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Review

Industrial symbiosis concept applied to green hydrogen production: a critical review based on bibliometric analysis

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Abstract
The use of fossil fuels has generated large amounts of greenhouse gas (GHG) emissions into the atmosphere, resulting in harmful environmental impacts. Faced with this situation, it is necessary to search for new sources of energy and fuels to mitigate the adverse effects of this excessive use and create opportunities for a cleaner energy transition. In this context, the production of green hydrogen (GH) stands out as an effective and more sustainable alternative, although it still faces obstacles to its wider use. These challenges can be solved with the application of industrial symbiosis (IS). The objective of this review was to identify the scenario and understand the application of the IS concept in GH production. To achieve this purpose, a bibliometric review of publications indexed in Scopus was carried out, also seeking to identify global positions in relation to the use of this technological approach. The results indicate that the theme presents emerging characteristics, such as the low concentration of data in a single author or country, characterizing a developing study concept.

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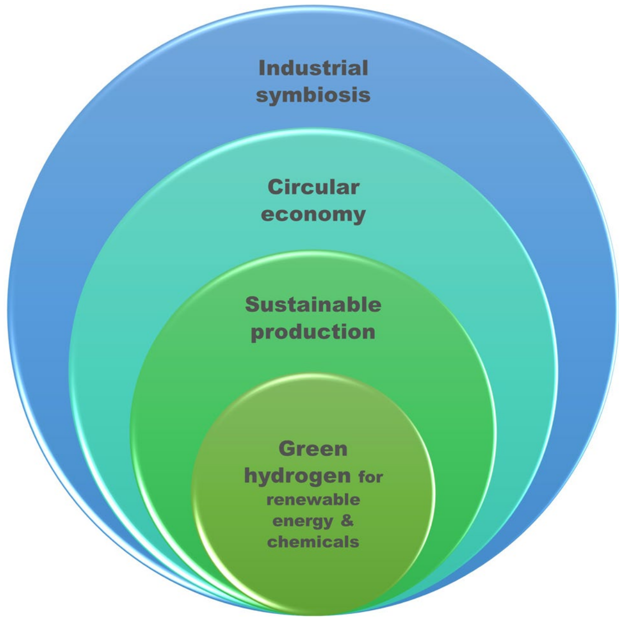
Graphical Abstract



Keywords Carbon emission · Circular economy · Energy transition · Industrial ecology

1 Introduction

The economic model underpinning the global consumption structure is linear and unidirectional, characterized by the sequence of extracting, producing, using, and discarding. This model is incompatible with a sustainable flow framework due to its intensive use of natural resources and the environmental degradation caused by waste generation and greenhouse gas (GHG) emissions [1].

To mitigate these negative environmental effects, alternative approaches have been developed. Among them, the circular economy (CE) has emerged as a conceptual framework that seeks to minimize environmental impacts in conjunction with industrial ecology (IE) [2]. An intrinsic principle of CE is IE, which aims to reduce industries' environmental footprints by fostering collaboration among them through industrial symbiosis (IS) [3]. IS, a widely studied concept in the development of eco-industrial systems, focuses on maximizing resource efficiency and minimizing GHG emissions by facilitating the exchange of by-products between industries [4]. This approach is particularly relevant for designing material and energy flows between industries from a systems engineering perspective [5].

In parallel with IS, other strategies have been explored to complement environmental preservation efforts by curbing the uncontrolled consumption of natural resources and reducing GHG emissions [6]. One promising avenue highlighted by Pein et al. [7] is green hydrogen (GH), which has gained attention as a sustainable alternative for renewable energy generation. GH production leverages renewable energy sources such as wind, solar, and hydropower, enabling the establishment of a more sustainable energy cycle.

The Global Hydrogen Review 2023, published by the International Energy Agency [8], depicts the current dominance of fossil fuels in hydrogen production, which contributes significantly to GHG emissions. Data from 2022 reinforces this reality, revealing that hydrogen production from natural gas without carbon capture, utilization, and storage (CCUS) accounted for 62% of global output, followed by coal-based production (primarily in China), which contributed 21%. These statistics highlight the urgent need for strategies to reduce GHG emissions from hydrogen production, particularly given the rising global demand for this clean energy vector. Emerging economies like Brazil are positioning themselves as key players in the green hydrogen market. With its advantageous climatic conditions for renewable energy generation—specifically wind, solar, and hydropower—Brazil holds significant potential to become a major exporter of low-carbon hydrogen [9].

This context provides the foundation for the present bibliometric evaluation, which aims to analyze the main trends and the current research landscape in applying the IS concept to GH production. Through performance analysis and network mapping of scientific literature, this study seeks to offer a comprehensive understanding of the state of research in this domain. By providing critical insights, it contributes to advancing knowledge in the field, facilitating future research, and guiding the development of effective strategies for renewable energy production and IS.

2 Bibliographic revision

2.1 Circular economy

The reuse of waste and its maximum optimization are central elements in the industries' commitment to a more sustainable environment. A flow designed to generate value from waste must emphasize the development of ideas that promote the use of waste in other activities, contributing to the reduction of pollutant emissions and minimizing the disposal of products and materials in the environment. These characteristics shape the concept of CE [2].

The CE concept is characterized as an innovative approach to resource management, aiming to minimize waste, reduce the consumption of raw materials and encourage the reuse and recycling of products and materials. This approach is recognized for its effectiveness in mitigating adverse environmental impacts and promoting sustainable economic opportunities [10].

In the context of these economic opportunities, IS stands out as an alternative within this concept, investing in the sustainable economic aspect. The fundamental objective of IS is to create more effective, economically viable and ecologically responsible systems, contributing to the construction of a future characterized by sustainability [11].

2.2 Industrial symbiosis

IS is an organizational practice centered on the strategic sharing of resources, such as waste, materials, water, logistics, equipment, and by-products, between different companies or sectors. This approach aims to optimize resource utilization for productive purposes, promoting both efficiency and sustainability. The essence of IS lies in fostering collaboration among companies to enhance production processes while minimizing resource consumption and energy usage. Geographic proximity between participating organizations often facilitates these synergies, enhancing the effectiveness of the partnerships [12].

The origins of the IS concept trace back to the 1980s and 1990s, when researchers and environmentalists began exploring collaborative approaches for companies to share resources and optimize processes to reduce waste and environmental impacts. Initially, IS was viewed as a localized solution to specific challenges, such as managing industrial waste [13]. Over time, the concept expanded to encompass broader sustainability goals, including energy efficiency, water resource management, and integration with CE principles. Today, IS is recognized as a cornerstone strategy for transitioning towards more sustainable production and consumption models [14].

The primary objective of IS is to achieve collective benefits that surpass what individual companies could attain in isolation. By leveraging synergies and the advantages of geographic proximity, IS enables cost reductions in raw materials, improved resource efficiency, mitigation of pollution and GHG emissions, and decreased waste management expenses. Furthermore, IS fosters external partnerships, drives innovation through the development of new products, enhances competitiveness, consolidates purchasing power, and promotes the implementation of joint strategies, including improved energy efficiency [15]. The multiplicity of these benefits underscores IS as a critical tool for industries striving to balance economic performance with environmental responsibility.

To optimize resource sharing and enhance IS implementation, advanced technologies play a crucial role. Yeo et al. [16] highlight the use of digital interconnection platforms, data monitoring and analysis systems, supply chain management technologies, and waste recycling and reuse technologies. Digital interconnection platforms, in particular, facilitate the identification of symbiotic opportunities, enabling companies to share information about available resources and requirements, and to establish collaborative partnerships. These platforms also provide tools for monitoring and analyzing resource consumption, waste generation, and operational performance, yielding actionable insights for decision-making and process optimization [17, 18].

The advantages of IS are not confined to specific industrial sectors. Industries such as manufacturing, agro-industry, and chemicals can significantly benefit from IS by adopting sustainable practices, enhancing competitiveness, and adhering to increasingly stringent environmental regulations [19]. For instance, the research by Savian et al. [20] illustrates the application of IS in GH production. Their findings emphasize the integration of IS and GH as a pathway to amplify sustainability while addressing the environmental and economic challenges associated with clean energy production.

