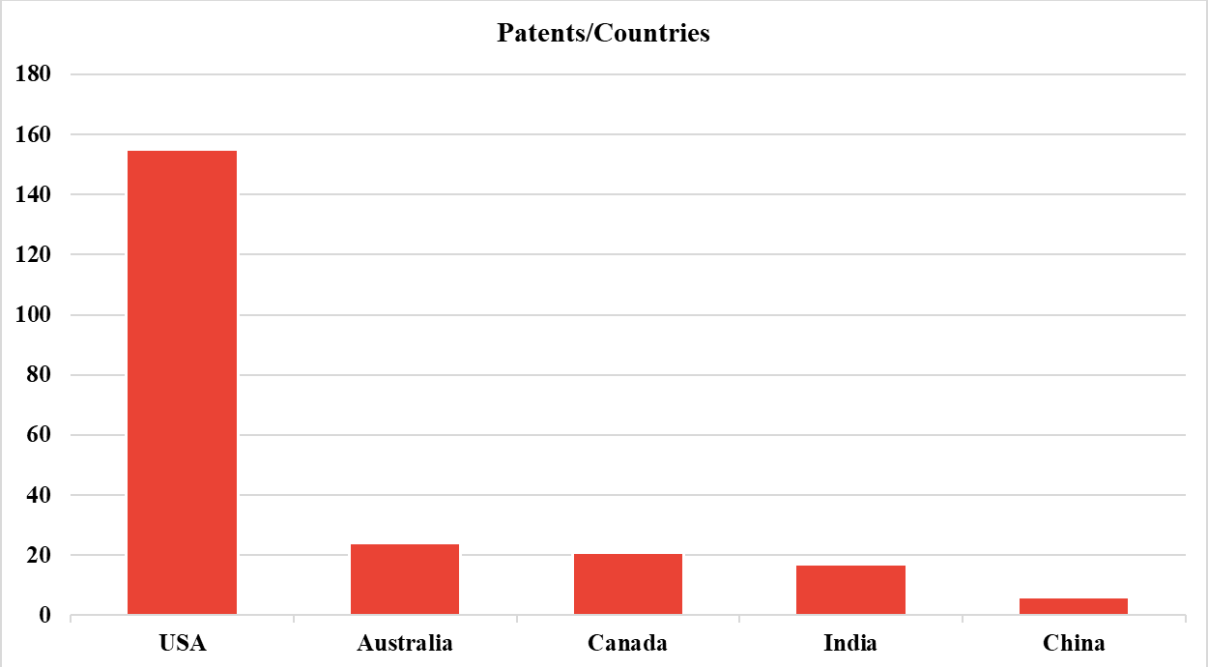


Source: Author (2023).

It is equally relevant to highlight that certain countries stand out in terms of the number of registered patents. The United States, Australia and Canada occupy, respectively, the first, second and third places in this ranking. The USA leads with approximately 61% of the

patents granted, while the other four most relevant countries, if added, have approximately only 27% of the productions. It is noteworthy that the predominant language used in the scientific writing of these patents is English. In short, the panorama of patents related to the production of biohydrogen in bioreactors is promising and has remained constant over the years, revealing the constant search for improvements in this area and exploring various applications of this production route.

Figure 19. Graph showing the number of patents per countries.



Source: Author (2023).

The United States ranks ninth in publications, with China holding the top spot. However, the U.S. surpasses China significantly in patents. The difference in bio-hydrogen production publications between the two countries is due to various factors. China's substantial investment in research and development in this domain results in numerous studies. Abundant natural resources and labor in China enable large-scale experiments and research, contributing to its prominence. In contrast, the U.S. leads in patents for bio-hydrogen production, thanks to a robust intellectual property protection system that encourages innovation. The tradition of substantial investment in research and development by U.S. companies and institutions may explain the notable quantity of patented discoveries and innovations in this field.

6. CONCLUSION

This research provides a comprehensive view of the current landscape of research and emerging global trends in the field of biohydrogen generation in bioreactors. There has been a notable increase in the volume of studies conducted, with China emerging as a leader in terms of both the quantity of publications and total citations in this research field. Consequently, it is reasonable to anticipate that this research field is poised for rapid expansion, with the potential for an increase in the publication of new studies in the coming years. However, it is essential to promote synergy and greater connection among different research groups in order to strengthen and expand collaboration among them. Additionally, keyword analysis revealed a focus on dark fermentation and indicated emerging research directions such as "Enterobacter aerogenes" and "lignocellulosic biomass." In the coming years, promising areas of investigation have the potential to attract the attention of scientists and funding organizations, while also giving rise to new paradigms for biohydrogen production in bioreactors.

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