Energy Conversion and Management: X 25 (2025) 100822

Contents lists available at ScienceDirect

Energy Conversion and Management: X

journal homepage: www.sciencedirect.com/journal/energy-conversion-and-management-x

Review of the trends, evolution, and future research directions of green hydrogen production from wastewaters – Systematic and bibliometric approach

Flavio Odoi-Yorke [a], Ephraim Bonah Agyekum [b,c,d,e], Mustafa Tahir [f,l], Agnes Abeley Abbey [a], Pradeep Jangir [c,g,h], Farhan Lafta Rashid [i], Hussein Togun [j], Wulfran Fendzi Mbasso [g,k,*]

[a] Department of Renewable Energy Technology, Cape Coast Technical University, Cape Coast, Ghana
[b] Department of Nuclear and Renewable Energy, Ural Federal University Named After the First President of Russia Boris Yeltsin, 19 Mira Street, Ekaterinburg 620002, Russian Federation
[c] Applied Science Research Center, Applied Science Private University, Amman, Jordan
[d] Jadara University Research Center, Jadara University, Jordan
[e] Tashkent State University of Economics, Islam Karimov Street 49, 100066 Tashkent City, Uzbekistan
[f] College of Electrical Engineering Zhejiang University Hangzhou, China
[g] Department of Biosciences, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences,Chennai 602 105, India
[h] Adjunct Professor, Department of CSE, Graphic Era Hill University. Graphic Era Deemed To Be University, Dehradun, 248002, India
[i] Petroleum Engineering Department, College of Engineering, University of Kerbala, Karbala 56001, Iraq
[j] Department of Mechanical Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq
[k] Laboratory of Technology and Applied Sciences, University Institute of Technology, University of Douala, PO Box: 8698, Douala, Cameroon
[l] Shaoxing Institute of Zhejiang University, Shaoxing 312099, China

ARTICLE INFO

Keywords:
Hydrogen energy
Wastewater treatment
Bibliometeric analysis
Water electrolysis
Microbial photoelectrochemical cell

ABSTRACT

For today's society, recognizing and identifying a sustainable energy source is crucial. The public, government, and business community have all expressed strong support for hydrogen energy, establishing it as a key fuel source for the future. This paper analyzes the state of wastewater for green hydrogen production research, focusing on global trends, evolution, potential hotspots, and future directions, using a systematic, bibliometric, and organized review of research publications from 2013 to 2023 in the Scopus database. The visualization and quantitative evaluation of the data was conducted using the VOSviewer software, and the Biblioshiny package in the R-software. The study also compared the various techniques that are used for the production of hydrogen using wastewaters. The research field experienced a 32.88 % annual growth, with 1,883 authors and 27.95 % international collaborations. Microbial photoelectrochemical cell, a recent energy generation technology, has gained interest due to its ability to treat various pollutants. This surge is attributable to technological advancements in wastewater hydrogen production, as part of global efforts to tackle environmental issues. This study advances knowledge and practices in the field of green hydrogen production using wastewater by illuminating new trends and intersecting themes. Potential future research directions on the topic were identified and proposed in this study.

1. Introduction

Lowering greenhouse gas emissions has been a top priority since the end of the 20th century. Thus, there is a global push to cut greenhouse gas emissions and limit the increase in global average temperature to 2 °C over pre-industrial levels [1]. The COP26 organized in the United Kingdom, COP27 in Egypt, and COP28 organized in United Arab Emirates have hosted several United Nations climate change conferences with the aim of combating high greenhouse gas emissions and expediting the energy transition. Placed in place of thermal power plants

* Corresponding author.
E-mail addresses: flavio.odoi-yorke@cctu.edu.gh (F. Odoi-Yorke), agyekumephraim@yahoo.com (E.B. Agyekum), mustafatahir@zju.edu.cn (M. Tahir), agnes.abbey@cctu.edu.gh (A.A. Abbey), pkjmtech@gmail.com (P. Jangir), farhan.lefta@uokerbala.edu.iq (F.L. Rashid), htokan_2004@yahoo.com (H. Togun), fendzi.wulfran@yahoo.fr (W.F. Mbasso).

https://doi.org/10.1016/j.ecmx.2024.100822
Received 23 September 2024; Received in revised form 14 November 2024; Accepted 28 November 2024
Available online 6 December 2024

are renewable energy sources like solar and wind power [2]. The interconnectedness of the water and energy systems, as well as their infrastructures, has received increased attention recently. All societies have long relied on energy and water for social and industrial activities. These two systems are entirely interdependent and are crucial to the stability, growth, and security of economies [3,4]. Energy is needed for the production, treatment, distribution, and transportation of water in all phases of social and industrial activity [5]. Conversely, water is a necessary component of most energy production processes. Meanwhile, the majority of the world's regions deal with one or both of the issues related to a shortage of water and/or energy resources [4].

Hydrogen is now generally acknowledged to be the energy carrier of the future for low carbon energy systems, including power generation, heat, industry, transportation, and energy storage [6–9]. Several processes, including chemical, electrochemical, thermochemical, and biological ones, can produce hydrogen gas from fossil fuels, water, organic wastes, and biomass [10–12]. It is anticipated that green hydrogen, or hydrogen generated from renewable resources, will emerge as the energy substitute that permits a significant reduction in global warming [13–15]. Hydrogen can be produced from renewable resources through various technologies, such as thermochemical cycles, electrolysis, photocatalysis, fermentation, and thermochemical conversion of biomass [16,17]. There are two types of water electrolysis (electrochemical and photoelectrochemical (PEC) water splitting) that are well-known methods for producing green hydrogen for more than 200 years (Fig. 1). The first one involves the use of electricity to split water into H_2 and O_2, which is an emission-free technology. PEC, on the other hand, uses both solar and electrical energy for this purpose [18]. The assessment of hydrogen gas from organic wastes has been studied using biological techniques, such as the dark and photofermentation processes. Nonetheless, biological hydrogen production methods have reported low hydrogen gas percentage and hydrogen gas production being limited by microbial factors, such as slow bacterial metabolism [19].

To be able to reduce GHG emissions and recover energy used during the treatment process, it is crucial to apply systems that can produce hydrogen while treating wastewater. The primary sources of wastewater are industrial and residential. Many freshwater sources around the world are contaminated today. It is anticipated that growing industrialization and population growth will cause clean water resources to become insufficient or contaminated. Six billion people are predicted to face challenges in obtaining clean water resources by 2050 [20].

Since water has the likelihood to be a sustainable and renewable source of hydrogen, research on producing hydrogen from it has been conducted for decades in academic publications. A number of studies have also conducted several review studies on this topic from different perspectives. For instance, [21] presented a distinctive analysis of wastewater treatment techniques used in hydrogen production to illustrate a sustainable and clean methodology. There was discussion and identification of several techniques for producing hydrogen from wastewater. Vidas and Castro [22] conducted a thorough analysis of various hydrogen production technologies, with a primary emphasis on water splitting through green electrolysis, which is integrated into the hydrogen value chain. Also, [23] reviewed the latest innovations in the study of a coupled system for producing hydrogen that also includes pollutant upgrading. Anodic reaction wastewater purification, which generates free radicals rather than oxygen evolution reaction (OER) for pollutant degradation, was methodically explained. Furthermore, [24] reviewed the most recent advancements in PEM water electrolysis, such as the high performance, low cost hydrogen evolution reaction (HER) and OER electrocatalysts. They also addressed the challenges, both new and old, associated with these catalysts and PEM cell components. In another study by Dange et al. [25] the authors discussed recent advances in wastewater-based microbial electrolysis cell-based biohydrogen production. Similarly, [26] reviewed the state of technology at the moment that allows water electrolysis systems to use impure water. Elgarahy et al. [27] reviewed wastewater-to-dihydrogen production,

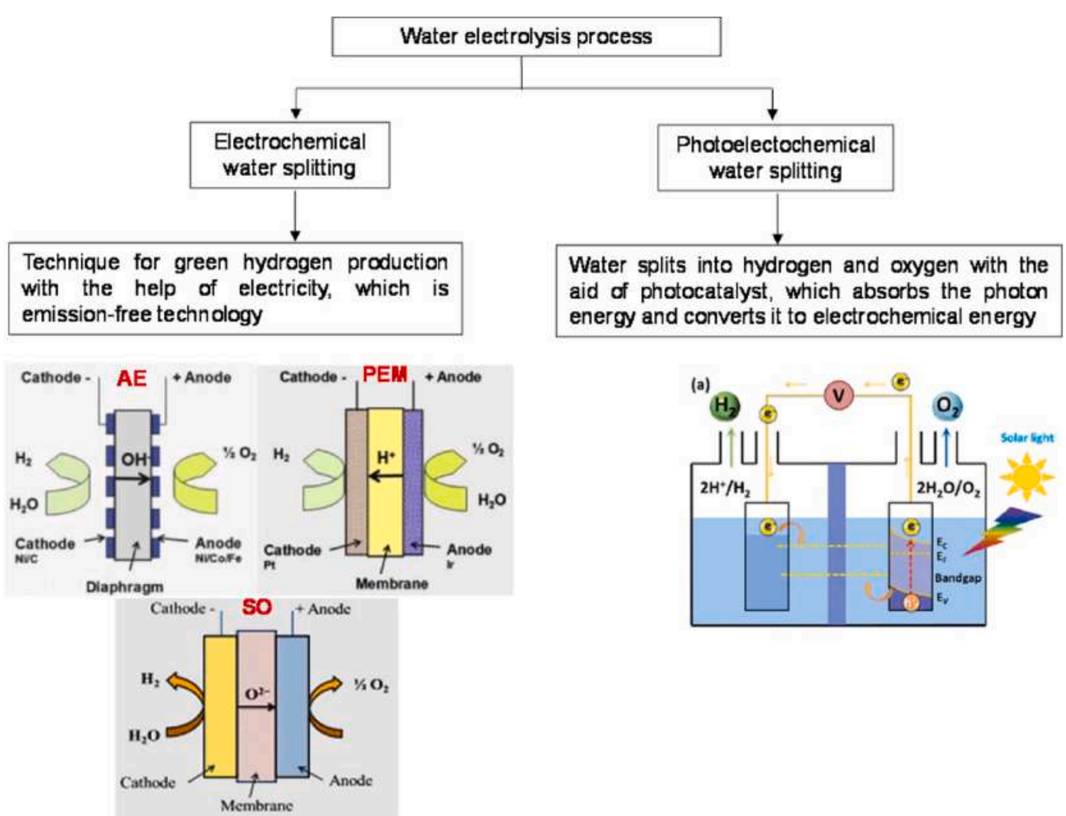

Fig. 1. The schematic diagram for each of the two types of water electrolysis processes [18].

concentrating on applications, governance, techno-economic factors, electrochemical processes, and storage of dihydrogen. Also, Tak et al. [28] discussed new methods for producing hydrogen from wastewater. The advantages and disadvantages of each technology were discussed, along with the technical details of the chemical reaction mechanism.