In summary, IS is a transformative concept that merges economic and environmental benefits through strategic collaboration and resource optimization. Its adaptability across sectors and compatibility with emerging technologies make it a vital component of sustainable industrial practices. Moreover, its integration with renewable energy initiatives like GH production highlights its potential to shape a greener and more efficient industrial future.

2.3 Hydrogen generation

Hydrogen, constituting approximately 90% of the mass of all matter, is the most abundant element on Earth. It is a colorless, odorless, tasteless, and highly flammable gas under standard pressure and temperature conditions (CNTP). Found primarily in molecular form, hydrogen is present in substances such as hydrocarbons and water. Notably, it possesses the highest energy density per unit mass among fuels, with a value of 120.7 kJ g^{-1}, making it an exceptional energy carrier [21].

As previously cited, according to the 2023 Global Hydrogen Review by the IEA [8], global hydrogen production reached approximately 95 million tons (Mt) in 2022, marking a 3% increase from 2021. However, despite advancements in cleaner hydrogen production technologies, the majority of hydrogen production remains heavily dependent on fossil fuels. Natural gas, without CCUS technologies, accounted for 62% of global production, while coal, primarily in China, contributed 21%. An additional 16% came as a byproduct of naphtha reforming in refineries and petrochemical industries, emphasizing the significant reliance on oil and its derivatives as indirect sources for hydrogen production.

This heavy dependence on carbon-intensive feedstocks highlights the urgent need for decarbonization in hydrogen production. Hydrogen has drawn significant interest as a potential cornerstone of the global energy transition due to its versatility as a clean energy carrier and storage medium. Its adoption aligns with the pursuit of net-zero GHG emissions and offers widespread industrial applications [22].

Hydrogen generation employs various technologies, with methane steam reforming (SMR), coal gasification, and water electrolysis being the most prominent. SMR, the predominant method, involves reacting natural gas with steam to produce hydrogen and CO_2, contributing significantly to GHG emissions. Coal gasification converts coal into synthesis gas, which is further processed to extract hydrogen, but its environmental impact remains substantial. In contrast, water electrolysis—especially when powered by renewable energy sources—provides a pathway to producing GH with no carbon emissions. The choice of technology depends on multiple factors, including cost, resource availability, and environmental objectives [23].

The environmental impact of hydrogen production has led to its categorization based on production methods and associated GHG emissions. This classification highlights the need for sustainable technologies to minimize emissions and support global decarbonization goals [24].

2.4 Hydrogen categories

As pointed out by Incer-Valverde et al. [25], the categories attributed to hydrogen are associated with the production methods of this element, being determined based on the type of process used, the energy sources used and the amount of CO_2 emitted into the atmosphere. It is possible to classify hydrogen into up to nine colors, with some of them standing out due to the potential for a cleaner production process or the high amount of GHG emitted in the production process. Among the most relevant colors are gray hydrogen, brown hydrogen, blue hydrogen, turquoise hydrogen, and GH.

GH is obtained from fossil energy sources, such as the steam reforming of natural gas or the gasification of mineral coal without CCUS. The gray designation is related to the carbon footprint associated with these energy sources, indicating that hydrogen production is characterized by significant carbon emissions as CO_2, making it harmful to the environment [26]. In turn, brown hydrogen is produced from mineral coal, through a gasification process, resulting in considerable carbon emissions, again as CO_2. The brown color is emblematic of highly polluting and unsustainable hydrogen production [27]. Blue hydrogen is generated from the same fossil energy sources used for gray hydrogen; however, it incorporates CCUS technologies to significantly reduce carbon emissions, such as CO_2, associated with its production. The blue color symbolizes the transition to a cleaner hydrogen production process with low CO_2 emissions [28]. Unlike the conventional production processes mentioned above, the synthesis of turquoise hydrogen through methane pyrolysis results in a solid carbon by-product, in the form of filamentous carbon or carbon nanotubes. This material can be used in subsequent production processes or present advantages in terms of ease of storage, thus resulting in a reduction in the carbon footprint [29].

Hydrogen production is moving towards more sustainable methods with a lower carbon footprint. The advancement of renewable energy and CCUS technologies are key trends shaping the future of hydrogen as a clean fuel. In this context, the green hydrogen category has gained greater prominence due to the possibility of achieving zero GHG emissions into the atmosphere, compared to other hydrogen categories, being a totally sustainable process and with positive perspectives for academic, industrial, social, and political [30].

The "green" designation characterizes its production process, which must be environmentally sustainable and not result in carbon emissions (such as CO_2), since the energy used is clean or renewable. These color categorizations constitute an effective way to classify hydrogen based on production methods, emphasizing the creation of new, cleaner, and more sustainable processes, such as GH, in the pursuit of a more environmentally responsible hydrogen economy [31].

2.5 Green hydrogen

GH is a form of hydrogen produced, in most cases, through a water electrolysis process that uses electricity generated from renewable sources, such as solar or wind energy. This production process makes GH a clean and sustainable source of energy, with diverse applications in sectors that seek to reduce their carbon emissions and depend less on fossil fuels. One of the main positive aspects related to GH is its usefulness, which can contribute to different segments resulting in a global demand for an efficient and highly sustainable product [32].

Thus, GH plays an important role in the transition to a more sustainable economy, due to the possibility of its application in several sectors including transport, energy storage, chemical production, power generation, industry and heat and steam generation [33].

Currently, most global hydrogen production is based on processes that extract the gas from fossil resources using gasification, steam reforming and pyrolysis processes. However, these conventional hydrogen production technologies are not adequately sustainable as they rely heavily on fossil fuels that cause carbon emissions. Processes that use renewable energy sources will be needed to produce hydrogen without emitting $CO_{2,}$ considering potential climate changes due to GHG emissions [34].

2.6 Production of green hydrogen from wind energy

In the process of producing GH from wind energy, turbines capture the kinetic energy of the wind and transform it into electricity using a generator. The electricity generated by wind turbines is then converted into a form suitable for transmission and distribution, which typically involves converting alternating current (AC) to direct current (DC). In this process, the energy is directed to an electrolyzer which, using demineralized water, separates the hydrogen and oxygen atoms from the water molecule through the electrolysis reaction, generating high purity oxygen and hydrogen [35]. The articles discussed in sequence in Sect. 2.3 are examples of routes that are being explored within the theme of GH production from its main sources of obtaining. Each study contributes to the understanding of the potential and challenges associated with different hydrogen production processes, reflecting the dynamics of research and innovation in the field of clean energy.

In studies by Lee et al. [36] the concept of a hybrid Triboelectric-Electromagnetic Self-adaptive (SA-TEH) wind energy collector was addressed; This system uses an approach based on rational mechanical analysis based on moving magnets. The SA-TEH was designed to capture wind energy, operating regardless of wind speed. The results demonstrated that the use of this type of technology can optimize GH production due to greater autonomy in energy supply. Razzhivin et al. [28] proposed to improve the stability of the wind-hydrogen power system and the overall stability of the power system through the application of synthetic inertia. Research has demonstrated that optimizing synthetic inertia parameters not only allows obtaining the required inertial response, but also results in an increase in the dynamic stability of the power system; consequently, improving the performance of the wind-hydrogen energy system. And Annan et al. [37] developed a trimaran substructure for an autonomous undocked system intended for GH production, called the Wind Trawler. This system performs dual functions as an energy generator and energy transport container. Ideal Wind Trawler mass steel substructures have demonstrated results that show promising competitiveness compared to conventional systems, especially when considering the elimination of mooring and electrical transmission subsystems.

2.7 Production of green hydrogen from solar energy

Photovoltaic solar panels, composed of photovoltaic cells, capture incident sunlight. When sunlight hits photovoltaic cells, photons of light excite electrons in the atoms of the cells' semiconductor material, creating a direct electrical current that is later converted to alternating current by an inverter [38]. This production process involves the use of electricity generated from photovoltaic solar panels to electrolyze water, dividing it into hydrogen and oxygen. GH produced by solar/photovoltaic energy can have high initial costs due to the infrastructure required for solar generation [39].

For example, Naqvi et al. [40] described the clean and economically viable hydrogen production process using an alkaline-based water electrolyzer. The system is powered by a photovoltaic module and uses a sodium hydroxide solution with a concentration of 27% by weight as the electrolyte. The electrolyzer is constructed with a stainless-steel anode and nickel-plated stainless-steel cathode, demonstrating an energy conversion efficiency of 15%. The paper also offers insights into possible future research directions aimed at improving electrolyzer efficiency. Alhussan et al. [41] used a new alternative algorithm that could obtain and process the amount of solar energy more efficiently and thus generate predictions about the generated energy capacity. The accuracy of the proposed algorithm was validated through two statistical analysis tests. It was found that, with the implementation of the suggested algorithm, the solar energy system can be better planned, thus reducing the risk of power outages and generating more efficient prevention plans. Karaca and Dincer [42] addressed the development, carrying out experimental tests and performance evaluation of a new photoelectrochemical reactor aimed at producing GH. Performance testing was conducted under various operating conditions, including with and without light exposure, to assess hydrogen production rates and energy efficiencies. The reactor achieved a maximum hydrogen production rate of 0.62 $\mu g\ s^{-1}$ at a solar irradiation intensity of 600 $W\ m^{-2}$ and an applied voltage of 2.0 V, with energy and exergy efficiencies measured at 0.193% and 0.196%, respectively. These findings highlight the reactor's potential for improving the feasibility of solar-driven hydrogen production, though efficiency improvements remain a key area for further research.

2.8 Production of green hydrogen from biogas

Biogas is a product resulting from the anaerobic digestion of organic matter (MO), anaerobic digestion is a biological process in which microorganisms are conditioned in environments without oxygen and decompose the MO, the effect of this process produces biogas composed mainly of methane (CH_4) in an average proportion of 60% and carbon dioxide (CO_2) in an average proportion of 40% [43]. Obtaining green hydrogen through biogas consists of carrying out the steam reforming process, in which methane is separated from carbon dioxide, and at the end of the process GH is extracted [44]. This type of GH is especially interesting for countries like Brazil, due to the large availability of agro-industrial waste [45].

As an example, Maluenda et al. [46] proposed the introduction of a stochastic model with probability constraints to optimize the operation of a system involving Photovoltaic BESS (Battery Energy Storage System) and an electrolyzer, actively participating in the energy and ancillary services markets. The results highlight the benefits of the proposed model, as it demonstrated a 10.2% increase in profits compared to the deterministic benchmark problem. Furthermore, the system has maintained low failure rates in providing the regulation service and achieves hydrogen production comparable to that of autonomous operation, outside the electricity grid.

Currently, hydrogen production is not limited to the use of a single energy source, and alternatives for obtaining GH from different renewable sources include wind, hydraulic and solar energy. However, offering alternatives to generate this scenario of possibilities depends on the available geographic and logistical capacity. A good example is the Brazilian energy matrix, with a predominance of hydroelectric sources, but with contributions from solar, wind, biomass, non-renewable and nuclear sources [47]. In this sense, Pang et al. [48] presented the concept of using IE through IS applied to hydrogen production, in which a renewable-based multienergy system (RMES) is proposed to combine four distinct systems: refrigeration, heating, hydrogen and energy.

2.9 The relationship between industrial symbiosis and green hydrogen

The hydrogen production system consists of essential steps, including the supply of renewable energy, the supply of water or effluents, the electrolysis of water and, finally, storage and distribution. These steps are fundamental for the complete flow of obtaining green hydrogen [49]. As in any production process, the supply flow can be adjusted to improve both economic and operational efficiency [50]. It is in this sense that the application of IS in hydrogen production is introduced, aiming to make the process more profitable, effective, and sustainable. The combination of these concepts can enable the formation of a production network that can provide opportunities for varied applications, leading to IS models even for application in other segments that are not directly involved with gas production [51].

To explore this alliance, Eljack and Kazi [52] assessed the challenges of an industrial-urban multi-sector symbiosis approach aimed at implementing the hydrogen supply chain. This symbiosis aims to optimize the interaction between different industries and urban planning, exploring several multifunctional applications of hydrogen that, with adequate planning, can be implemented effectively. Butturi and Gamberini [53] investigated the possibilities arising from the creation of synergies between industrial clusters and adjacent urban areas, aiming to improve local sustainability and facilitate the implementation of low-carbon mobility solutions using GH. The work identified that industrial synergies have great potential to be a starting point for generating this type of hydrogen. Sorrenti et al. [31] analyzed the impact of different energy sources on the production cost and carbon footprint associated with hydrogen production using GreenLab Skive, the first industrial facility in the world to integrate renewable energy generation into an industrial symbiosis network, as a case study. The results demonstrated that the use of an electrolyzer powered by wind, photovoltaic and grid energy to produce hydrogen and electricity results in a reduction in operational costs and carbon emissions, saving 30.6×10^7 kg of CO_2 and presenting a net present value twice as high compared to an electrolyzer connected only to the mains. Finally, Affery et al. [54] analyzed the feasibility of using GH, generated from solar energy, together with effluents from palm oil factories and wastewater. In this study, four integration schemes were applied, using an approach based on game theory for decision making. The proposed methodology demonstrated that maximizing collective well-being can be achieved through cooperation between all networks involved, aiming for Pareto optimization. This is in line with the commitment to combat climate change and achieve the sustainability objectives established in the global agenda.

One critical perspective on the stages of GH production is life cycle analysis (LCA). LCA allows for the assessment of environmental impacts at each stage of the process, from raw material extraction to the final disposal of the product. It considers essential factors such as energy consumption, waste generation, GHG emissions, and the utilization of natural resources. While biofuels are often seen as a low-carbon solution, concerns persist that their widespread adoption may lead to unforeseen environmental effects [55].

As highlighted in the study by Ajeeb et al. [56], an LCA of GH typically encompasses four main stages: the production of green electricity, GH production, hydrogen storage and compression, and its distribution and end-use. Each of these stages plays a pivotal role in determining the environmental impact and overall sustainability of GH production, offering multiple opportunities to reduce its ecological footprint.

The first stage involves generating electricity from renewable sources such as wind, solar, or hydropower. This electricity is essential for powering electrolyzers that produce hydrogen. Although renewable energy sources have minimal direct environmental impacts, the production, installation, and maintenance of renewable energy infrastructure (e.g., solar panels and wind turbines) can contribute to resource depletion and emissions [57]. To mitigate these impacts, efforts should focus on optimizing energy generation efficiency and reducing embedded energy in renewable technologies through better material selection and extended life cycles [58]. Additionally, integrating renewable energy generation with IS models can minimize operational inefficiencies and create synergies that further reduce the overall carbon footprint [59].

Hydrogen production via water electrolysis using electrolyzers represents a critical point in the environmental life cycle of GH. Material selection for electrolyzer manufacturing significantly influences environmental impact categories. Key materials such as nickel, platinum, and steel contribute heavily to these categories, emphasizing the importance of careful material choices to mitigate negative effects [60]. Although renewable electricity can greatly reduce carbon emissions during this process, challenges remain related to the energy intensity of electrolysis and the environmental impacts of constructing and operating electrolyzers. Addressing these challenges requires advances in equipment efficiency and the implementation of integrated energy management strategies. One such strategy is optimizing the synchronization between intermittent renewable energy generation and electrolyzer operation, enhancing overall system efficiency [61].

This stage presents its own environmental challenges, primarily related to the energy required for compression and the infrastructure needed for safe and efficient storage [62]. Hydrogen can be stored as a gas or a liquid, with each method involving distinct energy requirements and associated emissions. Gas compression requires substantial energy input, whereas liquid hydrogen storage demands energy-intensive cooling. Innovations in storage technologies that lower energy requirements and improve efficiency are essential for minimizing environmental impacts at this stage [63].

The final stage in the GH production chain involves the distribution and utilization of hydrogen. Transporting hydrogen, especially over long distances, requires additional energy for compression, liquefaction, or pipeline transport. During end-use, hydrogen can be applied across various sectors, including transportation, industry, and electricity generation. The environmental impact of this stage depends heavily on the efficiency of hydrogen conversion technologies (e.g., fuel cells or combustion systems) and the type of applications it serves [64]. Strategies to optimize the distribution network, minimize transportation losses, and adopt energy-efficient hydrogen technologies in end-use applications are critical to reducing the ecological footprint of this stage. Furthermore, integrating GH into a CE model—where hydrogen is recycled or reused—can further minimize waste and emissions [65].