This study combined the systematic and bibliometric approach to thoroughly assess the trends, evolution and future research direction of hydrogen production from wastewater. The utilization of bibliometric analysis has been observed in the investigation of research trends concerning the hydrogen economy [29], the linkages between nuclear energy and hydrogen production [30], the development of microbial electrolysis cells as a means of producing hydrogen [31], the transformation of food waste into hydrogen energy [32], the production of hydrogen through catalysis from organic waste [33], production of hydrogen through dark fermentation [34], and hydrogen safety [35]. However, there is very little information on a study that comprehensively utilize both bibliometric and systematic methods to review recent studies on hydrogen production from wastewaters. The following research questions are formulated in this study in an effort to look into the trends and developments in academic works related to hydrogen production from wastewaters: Q1: What modifications or advancements have been made to the field of hydrogen production from wastewaters between the years 2013 and 2023? We must examine the development of scholarly works pertaining to wastewater-derived hydrogen production in order to provide an answer to this question. Q2: How do studies on hydrogen production from wastewater relate to one another? To determine the relationship between keywords and their level of similarity, techniques such as factorial analysis, multiple correspondence analysis, multidimensional scaling analysis, and correspondence analysis will be employed. This analysis can offer valuable insights into the past, present, and future paths of the field, assisting academics in bridging knowledge gaps and developing research initiatives that propel the field forward. Two distinct bibliometric tools—the VOSviewer software for data visualization and clustering and the Biblioshiny package in the R-studio program—were used to accomplish the study's goals as previously stated.

The study is presented in the following order: the materials and methods employed for the analysis are presented in Section 2, Section 3 presents the results and discussions of the study, the final section, i.e., Section 4, presents the conclusions, and identified potential future research directions on the topic.

2. Research methodology

This section provides an explanation of the database, time frame, and method used in the selection of the articles under investigation, as well as the analysis techniques used. The process of compiling bibliometric data involves choosing the database, sifting through the bibliographic information, and refinining it. The next stage involved choosing the analytical software and deciding how to present the analysis's findings visually. A systematic review is a type of scientific study that compiles pertinent research on a particular topic and offers unbiased summaries of the findings. It can also mean the process of identifying and choosing research findings, extracting data, and analyzing outcomes that are observed in the scientific domain. This is particularly helpful in fields of study where there are many publications, each concentrating on a distinct point of view [36].

PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines and procedures were adhered to in this study [37–39]. Numerous databases are available for searching scientific documents, such as Scopus and the Web of Science (WoS). Being the largest scientific database, this study used data from the Scopus database for the analysis. The period for the analysis is from 2013 to 2023. The following keywords i.e., "green hydrogen" OR "clean hydrogen" AND "wastewater" were used in the search for the documents in Scopus database under the Article title, Abstract, and Keywords section. A total of 1585 documents were initially obtained upon the first search. Limiting the subject area to chemistry, chemical engineering, energy, and engineering resulted in a total of 1008 documents. The screening process continued by including only articles and documents written in the English language resulting in 765 documents. A total of 350 documents were deleted from the downloaded data upon further scrutiny because they were found to be out of scope. This resulted in a total of 415 documents which were found to be pertinent for the analysis. The protocol for the PRISMA approach adopted for the study is presented in Fig. 2.

Bibliometric analysis is a statistical assessment of published articles and reviews in reputable journals. It is a helpful method for determining how earlier publications will impact future research communities since it highlights important research trends and collaboration among researchers [40,41]. There are several software that have been developed to run bibliometeric studies. In this study the Biblioshiny software in the R-package, and the VOSviewer software were used in the quantitative analysis of the obtained data.

3. Results and discussion

The section highlights the publication volume, influence, themes, terminology, publication venues, co-authorship, and interdisciplinary links within green hydrogen production using wastewater. It also presents the key findings and recommendations from the top-cited papers.

3.1. Annual article production and top publishing countries

This bibliometric analysis summarizes research publications on green hydrogen production from wastewater between 2013 and 2023. Fig. 3 provides an overview of the key publication metrics. In total, 415 papers were published over this 10-year period, originating from 127 different sources. The number of publications grew at an average annual rate of 32.88 %. A total of 1,883 authors contributed to this research, with only 2 single-author papers. On average, each paper had 6.97 co-authors. About 27.95 % of papers involved international collaboration between co-authors. The 415 papers contained a total of 1,362 keywords. On average, each paper received 23.07 citations. This analysis shows a steady growth in publications on green hydrogen from wastewater between 2013 and 2023, with a high degree of collaboration between authors, particularly at the international level.

An extensive approach to monitoring research output, identifying new fields, evaluating external factors, and assessing researcher productivity is to conduct a bibliometric review of annual scientific publications. By supporting strategic choices in research planning, financing, policy-making, and cooperation, such analysis improves the dynamics of knowledge production and dissemination. Fig. 4 shows the annual publication trend from 2013 to 2023. The results indicate that the number of articles published in this field has been steadily increasing, with a significant surge observed in recent years, particularly from 2020 onwards. Prior to 2020, the number of publications remained relatively low, ranging from 6 to 29 articles per year. However, in 2020, there was a notable increase in publications, reaching 41 articles, which could be attributed to growing interest and research efforts in this area. The years 2021 and 2022 witnessed a remarkable spike in publications, with 70 and 87 articles, respectively. This trend continued into 2023, with 103 articles published, indicating a sustained and keen focus on this topic. The steady rise in publications, particularly in recent years, suggests a growing recognition of the importance and potential of green hydrogen production from wastewater. This highlights that researchers and scientific communities have identified this area as a promising avenue for sustainable energy production and waste valorization.

Furthermore, technological advancements and breakthroughs in the field could drive the surge in publications. As new and improved methods for hydrogen production from wastewater are developed, researchers will likely publish their findings, contributing to the overall

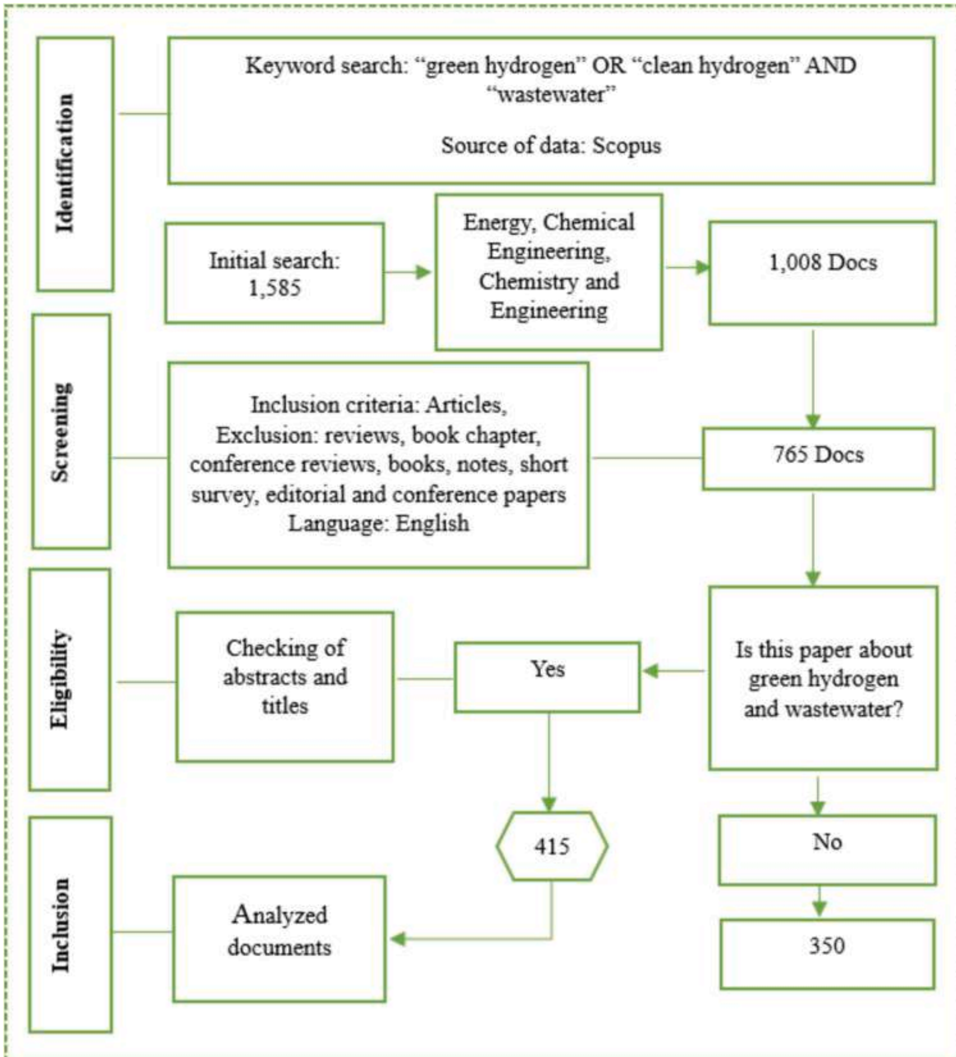

Fig. 2. Flow diagram for the PRISMA method.

Fig. 3. Summary of publication metrics.

knowledge base and accelerating progress in this area. The growing interest in green hydrogen production from wastewaters aligns with global efforts to address environmental challenges and promote sustainable practices [27,42]. Wastewater treatment and valorization have become increasingly important, and the potential to produce hydrogen as a clean energy source from this resource has gained significant attention [43–45].