To minimize the ecological footprint of GH production, it is crucial to enhance the efficiency of each stage. Improving the energy efficiency of electrolysis, optimizing renewable energy generation and storage, and integrating waste heat recovery systems can significantly reduce energy consumption and associated emissions [66]. Additionally, as discussed by Ismail [67], applying IS principles throughout the GH production chain can facilitate the reuse of by-products, such as heat or oxygen, and optimize resource utilization. By continuously advancing technology and integrating efficient processes across all production stages, the overall environmental impact of GH production can be minimized, positioning it as a more sustainable solution for the future energy landscape.

3 Bibliometric analysis

3.1 Bibliometric review

According to Ellegaard [68], bibliometric review is a scientific research method that uses quantitative and qualitative techniques to analyze scientific production in a specific area, allowing trends, authors, journals, and knowledge gaps to be mapped through bibliometric indicators. Tamala et al. [69] highlights that bibliometric mapping results can be improved with network analysis, which includes the evaluation of network metrics and cluster analysis for a deeper understanding of the dynamics of bibliometric data using specialized software.

To develop this research, the publications were initially examined through a performance analysis according to Chrysikopoulos et al. [70], and the objective of this analysis was to descriptively examine the search trend, authors, countries, and journals in relation to the keyword queries entered in the database. Next, network analyzes were performed through co-authorship and co-occurrence mapping. Co-occurrence, also known as semantic network, refers to relationships between keywords, while co-authorship concerns interactions between authors, contributing countries or affiliations for the development of fields or areas of research. The development of the proposed analyzes was carried out based on the elaboration of research parameters to obtain bibliometric data.

3.2 Bibliometric data

To carry out research with solid results, it is necessary to use comprehensive and reliable tools for querying and retrieving relevant scientific information. The Scopus database stands out as an essential resource, providing access to a wide range of high-quality scientific publications. In this study, the Scopus database was used. In the research by Pranckute [71] and Khan et al. [72], the use of Scopus and its contribution to obtaining high-impact research in various areas is highlighted. The database covers 36,377 books from 11,678 different publishers, in addition to all 34,346 peer-reviewed publications in different areas of knowledge. Furthermore, Scopus offers citation metrics that allow you to evaluate the impact and relevance of academic works, as well as providing access to detailed information about authors, their institutional affiliations and research trends, facilitating the analysis and monitoring of scientific development in several areas. With these characteristics, this database can meet the objectives of this research.

The search strategy used was created using a combination of keywords related to the research topic, aiming to obtain more focused results. To select and combine the keywords according to the proposed strategy, technical terms relevant to each area were considered, as well as words related to trends and updates, as well as the co-occurrence of keywords. In this context, keywords that frequently appear together in articles related to the topics covered were evaluated, also analyzing terms that reflect the most recent trends or emerging technologies.

In this sense, the following keywords were selected: Green Hydrogen, Industrial Symbiosis, Circular Economy, Eco-Industrial Parks, Network and Hybrid System. To build search expressions, we use the Boolean operators AND and OR, resulting in three main combinations:

- Combination 1: "Industrial Symbiosis" OR "Circular Economy" OR "Industrial Ecology" AND "Green Hydrogen"
- Combination 2: "Industrial Symbiosis" OR "Eco Industrial Parks*" AND "Hybrid System*" AND "Green Hydrogen"
- Combination 3: "Industrial Symbiosis" OR Netwok* AND "Green Hydrogen"

The database's filtering feature was used to refine the search criteria, considering the time interval between 2014 and 2024 and including only scientific articles published in English. Additionally, other specific restrictions were applied to increase the accuracy of the search results. Table 1 presents the search strings after the final refinement and all the refinement characteristics performed.

The data from each research address created was exported to perform bibliometric data analysis. Bibliometric analysis is often associated with the use of network visualization software, which ranges from applications such as VOSviewer to command-line based programs such as the Bibliometrix package. Other widely used bibliometric software includes Bibexcel, Pajek, Gephi, SciMat, Sci2, and UCINET [73].

The free software VOSviewer (version 1.6.20) was used to assist in carrying out the network analyses, and the data was extracted from the database in "csv" format (Microsoft Excel) to build and visualize links to bibliometric sources to obtain the refined information desired. According to Bukar et al. [74], in the current panorama of software for bibliometric analysis, VOSviewer stands out as a powerful and versatile tool. This software, based on the Java language and based on the concept of visualization of similarities (VOS), allows the creation and visualization of bibliometric network maps, including co-citation, bibliographic coupling, co-authorship relationships and co-occurrence of keywords. For this reason, it has been widely adopted in bibliometric and citation studies for building and visualizing bibliometric networks.

3.3 Performance analysis

From the combinations created, the search results initially generated a grand total of 3,271 searches without the assigned refinement boundaries. Individually, Combination 1 resulted in a total of 1,070 articles, Combination 2 1,228 articles and Combination 3 973 articles. With the application of the refinement parameters, a large decrease in the number of articles found was observed. Table 2 demonstrates the general result of the search.

Table 1 Refined search expressions used in Scopus to obtain combined data

Search combinations	Refined string search
"Industrial Symbiosis" OR "Circular economy" OR "industrial ecology" AND "Green Hydrogen"	(ALL ("Industrial Symbiosis") OR ALL ("Industrial Ecology") OR ALL ("Circular Economy") AND ALL ("Green Hydrogen")) AND PUBYEAR > 2013 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE, " ar ")) AND (LIMIT-TO (SUBJAREA, "ENER") OR LIMIT-TO (SUBJAREA, "ENVI") OR LIMIT-TO (SUBJAREA, "ENGI")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (EXACTKEYWORD, "Green Hydrogen") OR LIMIT-TO (EXACTKEYWORD, "Circular Economy") OR LIMIT-TO (EXACTKEYWORD, "Renewable Energy"))
"Industrial symbiosis" OR "Eco-Industrial Parks*" OR "Hybrid System*" AND "Green Hydrogen"	(ALL ("Industrial Symbiosis*") OR ALL ("Eco-Industrial Parks*") OR ALL ("Hybrid System*") AND ALL ("Green Hydrogen")) AND PUBYEAR > 2013 AND PUBYEAR < 2025 AND (LIMIT- TO (DOCTYPE, " ar ")) AND (LIMIT-TO (SUBJAREA, "ENER") OR LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA, "ENVI")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (EXACTKEYWORD, "Green Hydrogen") OR LIMIT-TO (EXACTKEYWORD, "Hybrid Energy System"))
"Industrial Symbiosis" OR Netwok* AND "Green Hydrogen"	(ALL ("Industrial Symbiosis") OR TITLE-ABS-KEY (Network*) AND ALL ("Green Hydrogen")) AND PUBYEAR > 2013 AND PUBYEAR < 2025 AND (LIMIT-TO (EXACTKEYWORD, "Green Hydrogen") OR LIMIT -TO (EXACTKEYWORD, "Hybrid Systems") OR LIMIT-TO (EXACTKEYWORD, "Energy Systems")) AND (LIMIT-TO (DOCTYPE, " ar ")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (SUBJAREA, "ENER") OR LIMIT-TO (SUBJAREA, "ENVI") OR LIMIT-TO (SUBJAREA, "ENGI"))

Table 2 Search results related to article number

Search combination	General result	Refined result
1. "Industrial Symbiosis" OR "Circular Economy" OR "Industrial Ecology" AND "Green Hydrogen"	1070	140
2. "Industrial Symbiosis" OR "Eco-Industrial Parks*" OR "Hybrid System*" AND "Green Hydrogen"	1228	129
3. "Industrial Symbiosis" OR "Netwok*" AND "Green Hydrogen"	973	96
Total	3271	365

The initial results of the search presented a more extensive introductory overview based on the significant number of articles found in the first instant of the search, as shown in Table 2, this scenario allows us to observe that the concepts of IS and GH are comprehensive and can be researched in a multidisciplinary way generating work that encompasses different areas of knowledge.