Fig. 5 depicts the number of articles produced by each country over the study period. The results indicate that China is the global leader in this field, with a significantly higher frequency of publications (1223) than other countries. This dominant position suggests that China has prioritized research and development efforts in this area, likely driven

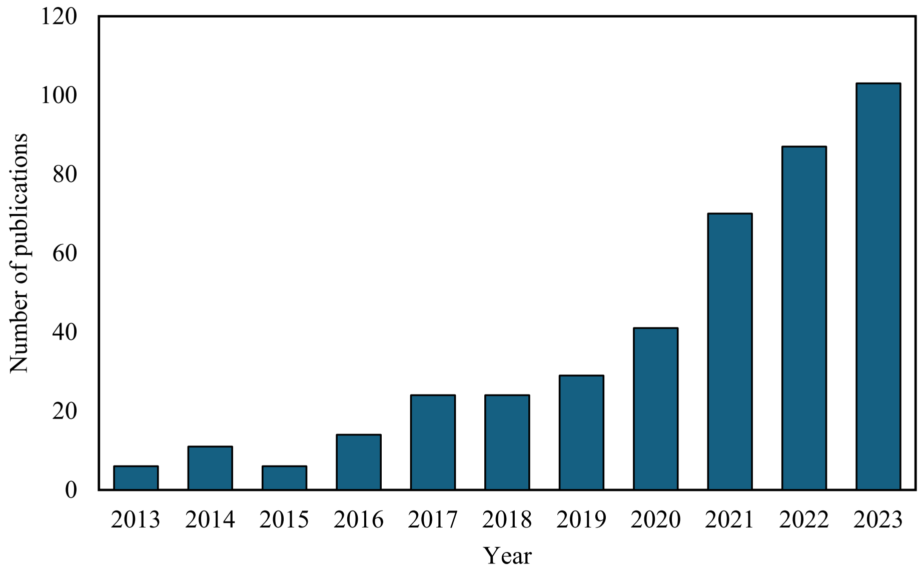

Fig. 4. Number of articles published annually.

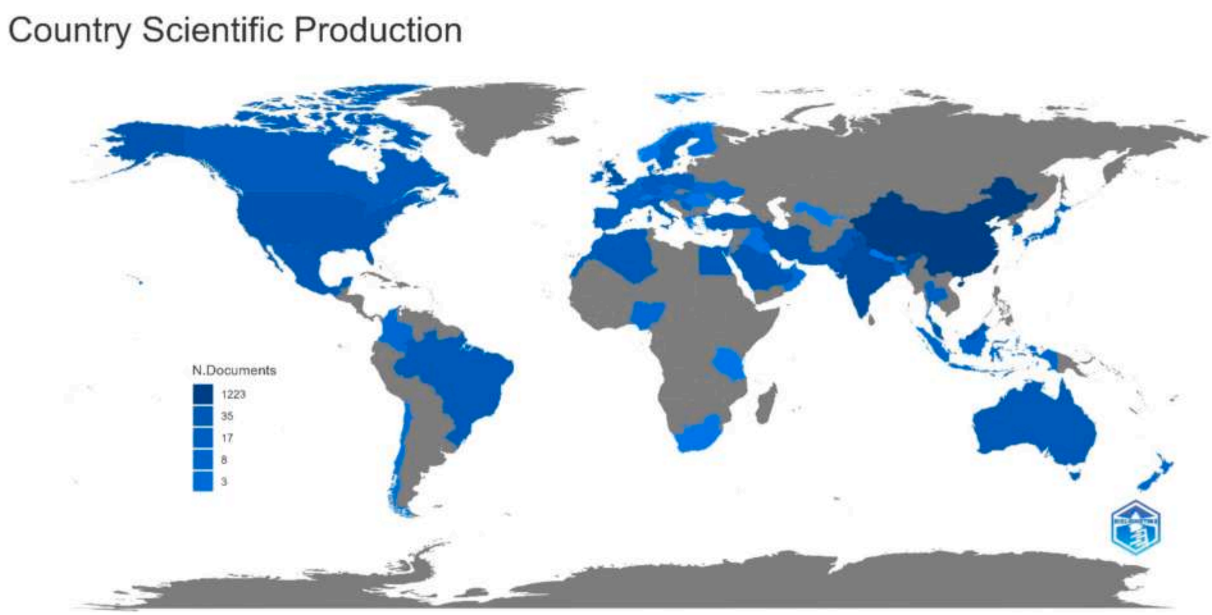

Fig. 5. Country scientific production.

by factors such as energy security, environmental sustainability, and the availability of research funding and resources. Other countries with notable contributions include India, the United Kingdom, the United States, Malaysia, Iran, Singapore, Pakistan, South Korea, and Mexico. These countries have also demonstrated substantial research interest and output, indicating their recognition of the potential of green hydrogen production from wastewater.

It can be seen that there is a diverse representation of countries from various regions, including Asia, Europe, North America, South America, Africa, and the Middle East. This widespread distribution suggests a global acknowledgment of the importance of this technology and its potential applications across different geographical and economic contexts. The presence of multiple countries within specific regions, such as Asia and Europe, presents opportunities for regional collaborations, knowledge sharing, and the development of region-specific strategies and technologies tailored to local conditions and resources. While some countries have established themselves as leaders in this field, others with relatively lower publication frequencies may represent emerging research hubs or countries with untapped potential. These countries could benefit from technology transfer, capacity building, and collaborative partnerships with more experienced nations to accelerate their research efforts and contribute to the global knowledge base.

3.2. Analysis of clusters of author keywords

Based on the evaluation of the data in the VOSviewer software using the fractional counting approach, a total of 6 clusters of author keywords were identified (see Fig. 6). The details of each cluster is as follows:

Cluster 1: in this cluster, words like adsorption, degradation, dye, green synthesis, methylene blue, nanocomposite, and response surface methodology are present. Studies in this cluster identified different methods of removing pollutants from different wastewaters. For instance, to create a BC/ZIF-8 (zeolite-like imidazolate framework) composite material, [46] produced biochar (BC) from canola straw,

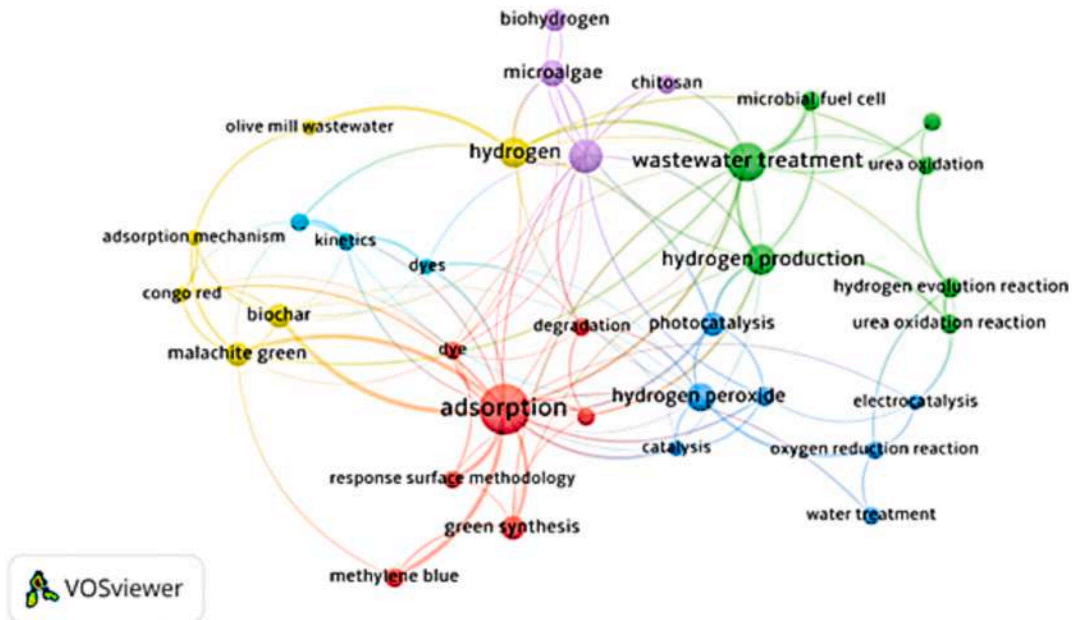

Fig. 6. Author keywords network visualization.

which is an inexpensive and environmentally friendly adsorbent. The study conducted batch experiments and characterization to assess the adsorption procedures and applications of a material, finding that BC/ZIF-8 significantly increased Boron's adsorption capacity by 76 % compared to ZIF-8 alone. By repurposing agricultural waste—nutmeg fruit rind—as an efficient adsorbent and then adding value and safely disposing of it. Vaishna et al. [47] demonstrated an inventive circular economic process that harmonizes with sustainable waste management and green chemistry concepts. They looked into the possibility of using nutmeg fruit rind waste, an easily obtained agricultural byproduct, to extract hexavalent chromium (Cr(VI)) from polluted streams. The results showed how effectively Cr(VI) ions were removed from the nutmeg fruit rind waste by adsorption, highlighting the method's potential as an inexpensive and environmentally friendly wastewater treatment method. Also, for the purpose of removing soluble dye from wastewater, new sustainable adsorbents consisting of graphene oxide (GO) and other materials, including durian shell activated carbon (DSAC), fish bone calcium oxide nanoparticles (CaONPs-FB), and calcium oxide nanoparticles derived from eggshells (CaONPs-ES), were synthesized, analysed, and demonstrated in the study of [48]. In the synthesis process, fermented maize grain extract (MES) was employed as a green cross-linker. Nanocomposites GO@CaONPs-ES/DSAC and GO@CaONPs-FB/DSAC showed promising adsorption capabilities for removing methylene blue dye from aqueous environments, with cross-linking increasing surface areas.