With the refinement parameters applied, the general overview of the articles found took on a scarcer characteristic, with a total of 365 articles found. As shown in Table 2, Combination 3 demonstrated the smallest number of results, possibly due to its concentration on the terms IS and GH, suggesting an emerging theme that is still little explored in the scientific literature. Likewise, Combinations 1 and 2 also showed a significant reduction after refinement. One of the objectives of the refinement is to direct the results to the core of the research, allowing an understanding of the stage of development of the topic. In this case, the reduction in the combinations mentioned may indicate an emerging theme at an early stage.

The characteristic of an emerging theme in a research field suggests that there are unanswered questions or little explored aspects, which may indicate opportunities for advancement in knowledge and opportunities for new discoveries. Furthermore, the theme proposed for this research has been increasing in the number of research over the years, representing a growing interest in the area, as can be seen in Fig. 1, which shows the trend of research on the proposed theme over the years.

The analysis in Fig. 1 highlights the values of the last five years starting from 2020, a period that marks the beginning of the significant increase in publications on the topic in question. This increase in interest can be attributed to the growing search for decarbonization, a process that aims to reduce CO_2 emissions into the atmosphere, aiming to improve environmental sustainability.

Currently, the predominant strategy highlighted is the energy transition, which is based on reducing the use of fossil fuels in favor of renewable energy sources, such as GH. This reflects a research trend aimed at improving the production of this type of fuel, aiming to make it more efficient, economically viable and ecologically sustainable.

In this context, IS emerges as a promising alternative to address challenges related to the production and sustainable use of alternative fuels, such as green hydrogen. Although we are currently in 2024, the year was considered

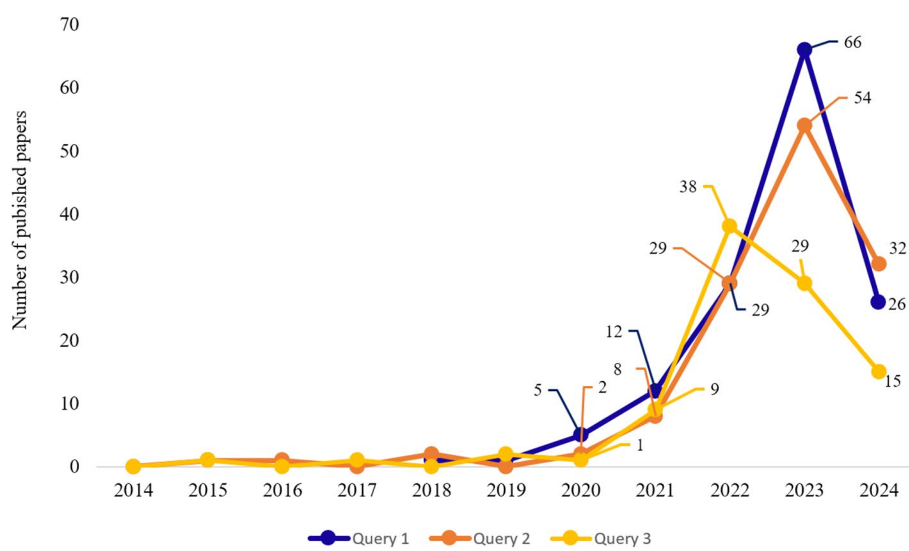


Fig. 1 Number of publications per year based on the three combinations applied

to offer an updated panoramic view of the research and highlight the topic's continued growth trend. Until April 2024, 73 articles related to the topic were identified, representing almost half of the total publications in 2023 (149), indicating a significant expansion in interest and scientific production in this area during the first half of the year.

3.4 Authors' performance

In addition to analyzing publication trends, an analysis of author performance was conducted to offer insights into the main contributors in this field of study and understand which researchers had a relevant impact. This analysis allows us to identify the most prolific authors and the most frequent collaborations between researchers. Table 3 presents the top contributors, ranked based on the number of articles published.

Table 3 includes a total of 14 articles authored by the top four contributors. This represents a significantly smaller number compared to the 87 articles analyzed by Kar et al. [75] in their study on the hydrogen economy. This difference suggests that research related to the application of IS in the production of GH is still in its early stages, characterized by a relatively limited number of publications per author. Such a pattern is typical of interdisciplinary fields and emerging topics, where scientific consolidation and the expansion of contributions are still ongoing.

Barhoumi EM stands out as the leading author in terms of the number of publications, with a total of five articles. His research focuses on the integration of multiple renewable energy sources for GH production, emphasizing the optimization of sustainability and economic viability in these processes. His work directly contributes to the advancement of the understanding of integrated systems and the practical application of IS concepts. Of note is his research entitled "Optimal design of standalone hybrid solar-wind energy systems for hydrogen refueling station case study" [76], which focuses on the optimization of standalone hybrid solar-wind energy systems to power electric vehicles (EVs) and produce GH for fuel cell vehicles (FCVs). By analyzing various renewable energy configurations—including PV panels, wind turbines, fuel cells, and electrolyzers—the study identifies the most cost-effective and efficient systems. The results highlight that a PV battery system achieves the lowest Net Present Cost (NPC), while wind-fuel cell systems incur higher costs due to expensive components.

Another prominent author, Okonkwo PC, often collaborates with Barhoumi EM, exploring similar topics, particularly in the development of IS strategies for GH generation. Among his most notable contributions is the article "Techno-economic analysis and optimization of solar and wind energy systems for hydrogen production: a case study" [77]. This study examines a hybrid energy generation system in Salalah, Oman, utilizing solar photovoltaic energy, wind energy, fuel cells, and hydrogen storage. The research concludes that this system offers the lowest levelized cost of hydrogen and energy compared to other proposed systems, demonstrating its economic viability.

Although Nadaleti WC has only three publications, he holds the highest citation count, highlighting the relevance of his studies in the field. His work focuses on the use of renewable energy, particularly wind power, for GH production. One of his most cited articles, with 31 mentions, investigates the feasibility of hydrogen production from wind energy in Brazil, evaluating different scenarios for practical application. Another noteworthy study is the article "Integration of renewable energies using surplus capacity from wind farms for hydrogen and electricity generation in Brazil and Rio Grande do Sul: energy planning and avoided emissions in a circular economy" [78], which addresses the integration of surplus energy in a CE context.

Frankowska, in turn, focuses her research on post-production stages of hydrogen, such as storage, distribution, and industrial applications. Her article, "Structural model of power grid stabilization in the green hydrogen supply chain system—conceptual assumptions" [79], represents a significant contribution to the field. This work proposes a theoretical multicriteria model for stabilizing power grid operations using hydrogen as an energy buffer, emphasizing its applicability in decentralized energy systems.

Table 3 Main authors related to IS combined with GH

Author	Number of articles published	Quotes
1. Barhoumi, EM	5	60
2. Okonkwo, PC	3	55
3. Nadaleti, WC	3	86
4. Frankowska, M	3	10

Table 4 Number of publications by country

Country	Number of articles	Quotes
1. China	47	511
2. Italy	46	571
3. Spain	25	297
4. India	23	266
5. Germany	22	289
6. Australia	22	257
7. USA	20	267
8. Brazil	19	153
9. United Kingdom	16	346
10. Turkey	15	287

3.5 Country performance

The 365 articles resulted in contributions from more than 70 countries. Identifying the most active countries on this topic can indicate potential opportunities for international partnerships and collaborations, in addition to highlighting areas in which certain countries have expertise and leadership in the field of study. Data referring to the countries with the highest number of publications were obtained from the Scopus database, while the number of citations was analyzed using the VOSviewer software. Table 4 presents the 10 countries with the highest number of publications, providing a clear view of the global distribution of contributions.

Countries with a higher volume of publications exhibit a more significant concentration of research activity, often establishing clear leadership in the field. In this context, China stands out as the leader in both the number of publications (47) and citations (511). This leadership is largely attributed to China's substantial resources and investments in renewable energy development. Studies by Huang and Liu [80] and Camargo et al. [81] emphasize that the Chinese government has allocated considerable funding to advance sustainable technologies, including GH production, as part of its comprehensive strategy to reduce carbon emissions and promote sustainable development. Additionally, China's robust industrial infrastructure and extensive production capacity provide a competitive edge, particularly in IS, where the efficient integration of industrial processes can deliver substantial economic and environmental advantages.

A study by Akhtar et al. [82], which focuses on the global IS research landscape, highlights China's leadership in this field, followed by the United Kingdom and the United States. Beyond China, the data in Table 4 underline the notable contributions of European countries such as Italy, Spain, Germany, and the United Kingdom, reflecting Europe's strength in research and development (R&D) in sustainable technologies. Turkey also demonstrates strategic importance due to its geographical location, bridging Europe and Asia, which bolsters its advancements in scientific publications. Although Brazil ranks among the top 10 countries with the highest number of articles, its output remains significantly lower compared to the leading nations. This disparity suggests untapped potential for Brazil to expand its investments in R&D related to IS and GH technologies, potentially positioning itself as a future leader in the field.

Overall, the performance analysis reveals relatively low numbers of publications and citations compared to other bibliometric studies, such as Alhassan et al. [83], which investigates the challenges of dry methane reforming for hydrogen production, or Yan et al. [84], which explores carbon neutrality in industrial parks through a literature review and knowledge mapping. However, the emerging nature of the topic likely accounts for these modest figures, as GH and IS remain in early stages of exploration across various dimensions. This underscores the need for continued research and development to fully unlock the potential of these technologies in advancing sustainable energy solutions. An example of growth in this area is the study by Neri et al. [85], which presents a multi-objective network design model for urban-industrial symbiosis, incorporating anaerobic digestion, cogeneration, photovoltaics, and hydrogen production technologies. Furthermore, research by Savian et al. [20] and Sorrenti et al. [31] also contribute to this emerging field.

Additionally, the United Nations Industrial Development Organization (UNIDO) published a report in 2023 titled Applications of Green Hydrogen in Eco-Industrial Parks Best Practice Series [86], which refers to areas or industrial clusters where there is a collective use of green hydrogen (including its production, transport, and application) and electricity from renewable energy. These regions also use diverse resources to serve multiple purposes such as material manufacturing, heating and cooling, local transportation, and industrial raw materials.

3.6 Network analysis

Chu et al. [87] addresses that network analysis is an important tool for understanding the interconnections and relationship patterns between the elements of a data set, such as co-authorship of authors, countries, and keywords and in parallel it is important to analyze the clusters generated by the Software.

In the study carried out by Zupic and Cater [88], cluster analysis is emphasized. Cluster analysis on a network map consists of identifying groupings of interconnected elements based on their relationships and proximity. Each cluster represents a set of elements that are more strongly related to each other than to elements from other clusters. The size of a cluster on a network map indicates the density of connections between the elements that compose it. The larger the cluster size, the greater the density of internal connections, suggesting a strong cohesion and interrelationship between the elements.

Using VOSviwer, three network maps related to co-authorship of authors and countries and co-occurrence of keywords were generated. Figure 2 shows the collaboration network between authors.

The presented collaboration network reflects the interaction among various research groups working on GH production and its application within the concept of IS. The network analysis reveals that research in this field is characterized by a high level of collaboration, with different clusters representing groups of researchers who share similar interests and frequently publish together. The clusters identified in the network are differentiated by colors and reflect subthemes or specific approaches within the field of study. Each cluster includes authors with greater connectivity within their networks, indicating a higher frequency of co-authorship or collaboration on scientific projects and publications. For instance:

- Red Cluster (Yang Y and main collaborators): This is the largest cluster and represents a central network of authors with significant contributions that connect smaller clusters. The predominance of Yang Y suggests that this author leads studies that broadly influence the field, integrating various approaches such as energy efficiency analyses and technical studies related to GH. One of Yang Y's notable studies, "Roadmap to hybrid offshore system with hydrogen and power co-generation," [89], explores the integration of hydrogen production and power co-generation in offshore systems. This research provides a comprehensive framework for optimizing the use of renewable energy resources in offshore environments, thereby improving energy efficiency and reducing carbon emissions. The high density of

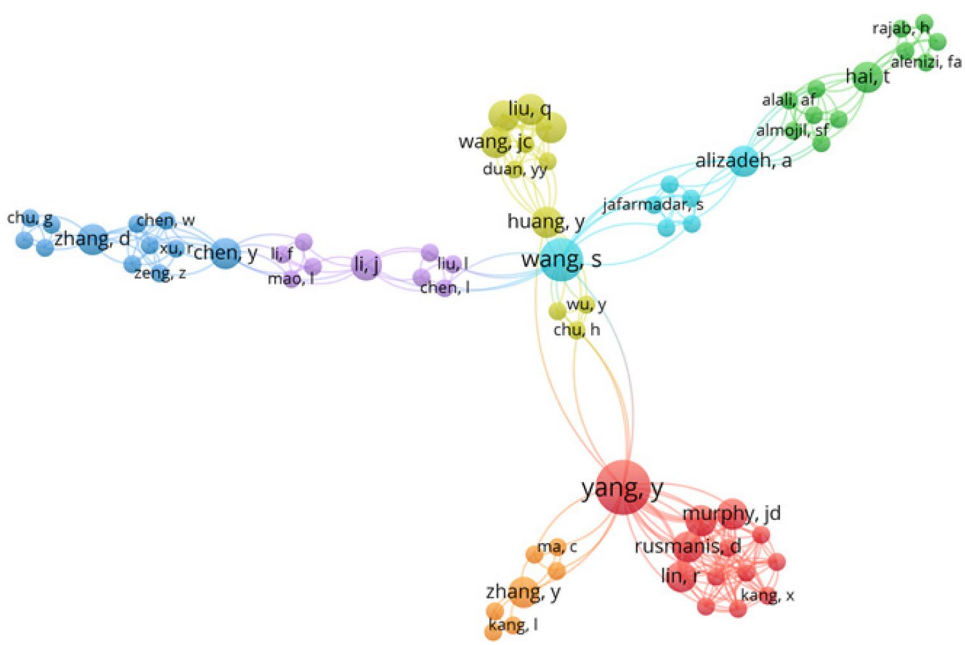


Fig. 2 Author collaboration network

connections in this cluster indicates extensive and diversified collaboration that has a profound influence on research in the field.

- Blue Cluster (Chen Y, Zhang D and main collaborators): This group stands out for addressing specific processes, such as the use of materials for carbon capture and storage applied to hydrogen production. The connections among the authors suggest a technical focus, with a strong emphasis on improving industrial processes related to sustainability. the contributions from Chen Y D include the study "Optimal sizing for a wind-photovoltaic-hydrogen hybrid system considering levelized cost of storage and source-load interaction" [90], which delves into optimizing hybrid systems combining wind and solar energy with hydrogen production. This research highlights key innovations for balancing energy supply and demand while minimizing costs, which is essential for industrial-scale hydrogen production. Zhang D contributed with the estude "Machine learning-based techno-econo-environmental analysis of CO2-to-olefins process for screening the optimal catalyst and hydrogen color" [91], The contribution of this research is to provide an integrated methodology that accelerates the transition to a circular economy by transforming CO_2 into valuable chemicals, promoting a sustainable approach. The analysis of hydrogen colors helps to balance costs and environmental impacts, while the use of machine learning revolutionizes the way emerging technologies are optimized.
- Green Cluster (Alizadeh A and collaborators): This cluster reflects research focused on the development of innovative technologies, particularly in emerging countries or regions with high potential for green hydrogen production. Alizadeh A appears as a central figure, indicating leadership in research related to process optimization and economic feasibility studies. A notable example is Alizadeh's study, "Numerical assessment of a hybrid energy system based on solid oxide electrolyzer, solar energy and molten carbonate fuel cell for the generation of electrical energy and hydrogen fuel with electricity storage option "[92], which investigates hybrid systems combining solid oxide electrolyzers, solar energy, and molten carbonate fuel cells. This work provides valuable insights into enhancing hydrogen and energy generation efficiency while incorporating electricity storage, showcasing how hybrid technologies can optimize renewable energy use.
- Yellow Cluster (Wang S and Liu Q): This group seems to explore ergonomic and methodological aspects of hydrogen production, focusing on optimizing tools and equipment used in industrial processes. Wang S has published notable works such as "Optimal Scheduling of Integrated Energy Network with Electricity-Hydrogen-Storage Considering Ladder Carbon Trading Mechanism" [93], which discusses the integration of hydrogen storage within energy networks, highlighting the role of carbon trading policies in improving system efficiency. Similarly, Liu Q's work, "A multi-dimensional feasibility analysis of coal to methanol assisted by green hydrogen from a life cycle viewpoint" [94], provides critical insights into the environmental and economic benefits of integrating green hydrogen into industrial processes like methanol production, underscoring the importance of lifecycle assessments for policy and industrial decision-making.
- Orange Cluster (Murphy JD and collaborators): This cluster is notable for integrating practical approaches and case studies related to the implementation of IS. The authors in this group frequently examine the socioeconomic and environmental impacts of technologies associated with GH. For example, Murphy JD's study "Electrofuels in a circular economy: A systems approach towards net zero" [95], focuses on the use of electrofuels, produced with green hydrogen, in circular economy frameworks. This research provides practical guidance for achieving net-zero emissions while leveraging the synergies between energy and waste management systems.