Cluster 2: themes in this cluster include green hydrogen, hydrogen evolution reaction, hydrogen production, microbial fuel cell, urea oxidation, urea oxidation reaction, and wastewater treatment. In this cluster, the authors focused on the use of industrial and domestic activities for the production of hydrogen. For instance, [49] used advanced alkaline water-splitting technology to study the production of hydrogen from wastewater effluents collected from municipal wastewater treatment plant and their membrane filtrates. According to the study, municipal wastewater treatment facilities may be able to achieve energy independence by producing green hydrogen with efficiency from wastewater and advanced treated water. Ardo et al. [50] utilized immobilization of microalgae onto polyurethane foam to enhance hydrogen yield, facilitate harvesting for repurposing, and prevent cell washout from cultivation systems. Microalgae were first immobilized for seven days using cubes of polyurethane foam with edge lengths of 0.5, 0.75, 1, and 2 cm. After that, they were added to the medium used for municipal wastewater treatment in order to supply attached microalgae with food for dark fermentation. The study found that 1 cm cubes could produce hydrogen volumes of 20–21 mL, with 70 % chemical oxygen demand and 57 % ammoniacal nitrogen removal efficiencies. However, smaller cubes struggled due to microalgae losses and larger cubes produced less hydrogen. Another study by [51] provided a DuPont Water Solutions WAVE software-based treatment system selection analysis for a municipal wastewater stream. The findings, which came from an examination of seven distinct processing case studies involving reverse osmosis and ultrafiltration, demonstrated that the use of 2-pass membrane systems permits the recovery of water from municipal wastewater that satisfies the standards for the quality of water meant to be used as an electrolyzer feedstock because the resultant water had a conductivity of less than 5 μS/cm. The water reclamation level that could be achieved at an energy consumption of 606.1–2 694 kWh/d, depending on the case study, varied from 68.8 to 84.1 %. Furthermore, [52] showed how a microbial peroxide-producing cell (MPPC) that is inexpensively designed to use a range of catholyte and minimal electrode materials can use household sewage water as anodic feed for the electrochemical production of H_2O_2 in the catholyte while treating wastewater concurrently. During a 37-day batch in the MPPC with a 50 mM H_2SO_4 catholyte and a bare activated charcoal electrode, the electrochemical output using household wastewater produced a maximum of 62 mM H_2O_2. La_2NiO_4, a two-dimensional porous perovskite oxide based on nickel and designed for full spectrum sunlight irradiation, was synthesized for the purpose of photoelectrocatalytic urea oxidation by Xiong et al. [53]. Low-energy hydrogen production using urea wastewater resulted in an optimal yield of 22.76 μmol $cm^{-2}h^{-1}$.

Cluster 3: items such as catalysis, electrocatalysis, green chemistry, hydrogen peroxide, oxygen reduction reaction, photocatalysis, and water treatment appeared in this cluster. In order to address the issues of environmental pollution and the energy crisis, photocatalysis and photoelectrocatalysis have been utilized extensively as low-cost, environmentally friendly pollutant treatment technologies that simultaneously break down pollutants and generate clean energy. With the help of a mesoporous nanoscale $WO_3/BiVO_4$ heterostructure photoanode, Davies et al. [54] was able to efficiently break down ibuprofen in wastewater while also producing green hydrogen at the cathode in imitation of sunshine. They found that after 145 min, ibuprofen (starting concentration of 100 mg/L) degraded almost completely (>96 %), with no dangerous intermediates (ascertained by mass spectrometry analysis) and a simultaneous evolution of H_2 of 114 μmol/cm^2. Fakourian and Alizadeh [55] presented a study that looked into a potential design for an integrated photovoltaic (PV)–electrolysis system that would produce hydrogen from the wastewater of coal utility boilers. With the best configurations and necessary losses taken into account, a numerical model was created for integrated PV solar panels and a polymer electrolyte membrane (PEM) electrolyzer. The system was found to be 60–62.5 % and 18–20 % efficient, respectively, based on the model's investigation of its efficiency. Li et al. [56] evaluated the creation of a bifunctional electrocatalyst for the HER and ultrathin NiO nanosheets (a-RuO_2/NiO) that is made up of numerous amorphous/crystalline interfaces. A 10 mA cm^{-2} current density in a urea electrolyzer requires only 1.372 V of voltage. Adding amorphous RuO_2 increases magnetization and spin-polarized electrons, accelerating urea oxidation reaction kinetics. Amorphous/crystalline interfaces facilitate charge-carrier transfer, and a customized d-band center optimizes oxygen-produced intermediate adsorption.

Cluster 4: items such as adsorption mechanism, biochar, congo red, hydrogen, malachite green, and olive mill wastewater forms the words in this cluster. Common dyes used in the textile printing and plastic industries are malachite green (MG) and Congo red (CR). Because it works so well against fungus and protozoa infections in aquatic organisms, MG is also frequently used as a fungicide in aquaculture [57,58]. MG and CR are synthetic dyes with high toxicity and solubility, potentially harming animals' liver, kidneys, and lungs. They can also attach to DNA nucleophilic sites, causing cancer. Overuse of these dyes can lead to contamination and poisoning of the aqueous system, necessitating proper removal from water bodies. So, before being dumped into water bodies, wastewater containing dye needs to be treated. MG and CR can be extracted from water environments using a variety of methods, such as coagulation, membrane separation, Fenton oxidation, electrochemical, adsorption, etc. Among these, adsorption has gained popularity as a technique for eliminating dyes from water because of its low sludge yield, high efficiency, and affordability [59,60]. The study of [61] suggested a biochar NCBC made by co-modifying urea and calcium chloride with Medulla Tetrapanacis. NCBC displayed a micro-mesoporous composite structure and a massive surface area (750.09 m^2/g).

Cluster 5: themes studied in this cluster include biohydrogen, chitosan, microalgae, and wastewater. This cluster basically looked at the use of microalgae to treat wastewater from homes, industries, and farms for the production of biohydrogen. Wastewater treatment is typically costly and frequently results in additional pollution. The people who live nearby may be seriously endangered if untreated or partially treated wastewater is released into the environment or into bodies of water [62]. Using microalgae is a desirable and beneficial treatment method because it can absorb and use different carbonaceous sources as well as inorganic nutrients found in wastewater medium, such as phosphates and nitrates [63]. Microbial photolysis, as stated by Wang and Yin [64], is the process by which cyanobacteria and microalgae use water and sunlight to produce hydrogen. This is a more cost-effective process than the thermochemical one. Using fermentation technology, which combines dark fermentation and photo fermentation, are the primary mechanisms of producing biohydrogen. Biochemical photolysis, both direct and indirect, is used in photosynthesis technology [65,66]. The results by Hwang et al. [67] indicate that *C. reinhardtii* can produce 50 % more H_2 in diluted pretreated olive mill wastewater and that *Micractinium reisseri* YSW05 can be cultured from diluted effluent wastewater containing acetate/butyrate. It has been reported that *Chlorella sp.* can produce 16–48 mL g^{-1} VS of H_2 from wastewater following chemical and enzymatic pretreatment [68].

Cluster 6: the items in this cluster include themes such as dyes, kinetics, and thermodynamics. Any successful sorption process needs kinetic analysis. The study of [69] utilizing slow pyrolysis produced biochar (PS-B), a novel and effective sorbent for the elimination of brilliant green (BG), a toxic dye, from aqueous solution by thermochemically converting peach stones (PS), lignocellulosic waste (LCW) from the food industry. The results showed that material loss during slow pyrolysis caused the volume shrinking phenomenon in addition to changing the chemical structure of the samples, producing a rougher, more porous structure with less crystallinity. Additionally, it was shown that biochar released five times less total organic carbon (TOC) than native material. From olive mill wastewater (OMWW), Mechnou et al. [70] created an aluminum/carbon composite, which was effectively used to treat a real discharge from a denim dye bath and remove/separate acid yellow 61 (AY61) and malachite green (MG). Endothermic, physical and disordered adsorption were demonstrated by the thermodynamic results. Electrostatic, hydrogen, and π-π interactions were responsible for the substrates' attachment to the surface, with multiple sites contributing in both parallel and non-parallel orientations.

3.3. Conceptual structure

The conceptual framework draws attention to the core ideas, subjects, and connections found in the information gathered for the bibliometric study. The conceptual framework of this study is centered on the factorial analysis of keywords, thematic evolution, and thematic maps.

3.3.1. Thematic map and evolution and factorial analysis

Fig. 7 displays the thematic map of the authors' keywords. It can be observed that the author's keywords are categorized into different themes related to hydrogen production from wastewater. The themes are arranged along a horizontal axis representing the "Relevance degree (Centrality)," which likely indicates the importance or prevalence of each theme within the research domain. The "Basic Themes" are positioned on the far right, representing the most fundamental and widely studied topics. These include "wastewater treatment," "hydrogen," "hydrogen production," and "biochar." These themes can be considered the core areas of research in this field. Moving left, the "Motor Themes" encompass more specific and emerging areas driving current research. These include "adsorption," "hydrogen peroxide," "green chemistry," "hydrogen evolution reaction," "urea oxidation reaction," and several others. These themes represent active areas of investigation and potential breakthroughs in hydrogen production from wastewater.

Further left, the "Niche Themes" represent more specialized or niche research areas. These include "methane," "algae," "anaerobic digestion," "ammonium," "chlorella pyrenoidosa," and others. While not as central as the motor themes, these niche areas may hold potential for novel approaches or applications. The "Emerging or Declining Themes" are positioned on the far left, indicating either emerging topics or those declining in relevance. "Water splitting" is the only theme in this category, suggesting it may be an emerging area of interest or a declining research focus.

The positioning of these themes along the centrality axis provides insights into the current research scope and potential future directions [71]. In view of this, exploring novel materials and processes related to the "Motor Themes": Themes like "carbon quantum dots," "photocatalysis," "biodegradation," "bio-hydrogen," and "catalyst" indicate active research areas focused on developing new materials, catalysts, and processes for efficient hydrogen production from wastewater. Investigating these themes further could lead to breakthroughs and improvements in the overall process. Integrating niche themes like "methane," "algae," "anaerobic digestion," "ammonium," and "chlorella pyrenoidosa" with motor themes could open up new avenues for research. For example, exploring the use of algae or anaerobic digestion in combination with photocatalysis or catalytic processes could lead to novel hybrid approaches. The "Emerging or Declining Themes" category includes "water splitting," which could be an emerging area of interest. Researching water splitting methods in the context of hydrogen

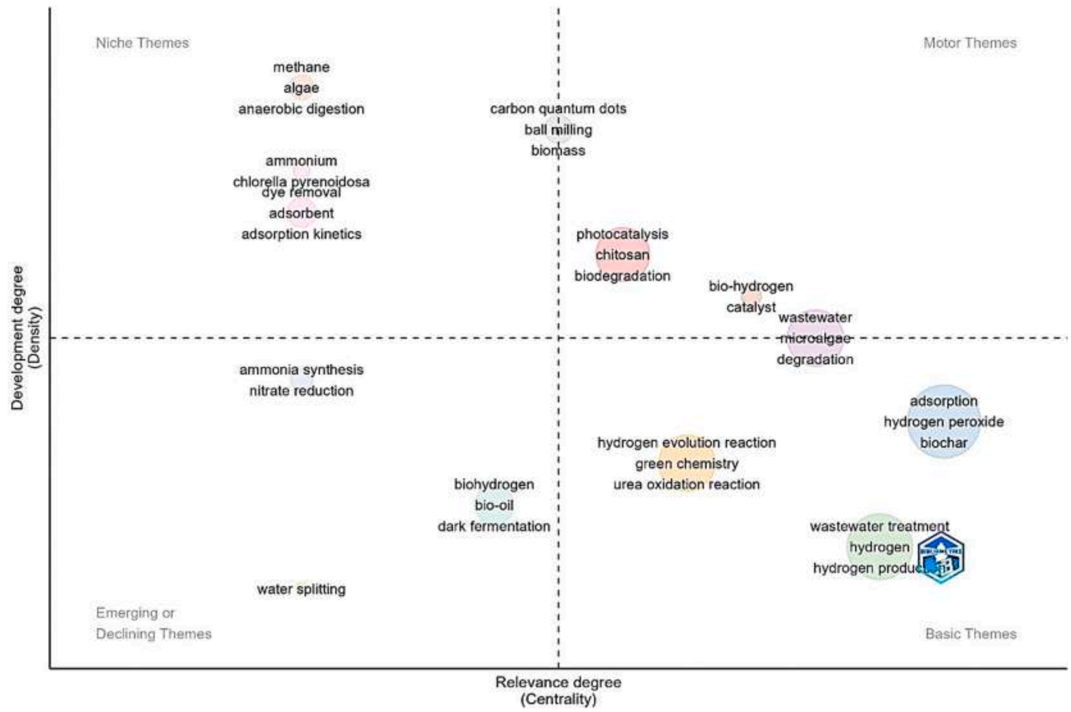

Fig. 7. Thematic map (120 author keywords).

production from wastewater could potentially yield innovative solutions. While the "Basic Themes" represent the core areas, there may still be challenges or limitations within these themes that require further investigation. For example, improving the efficiency of wastewater treatment processes or developing more cost-effective and sustainable methods for hydrogen production could be important research directions.

The evolution of author keywords is presented in Fig. 8. The evolution of author keywords is over three time periods: 2013–2016, 2017–2019, and 2020–2023. It can be seen that in the earliest period (2013–2016), the prominent keywords include "wastewater," "photocatalysis," "lipid accumulation," "hydrogen production," and "microalgae." This suggests that early research focused on exploring photocatalytic processes, microalgae-based systems, and fundamental aspects of hydrogen production from wastewater, potentially also addressing challenges like lipid accumulation. During 2017–2019, the keyword expanded significantly. "Adsorption," "hydrogen production," "wastewater treatment," "chitosan," "hydrogen," "hydrogen peroxide," and "biohydrogen" emerged as prominent themes. This indicates a shift towards several approaches, including adsorption processes, advanced wastewater treatment techniques, the use of chitosan (a biopolymer), and the exploration of biohydrogen production pathways. In the most recent period (2020–2023), the keywords further diversified, highlighting the maturation and expansion of the research field. "Wastewater treatment," "adsorption," "thermodynamics," "chitosan," "biochar," "biohydrogen," and "carbon quantum dots" appear as prominent themes. This suggests a continued emphasis on wastewater treatment and adsorption processes, alongside emerging interests in thermodynamic considerations, biochar applications, biohydrogen production, and the exploration of novel materials like carbon quantum dots.

The early focus on photocatalysis and microalgae-based systems evolved into more diverse and applied research areas, including adsorption, advanced wastewater treatment, biohydrogen production, and the exploration of novel materials. The emergence of keywords like "thermodynamics," "biochar," and "carbon quantum dots" indicates a

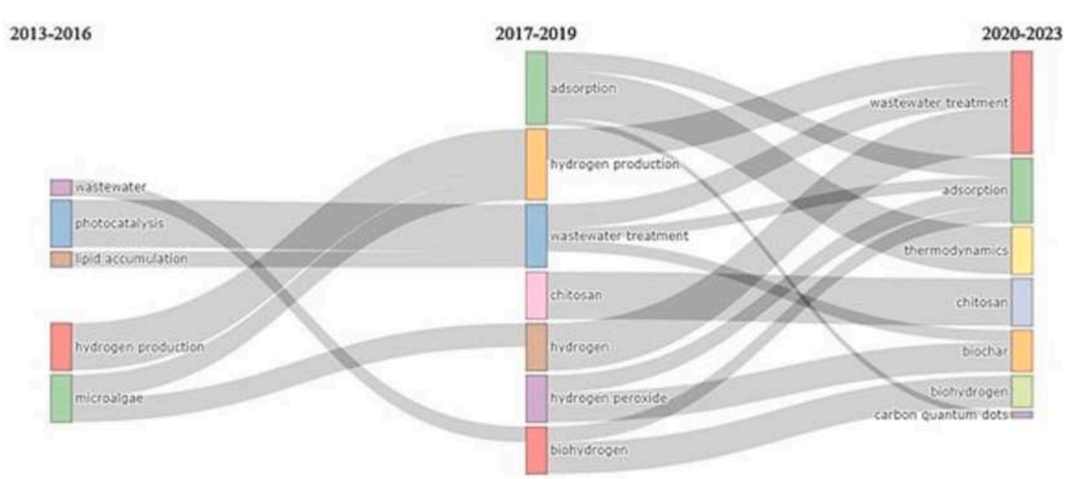

Fig. 8. Author keywords evolution.

convergence of various disciplines, such as materials science, chemical engineering, and biotechnology, to address challenges in hydrogen production from wastewater. The exploration of new materials (e.g., carbon quantum dots) and processes (e.g., biohydrogen production, adsorption) suggests the potential for technological breakthroughs and improved efficiency in hydrogen production from wastewater. The consistent presence of keywords like “wastewater treatment” and “adsorption” highlights the importance of developing practical and scalable solutions for real-world applications. The appearance of new keywords in the latest period (2020–2023), such as “carbon quantum dots” and “thermodynamics,” suggests emerging research opportunities that could lead to novel insights and advancements in the field.

Fig. 9 shows a factorial analysis based on author keywords. The figure displays the keywords distributed along two dimensions, Dim 1 (16.47 %) and Dim 2 (9.89 %). It can be observed that, along the horizontal Dim 1 axis has a gradient of keywords ranging from waste treatment and remediation on the left side to more advanced processes and materials on the right side. On the left side, keywords such as “waste water treatment,” “green water treatment,” “response surface methodology,” and “Congo red” suggest a focus on conventional wastewater treatment methods, dye removal, and optimization techniques. Moving towards the center, keywords like “activated carbon,” “uranium,” “olive mill wastewater,” and “wastewater treatment” indicate research related to adsorption processes, heavy metal removal, and industrial wastewater treatment. On the right side, keywords such as “steam reforming,” “kinetics,” “isotherms,” and “photoelectrocatalysis” represent more advanced and emerging themes related to hydrogen production processes, catalyst kinetics, adsorption isotherms, and photoelectrochemical approaches.

Conversely, along the vertical Dim 2 axis, exist a distinction between themes related to hydrogen production and oxidation processes at the top, and themes associated with wastewater treatment and electrochemical processes at the bottom. The top region features keywords like “urea oxidation,” “hydrogen,” “hydrogen evolution reaction,” and “photoelectrocatalysis,” indicating research focused on hydrogen production through oxidation reactions and photoelectrochemical methods. In contrast, the bottom region includes keywords such as “electrocatalysis,” “waste water treatment,” and “green water treatment,” suggesting research areas related to electrochemical processes and conventional wastewater treatment methods.

Fig. 9 illustrates the diverse range of research areas encompassed within the field of hydrogen production from wastewater, spanning from conventional waste treatment to advanced materials and processes. The presence of keywords like “steam reforming,” “photoelectrocatalysis,” and “kinetics” suggests an interest in exploring emerging technologies and processes for more efficient hydrogen production from wastewater. Keywords related to industrial wastewater, such as “olive mill wastewater” and “activated carbon,” indicate research aimed at addressing practical industrial applications and treatment challenges. The distribution of keywords along the two dimensions suggests potential opportunities for integrating different approaches, such as combining advanced hydrogen production processes with wastewater treatment methods or incorporating adsorption and electrochemical techniques. Several themes, from materials science to electrochemistry and process engineering, implies the need for interdisciplinary collaborations to address the complex challenges in this field. It is worth mentioning that, this factorial analysis provides insights into the breadth of research areas, emerging technologies, and potential synergies within the field of hydrogen production from wastewater, highlighting the dynamic and interdisciplinary nature of this research domain.

3.4. Analysis of keywords

Fig. 10 displays the most frequent keywords and their respective frequencies. Likewise, the word cloud of author keywords is shown in Fig. 11. The results show a high frequency of terms like “adsorption,” “wastewater treatment,” “hydrogen production,” “photocatalysis,” “biohydrogen,” “hydrogen evolution reaction,” “electrocatalysis,” and “water electrolysis.” The implication is that these topics and processes are central to the research efforts in green hydrogen production from wastewaters.

The adsorption processes, mainly using materials like “biochar” and “activated carbon,” seem to play a significant role in treating wastewaters and potentially facilitating hydrogen production. Photocatalytic processes and electrocatalytic processes, such as the “hydrogen evolution reaction” and “oxygen reduction reaction,” appear to be actively explored as means for hydrogen generation from wastewaters. The presence of terms like “microbial fuel cell” and “bio-hydrogen” indicates the involvement of biological and microbial processes in hydrogen production from wastewaters.