Furthermore, the analysis shows that the number of publications is not directly related to the central position within the collaboration network. While authors such as Barhoumi, Okonkwo, and Nadaleti lead in publication volume (as shown in Table 3), authors like Yang Y, Wang S, Huang Y, and Alizadeh A stand out due to the density of connections within their clusters. This indicates that the scientific contributions of the latter go beyond the number of published works, playing a crucial role in knowledge dissemination and collaborative advancement in the field. For instance, Wang S's works bridge theoretical methodologies with practical applications, while Liu Q's contributions provide a multidimensional perspective on the economic and environmental viability of green hydrogen-assisted industrial processes.

Additionally, the presence of Alizadeh A and Wang S as central figures in their respective clusters highlights their ability to foster collaboration between different research groups. Alizadeh A's work has been pivotal in bridging theoretical research and practical applications, as demonstrated in studies related to hybrid energy systems integrating renewable energy sources, while Wang S has contributed to the integration of methodological frameworks across diverse industrial contexts.

Finally, the collaboration network demonstrates that, although research on GH is relatively concentrated among a few groups, there is a growing trend of integration between different clusters. This reinforces the interdisciplinary and

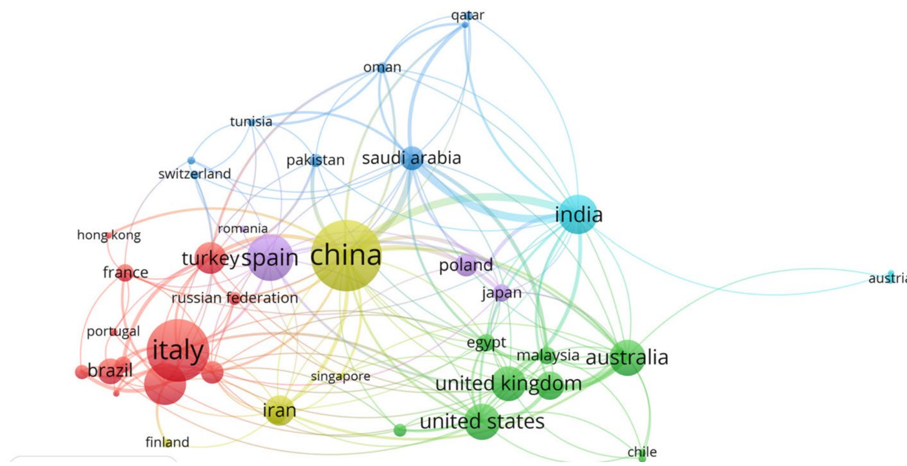


Fig. 3 Collaboration network between countries

global nature of research in this area, further emphasizing the need for collaborative efforts to address the multifaceted challenges of green hydrogen production.

The analysis of countries' co-authorship allows us to understand international relations in scientific production, identifying which nations are most involved in certain areas of research and how they relate to each other. Figure 3 shows the collaboration network between countries.

The collaboration network shown in the image highlights the global interconnection of countries involved in IS and GH research. The network is built on the basis of co-authorship of scientific publications, where the lines represent collaborations between countries. Countries with a higher number of connections, such as China, the United States, Italy, India, and Germany, are central players in this field, a similar behavior is noted in Jaradat et al. [96]. These nations demonstrate leadership in advancing IS and GH research, reflecting their key role in global collaborative efforts. The network is divided into clusters, each identified by a distinct color. These clusters represent specific regional or thematic groupings of research collaborations, which can be analyzed to understand their unique contributions to the field. Fernadez-Arias et al. [97], which discusses the generation of technologies for GH, which uses a bibliometric review, finds parallel results with clusters that have similar characteristics, such as China, the United States, Italy, India and the United Kingdom, which also have highlights in their clusters. Analyzing the results in Fig. 3 about the clusters, we can conclude:

- Red Cluster (e.g., Italy, Brazil, Spain, Turkey): This cluster highlights the contributions of European and South American countries, particularly Italy and Brazil, which focus on integrating industrial symbiosis concepts with renewable energy systems. Italy's role is prominent in exploring circular economy approaches and decarbonization strategies, while Brazil brings insights into renewable-based hydrogen production, leveraging its abundant biomass and wind energy resources. Spain and Turkey also contribute significantly, especially in applying IS strategies to enhance resource efficiency in hydrogen production.
- Yellow Cluster (e.g., China, Iran):This cluster represents the dominant role of China in GH research, supported by its strong emphasis on technological innovation and large-scale renewable energy projects. Collaborations with countries like Iran suggest a focus on low-cost hydrogen production methods and scalable energy solutions, addressing the challenges of high-energy demand regions.
- Green Cluster (e.g., United States, United Kingdom, Australia): This group features countries that are leaders in advanced hydrogen technologies and policy frameworks for sustainable development. The United States contributes through cutting-edge research on hydrogen storage, transportation, and economic feasibility, while the United Kingdom focuses on policy integration and green hydrogen infrastructure development. Australia plays a key role in exploring the export potential of hydrogen, leveraging its natural solar and wind resources.
- Blue Cluster (e.g., India, Saudi Arabia): This cluster showcases the contributions of emerging economies like India and Saudi Arabia. India's research is driven by its need for low-carbon, affordable hydrogen solutions, addressing domestic energy challenges while promoting IS practices. Saudi Arabia, with its substantial investments in green energy, is emerging as a key player in hydrogen export markets.
- Purple Cluster (e.g., Poland, Japan): Countries in this cluster focus on niche technologies and specialized applications of green hydrogen. For instance, Japan is a leader in fuel cell development and exploring hydrogen's role in the

transportation sector, while Poland investigates the integration of hydrogen in industrial processes and its potential role in energy security.

The participation of emerging countries, such as Brazil and India, is particularly significant as it expands the geographical and thematic diversity of research. As noted by Neves et al. [98], these nations often address localized challenges while contributing to global advancements in IS and GH. For instance, Brazil's focus on integrating renewable energy with hydrogen production aligns with its abundant natural resources, while India's contributions target cost-effective solutions for its growing energy needs.

The collaborative structure aligns with findings from Panchenko et al. [99], which identified the United States, China, Italy, Germany, and India as the most active countries in IS and GH research. These nations not only lead in publication output but also foster significant partnerships, creating a dense network of knowledge exchange. Such collaborations are essential for addressing the interdisciplinary challenges posed by hydrogen production and its integration into industrial symbiosis systems.

The network depicted in the image is a snapshot of research at a given time, and it is expected to evolve as new countries join and existing collaborations deepen. Emerging economies are likely to play a more prominent role, contributing innovative approaches tailored to their specific needs and contexts. This dynamic nature highlights the importance of fostering global partnerships to accelerate the development of GH technologies and their application in IS.

The network analysis demonstrates that research on IS and GH is both interdisciplinary and highly collaborative, involving a mix of leading nations and emerging players. The identified clusters underline distinct regional priorities and technological focuses, collectively contributing to the advancement of sustainable hydrogen production. This global effort underscores the necessity of continued international cooperation to overcome challenges and maximize the benefits of green hydrogen within the framework of industrial symbiosis.

For keyword co-occurrence network, it is possible to identify which terms are frequently associated, forming groupings or thematic clusters. These clusters represent areas of interest or dominant themes in research, allowing a deeper understanding of the interconnections between different concepts and themes. Figure 4 demonstrates the co-occurrence network between keywords.