Likewise, materials like “malachite green,” “methylene blue,” “congo red,” and “dyes” frequently appear, suggesting their use as model pollutants or target compounds for wastewater treatment and hydrogen production studies. The term “nanocomposite” implies the exploration

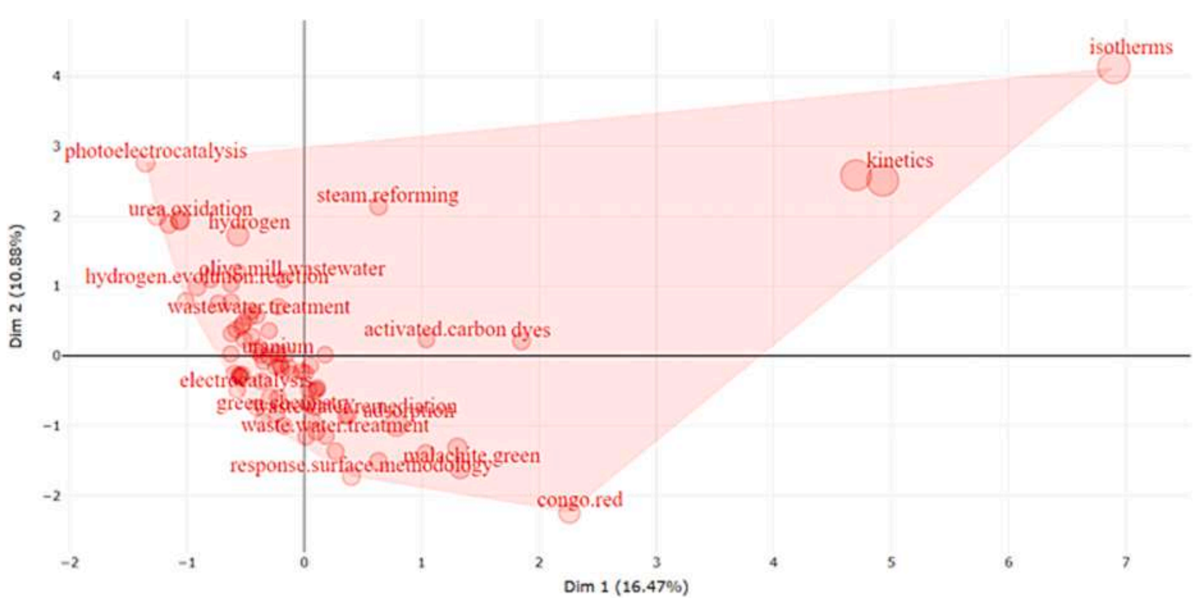

Fig. 9. Factorial analysis.

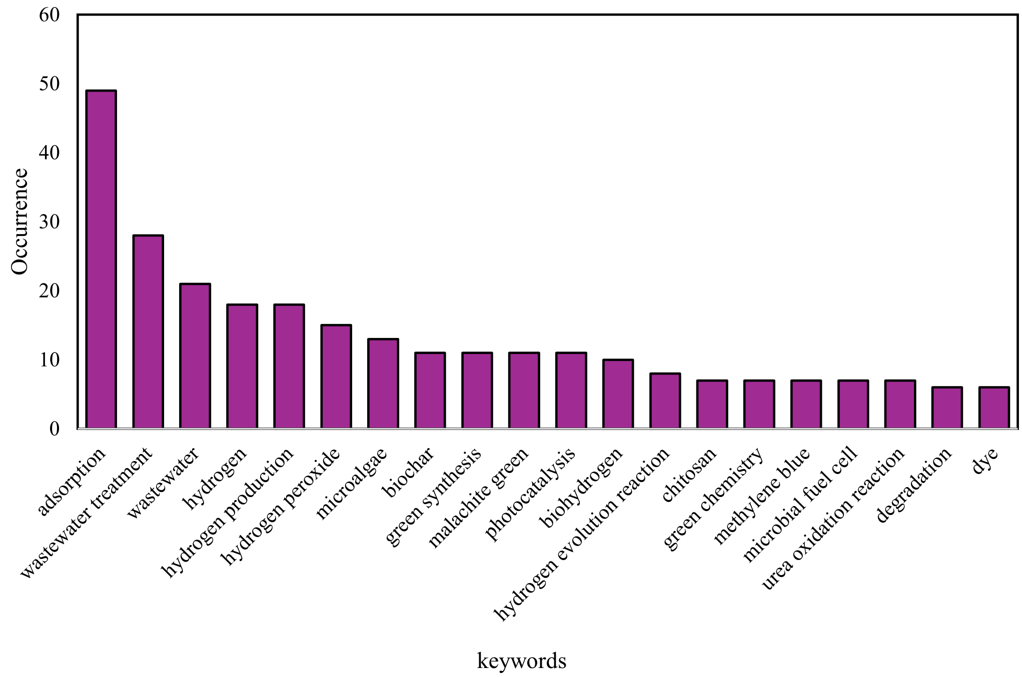

Fig. 10. Most relevant keywords.

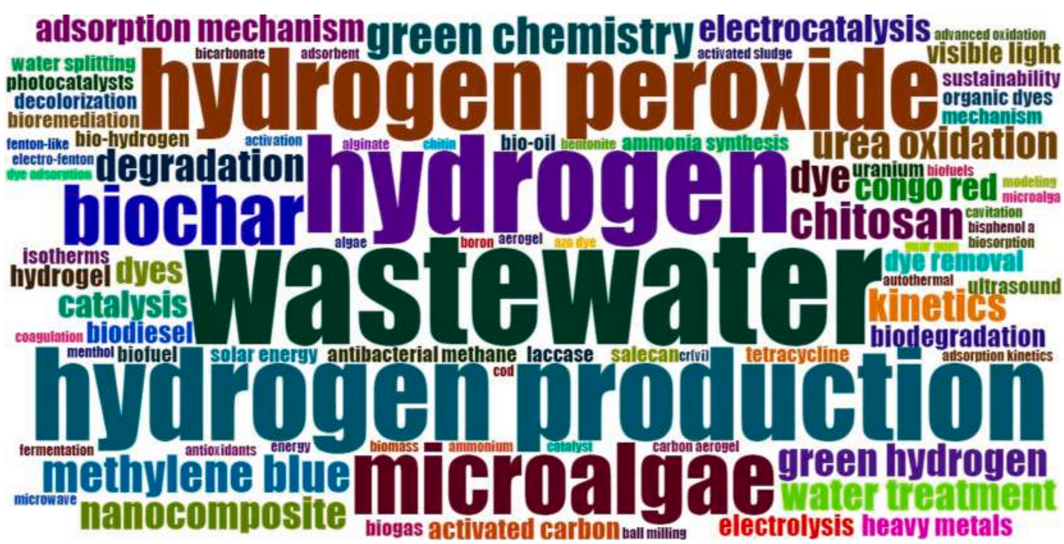

Fig. 11. Word cloud for author keywords (150 words).

of nanomaterials and their composites as potential catalysts or adsorbents in these processes. “Chitosan” and “hydrogel” appear as materials of interest, possibly for their adsorption or catalytic properties.

Similarly, the occurrence of terms like “green synthesis,” “green chemistry,” and “green hydrogen” highlights the emphasis on environmentally friendly and sustainable approaches to hydrogen production from wastewaters. Terms such as “biodiesel,” “bio-oil,” and “biofuel” suggest potential applications or byproducts of the wastewater treatment and hydrogen production processes. The presence of “antibacterial” could indicate studies on the antibacterial properties of materials or processes related to wastewater treatment and hydrogen production. Correspondingly, terms like “kinetics,” “thermodynamics,” “response surface methodology,” and “adsorption mechanism” highlight the use of analytical and computational techniques to understand and optimize the processes involved in green hydrogen production from wastewaters.

The trend of various topics related over time is presented in Fig. 12. The results are summarized into early research trends, established and persistent topics, and emerging and recent trends. The topics “microalgae,” “degradation,” and “kinetics” are categorized as early research trends. The implication is that these were among the initial focus areas in the research on green hydrogen production from wastewaters. It can be seen that the use of microalgae for wastewater treatment and hydrogen production has been explored since around 2016, reflecting the interest in biological approaches and the potential of microalgae as a renewable resource. Studies on the degradation of various pollutants and the kinetics of processes involved in wastewater treatment and hydrogen generation were also prevalent in the early stages of this research field.

Similarly, the established and persistent topics comprise terms like “wastewater,” “biohydrogen,” and “dye.” The suggest that these topics have been consistently researched over an extended period. Wastewater treatment and biohydrogen production have been core areas of focus,

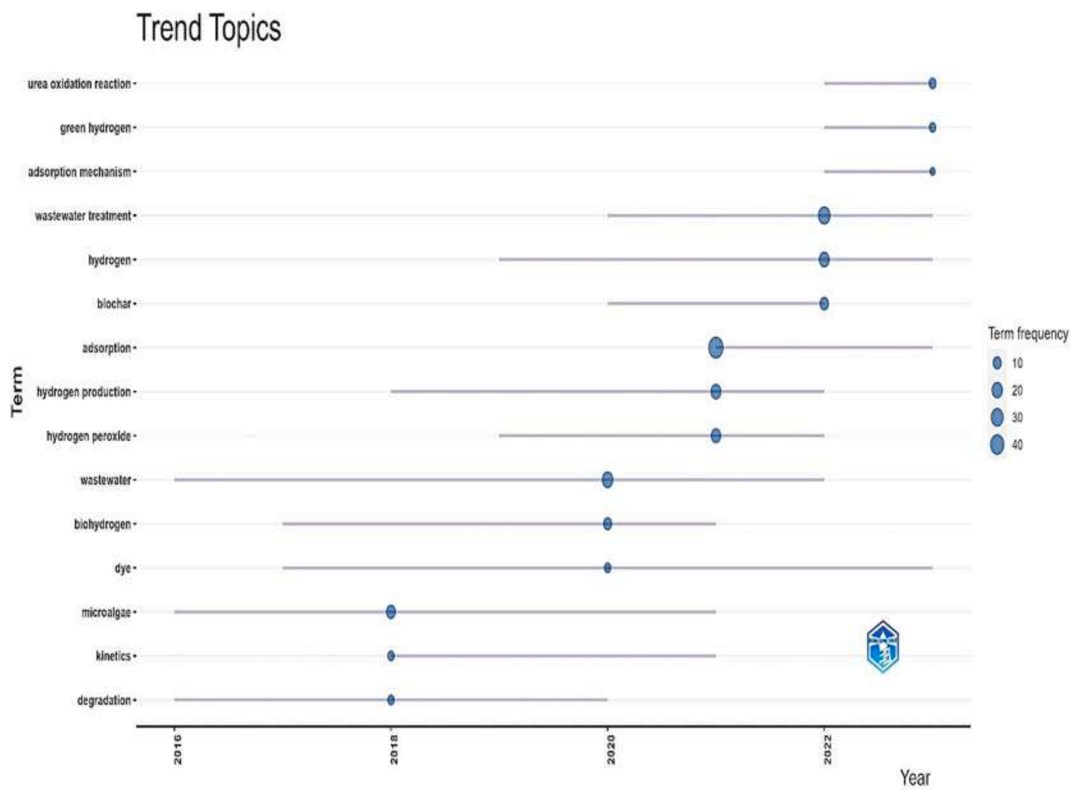

Fig. 12. Trend of topics.

indicating the fundamental goals of this research area. The presence of "dye" indicates using dyes as model pollutants for studying wastewater treatment processes and their integration with hydrogen production.

Furthermore, emerging and recent trends consist of topics such as "adsorption," "hydrogen production," "hydrogen peroxide," "wastewater treatment," "hydrogen," "biochar," "urea oxidation reaction," "green hydrogen," and "adsorption mechanism," indicating their growing importance in recent years. The increasing interest in adsorption processes, particularly using materials like biochar, suggests exploring efficient and sustainable methods for wastewater treatment and potential integration with hydrogen production. The focus on "hydrogen production," "hydrogen peroxide," and "green hydrogen" highlights the emphasis on developing and optimizing processes for generating hydrogen from wastewaters in an environmentally friendly manner. The emergence of terms like "urea oxidation reaction" and "adsorption mechanism" indicates a deeper understanding of these systems' underlying processes and mechanisms.

The evolution of research topics pinpoints the progression of this field, starting from fundamental studies on microalgae, degradation, and kinetics and gradually moving towards more applied aspects like adsorption, wastewater treatment, and hydrogen production processes. The persistent focus on topics like wastewater treatment and biohydrogen production demonstrates the core objectives of this research area, which are to develop sustainable solutions for waste valorization and clean energy generation. The recent trends suggest a shift towards more advanced and specialized topics, such as adsorption mechanisms, urea oxidation reactions, and green hydrogen production, indicating the maturation of this field and the pursuit of more efficient and environmentally friendly processes. The integration of various topics, including adsorption, biochar, wastewater treatment, and hydrogen production, highlights the interdisciplinary nature of this research area and the potential for synergistic approaches combining different technologies and processes. The increasing emphasis on "green hydrogen" and environmentally friendly processes aligns with global efforts towards sustainable development and the transition towards a circular economy, where waste is transformed into valuable resources.

3.5. Journals, collaboration, and other disciplines

3.5.1. Most relevant sources

A thorough grasp of the international scientific scene can be gained from a bibliometric analysis of the leading publishing nations and journals. This analysis can reveal information about research leadership, collaboration trends, and the function of national funding and policy. It facilitates benchmarking progress and helps shape future research agendas by identifying important journals for the dissemination of high-impact research. The most relevant sources (i.e., journals) and their corresponding number of articles are shown in Fig. 13. The results indicate that the top sources include high-impact journals such as Bioresource Technology, Chemical Engineering Journal, Journal of Environmental Chemical Engineering, Journal of Cleaner Production, and International Journal of Hydrogen Energy. These journals cover broad areas of environmental engineering, chemical engineering, cleaner production processes, and hydrogen energy, indicating the multidisciplinary nature of this research field. On the other hand, several specialized journals focused on specific research areas are well-represented, such as Separation and Purification Technology, Colloids and Surfaces A: Physicochemical and Engineering Aspects, International Journal of Biological Macromolecules, and RSC Advances. These journals highlight the diversity of research approaches and methodologies employed in green hydrogen production from wastewaters, and they concentrate on separation processes, colloidal and interfacial phenomena, biological macromolecules, and general chemical sciences. It can be seen that, the list includes some relatively new or emerging journals, such as ACS Sustainable Chemistry and Engineering, ACS Omega, and Sustainable Energy and Fuels, dedicated to sustainable processes, green chemistry, and renewable energy technologies. These journals indicate the growing interest and focus on sustainable and environmentally friendly approaches to hydrogen production from wastewaters.

A bibliometric analysis of country-level collaboration offers a

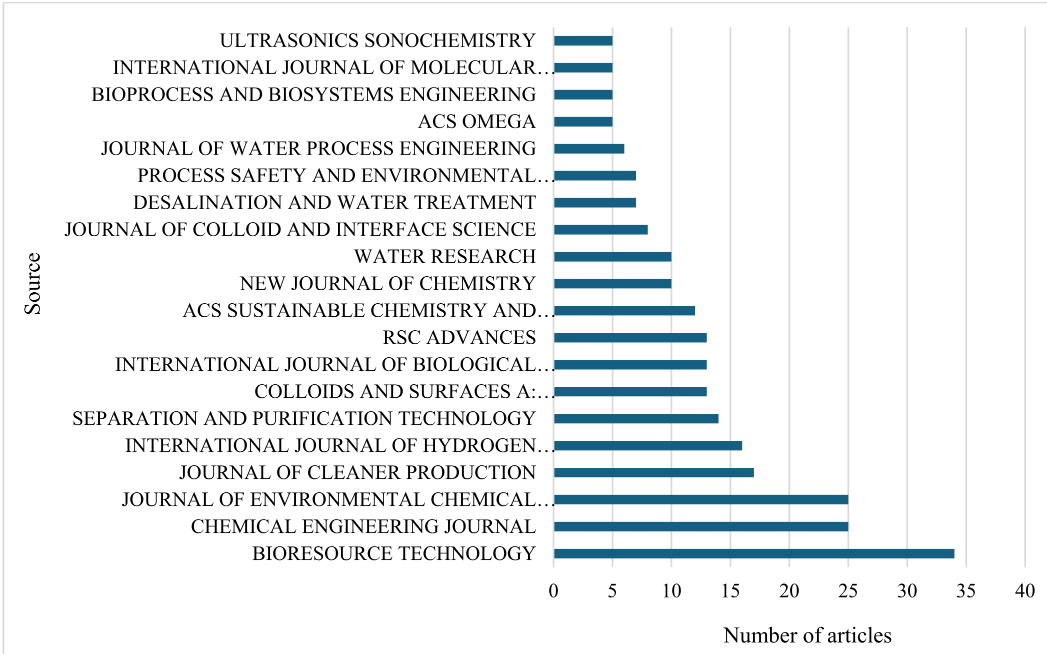

Fig. 13. Most relevant sources.

thorough understanding of international research, highlighting its advantages and disadvantages, advancing equity, and pointing out new areas of study. This analysis supports the creation of plans for strengthening international research cooperation, raising the caliber and influence of science, and tackling global issues. Fig. 14 shows the frequency of collaboration between countries. The results shows a diverse range of country collaborations spanning various regions, including Asia, Europe, North America, South America, Africa, and Oceania. This global distribution of collaborations highlights the widespread interest and research efforts in green hydrogen production from wastewaters, as well as the recognition of the potential benefits of international cooperation in this field. It can be observed that China has emerged as a major research hub, with numerous collaborations involving countries such as Australia, Canada, India, Iran, Malaysia, Pakistan, Saudi Arabia, Singapore, Thailand, the United Kingdom, and the United States. Other countries with significant collaboration networks include India, Iran, Korea, Malaysia, Pakistan, Saudi Arabia, the United Kingdom, and the United States. These countries appear to be actively engaged in international research partnerships, leveraging the expertise and resources of multiple nations.

Furthermore, the results show several instances of regional collaborations, such as within Asia (e.g., China-India, China-Malaysia, India-Thailand), Europe (e.g., Germany-Austria, Germany-Poland, France-Finland), and the Middle East (e.g., Saudi Arabia-Kuwait, Turkey-Oman). The regional collaborations may be facilitated by geographical proximity, shared research interests, and existing scientific networks or

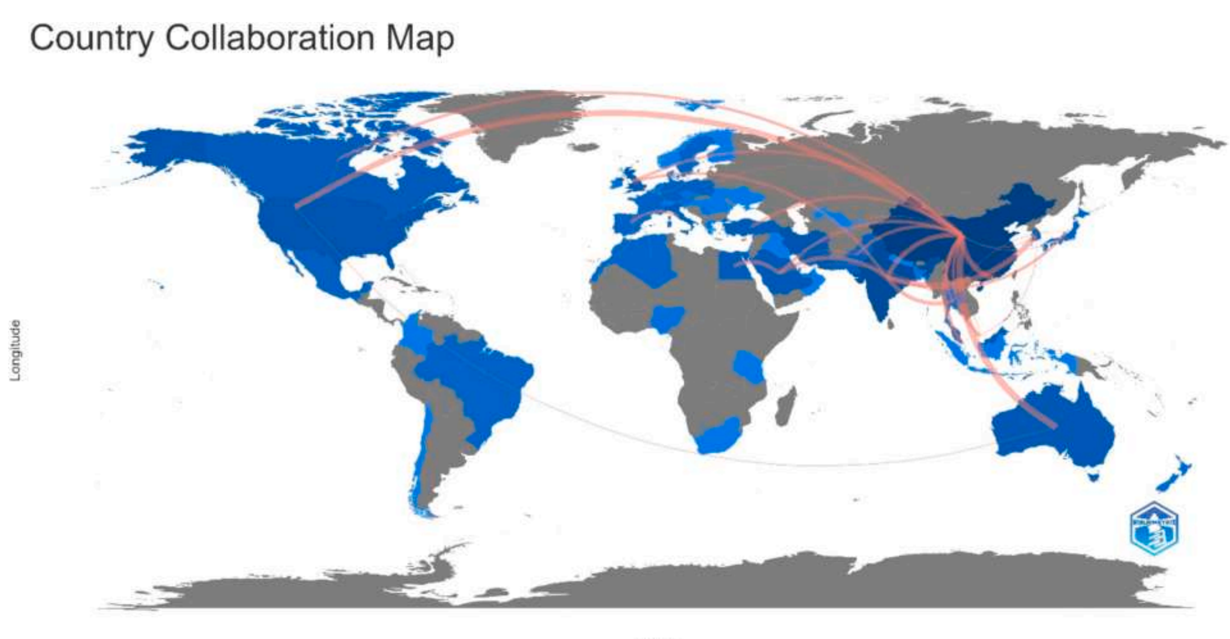

Fig. 14. Countries collaboration map.

collaborations in related fields. While regional collaborations are present, the results also show instances of intra-regional collaborations, such as China-Australia, India-Algeria, and Saudi Arabia-Belgium. These intra-regional collaborations suggest the existence of extended research networks and the willingness of countries to collaborate beyond their immediate geographical regions.