The keyword co-occurrence network provides valuable insights into research trends related to IS and GH. A notable feature of the results depicted in Fig. 4 is the connection between terms associated with GH development and those

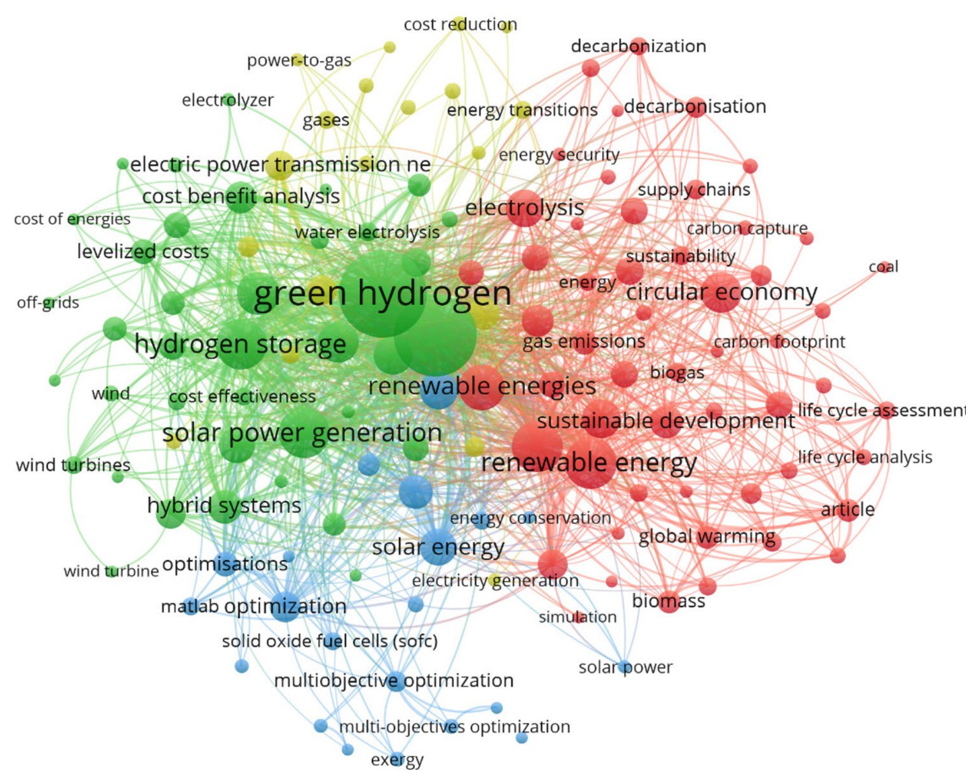


Fig. 4 Keyword co-occurrence network

linked to IS, indicating a modest but identifiable interaction between these two concepts. Raman et al. [100], for example, focus primarily on the GH landscape with a broader and more generic approach. Their findings highlight frequently occurring keywords such as hydrogen storage, GH, renewable energy, and GHG emissions. However, terms directly associated with IS are notably absent, highlighting that the link between these two concepts has not yet emerged prominently in the broader research context. A similar pattern is observed in studies that focus exclusively on IS or related fields, such as the bibliometric analysis by Alka et al. [101], which focuses on the CE without integrating terms relevant to GH.

The network analysis in Fig. 4 reveals that research in this domain predominantly focuses on concepts such as CE, GH, electrolysis, renewable resources, and hydrogen storage. These keywords form a network of significant interconnections, creating dense clusters that signal a growing focus and emerging interest in these research areas. This interpretation is reinforced by an in-depth analysis of the articles linked to these keywords, offering a clearer understanding of the specific research segments where these terms frequently appear. Furthermore, the visualization highlights key clusters of interconnected keywords, each representing distinct but interrelated domains of interest within the broader scope of the field that are represented by different colors:

- Green Cluster: Green Hydrogen and Associated Technologies: This is the largest and most densely connected cluster, with "green hydrogen" at its core, reflecting the predominant focus of research efforts. Adjacent keywords such as "hydrogen storage," "electrolyzer," "solar power generation," "hybrid systems," and "power-to-gas" suggest that studies are centered on the development of technologies for the production, storage, and utilization of green hydrogen. Terms like "levelized costs" and "cost–benefit analysis" underscore a significant concern with the economic feasibility and cost analysis of the technologies involved. The connections with "wind turbines" and "solar energy" highlight the integration of renewable energy sources into GH production, reinforcing the trend toward technological innovation and sustainability.
- Red Cluster: Circular Economy and Sustainability: The second most relevant cluster is centered on keywords such as "circular economy," "sustainability," and "renewable energy." This grouping reflects a growing interest in applying CE concepts to the use of GH, with a focus on reducing GHG emissions ("gas emissions") and environmental impacts ("carbon footprint"). Keywords such as "biomass," "carbon capture," and "life cycle assessment" highlight the importance of LCA and strategies to minimize environmental impacts along the GH value chain.
- Blue Cluster: Optimization and Simulation: The blue cluster features keywords such as "multiobjective optimization," "simulation," "matlab optimization," and "exergy." This cluster indicates a focus on computational tools and optimization methods applied to GH production. The use of simulations to maximize the energy and economic efficiency of technologies emerges as a critical area of research.

The keyword "green hydrogen" dominates the network, confirming its central role in current research. The dense connectivity of the green cluster reflects the importance of both technological and economic development in advancing GH production. While the term "industrial symbiosis" is not explicitly present, related concepts such as "hybrid systems" and "circular economy" suggest indirect connections to this theme, signaling opportunities for further exploration.

The integration of renewable energy, particularly solar power, into GH production is prominently emphasized. Furthermore, the connections between clusters suggest that the combination of circular economy principles, optimization tools, and renewable energy integration represents a key trend in advancing research on green hydrogen. This analysis of the co-occurrence network provides critical insights for identifying emerging research trends and gaps, especially in linking IS more explicitly with GH production.

4 Conclusions

Bibliometric analysis is a methodology that allows you to examine and evaluate a certain field of knowledge through metrics and quantitative analysis of published research. Its objective is to identify trends, research topics, evaluate scientific productivity and identify relevant sources of information. In this context, a bibliometric analysis was conducted focusing on the use of IS in GH production.

The results of this analysis revealed a gap in research addressing the application of IS in GH production. Although the number of publications related to each of these concepts individually is relatively high, research connecting both themes is scarce. Furthermore, it was found that the number of publications per author was not significant, and the co-authorship network map did not show robust connections between the clusters, suggesting an initial stage of collaboration between researchers and scientific production in this area. This would explain the scarcity of results in research on the connection between these themes. All stages of the bibliometric analysis, even though they did not present significant results, were important in shaping the research scenario, confirming that the material available in scientific literature is still in the exploration phase, with opportunities for the development of new research branches.

The bibliometric analysis also made it possible to identify the countries with the greatest scientific production in this field. China was identified as the top country in terms of publications, followed by Italy, Spain, India, and Germany. This global panorama indicates the involvement of both developed and developing countries in promoting sustainable technologies for a renewable energy transition. The co-occurrence of keywords can guide the main characteristics of the searches found, being the main.

These results suggest that there is room to stimulate interdisciplinary collaboration and establish strategic partnerships in research on the application of IS in GH production. Furthermore, they highlight the need to strengthen collaboration between researchers and institutions in different countries to promote significant advances in this area and boost the transition to a more sustainable and low-carbon economy.

Future perspectives for the use of IS in GH production indicate a significant advance in scientific research. SI, which involves the integration of industrial processes to maximize resource efficiency and minimize waste, can be crucial to the economic and environmental viability of GH production. Some of the concepts involved in developing future technologies include water electrolysis, smart grids, anaerobic digestion, steam reforming, industrial waste revaluation, and storage and transportation. These are some of the themes that most encompass the use of IS linked to GH and based on this, future research may feature greater involvement of these concepts in their results.

Applying these principles to the production of GH promises to reduce costs, increase energy efficiency, and minimize the carbon footprint, contributing to the global energy transition. The future of industrial symbiosis in GH production depends on continued research and technological innovation. Collaboration between industrial sectors, governments and research institutions will be vital to develop and implement these technologies effectively.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate Not applicable. All authors consent to participate in the writing and publication of the manuscript.

Consent for publication All authors agree to publish this manuscript.

Competing interests The authors declare no competing interests.

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