3.5.2. Corresponding authors countries

Fig. 15 displays the single country production (SCP) and multiple country production (MCP) articles produced for various countries. It can be deduced from the figure that for most countries listed, the number of articles with SCP is higher than those with MCP. This implies that, a significant portion of research being conducted within national boundaries. Countries like China, India, Iran, Egypt, USA, Korea, Turkey, Mexico, Portugal, Germany, and Saudi Arabia have a notably higher SCP count than MCP, suggesting a strong domestic research base and focus on this topic. While SCP dominates, several countries exhibit substantial MCP counts, indicating active international collaborations in this research area. China, India, Malaysia, Iran, and Pakistan stand out with relatively higher MCP numbers, suggesting their involvement in collaborative research efforts with other countries. The MCP numbers for the United Kingdom, Australia, Sweden, Morocco, and Saudi Arabia also indicate their participation in international collaborations, albeit to a lesser extent.

The presence of both SCP and MCP across various regions, including Asia, Europe, North America, South America, and the Middle East, highlights the global interest and research efforts in green hydrogen production from wastewaters. Countries within close geographical proximity, such as Southeast Asia or the Middle East, may have stronger collaborations due to shared regional interests, resources, and research networks. Countries with a high SCP count may possess strong domestic research capabilities, funding resources, and infrastructures to support independent research in this field. On the other hand, countries with higher MCP counts may seek international collaborations to leverage complementary expertise, resources, or infrastructures that are not readily available domestically.

3.5.3. Most relevant affiliations or institutions

The most relevant affiliations and their respective number of articles produced are displayed in Fig. 16. It can be observed that several Chinese universities and research institutions dominate the list, indicating China's strong focus and significant contributions to this research area. Notable institutions include Northwest A&F University, Huazhong University of Science and Technology, Hunan University, Sichuan University, Zhejiang University, Anhui Agricultural University, and Guangxi University. Other prominent institutions from various countries include Nanyang Technological University (Singapore), Chulalongkorn University (Thailand), King Saud University (Saudi Arabia), National Institute of Technology (India), National Kaohsiung University of Science and Technology (Taiwan), University of Porto (Portugal), and The University of Adelaide (Australia). While Chinese institutions have a significant presence, there is also representation from other countries and regions, such as Southeast Asia (e.g., Singapore, Thailand), the Middle East (e.g., Saudi Arabia), South Asia (e.g., India), Europe (e.g., Portugal), and Australia. This geographic distribution suggests a global interest and research efforts in green hydrogen production from wastewaters, reflecting the widespread recognition of its potential and the international collaboration in this field.

The affiliations cover various institutions, including universities, research centers, and agricultural universities, indicating a multidisciplinary approach to this research area. The presence of agricultural universities, such as Anhui Agricultural University and Hunan Agricultural University, suggests a focus on the biological and agricultural aspects of wastewater treatment and hydrogen production processes. Institutions like the Research Center of Lake Restoration Technology Engineering for Universities of Yunnan Province and the Institute of Chemical Industry of Forestry Products highlight specialized research centers dedicated to environmental remediation and sustainable processes. The list includes institutions from various countries, indicating the potential for international collaboration and knowledge sharing in this research field. Cross-institutional collaborations within and across countries can facilitate the exchange of expertise, resources, and best practices, driving further advancements in green hydrogen production from wastewaters.

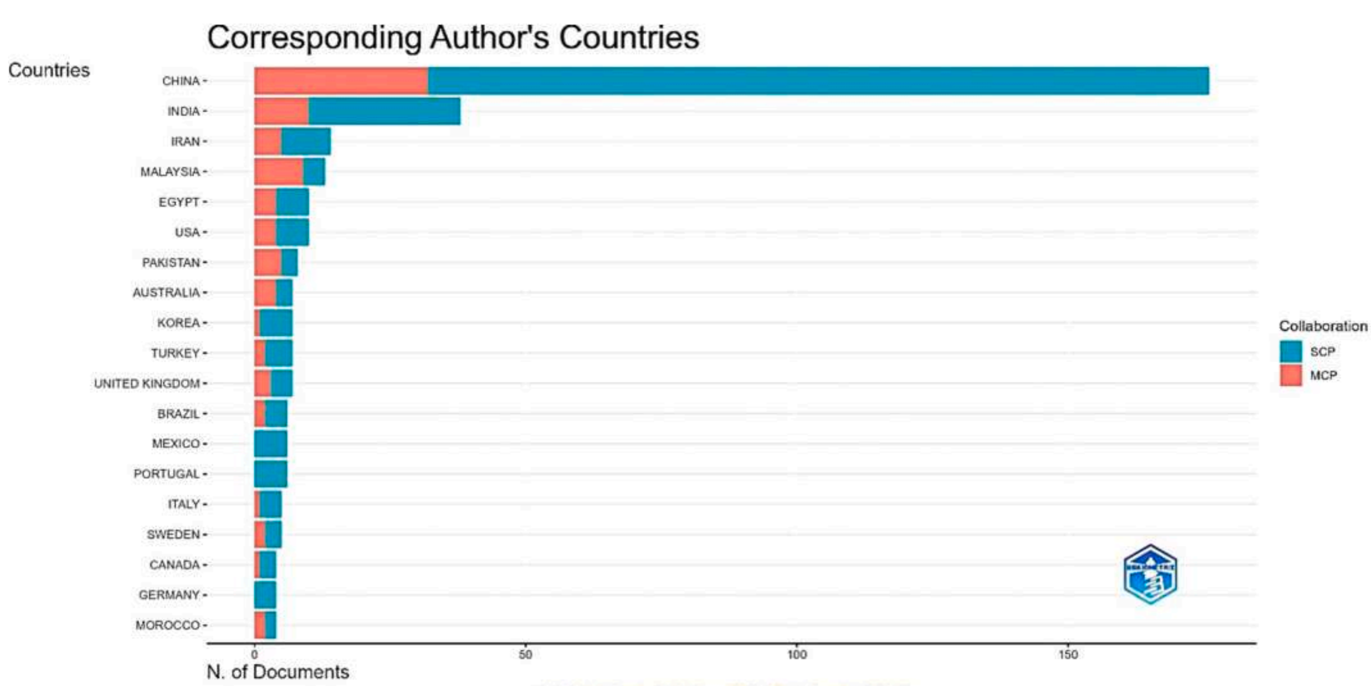

Fig. 15. Corresponding authors' countries.

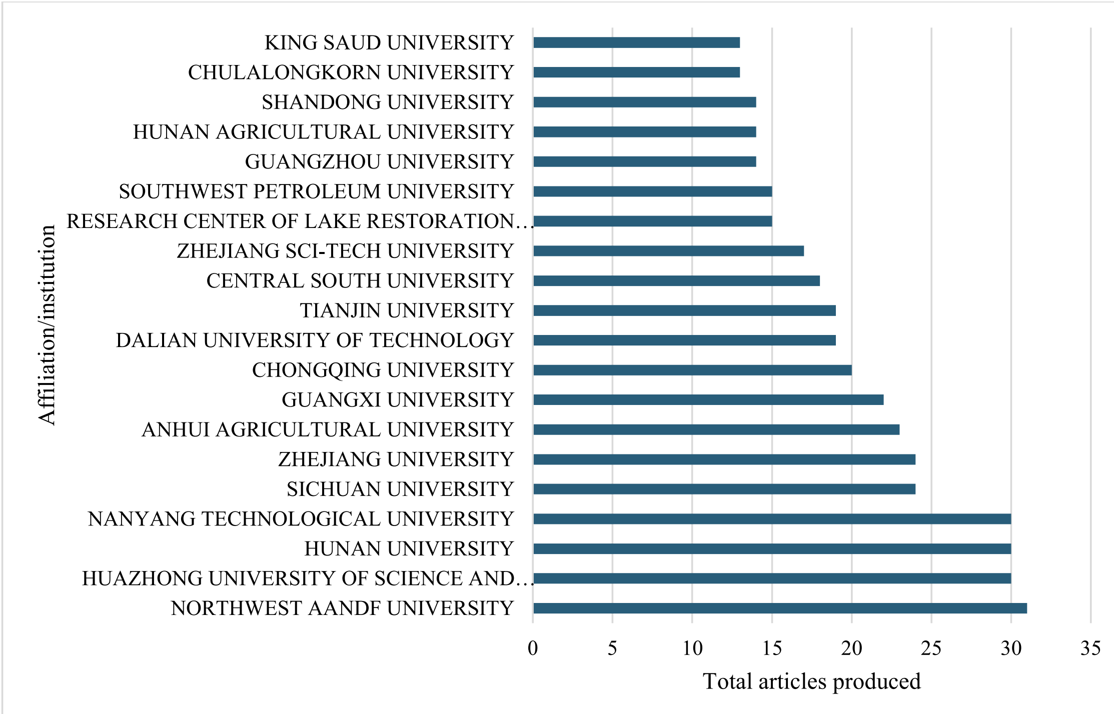

Fig. 16. Most relevant affiliations.

3.5.4. *Most cited countries*

Fig. 17 presents the top 20 most cited countries. Generally, the total citations (TC) and average article citations indicate the impact and influence of a country's research contributions in this field. It can be seen that countries like China, India, Malaysia, Iran, and Egypt emerge as prominent research hubs in this field, with high TC and decent average article citations. These countries likely possess well-established research programs, dedicated resources, and a critical mass of researchers contributing to advancing green hydrogen production from wastewater. Countries with relatively lower TC but higher average article citations, such as Poland, the United Arab Emirates, and Belgium, indicate that their research contributions, although fewer in number, have a significant impact and are highly cited. This pattern suggests that these countries may produce high-quality, influential research in specific areas or sub-domains of green hydrogen production from wastewater. Countries like Brazil and Singapore, while having lower TC and average article citations than others, still demonstrate research activity and contributions to this field. These countries may represent emerging research hubs or have recently increased their focus on this topic, potentially indicating future growth in their research outputs and

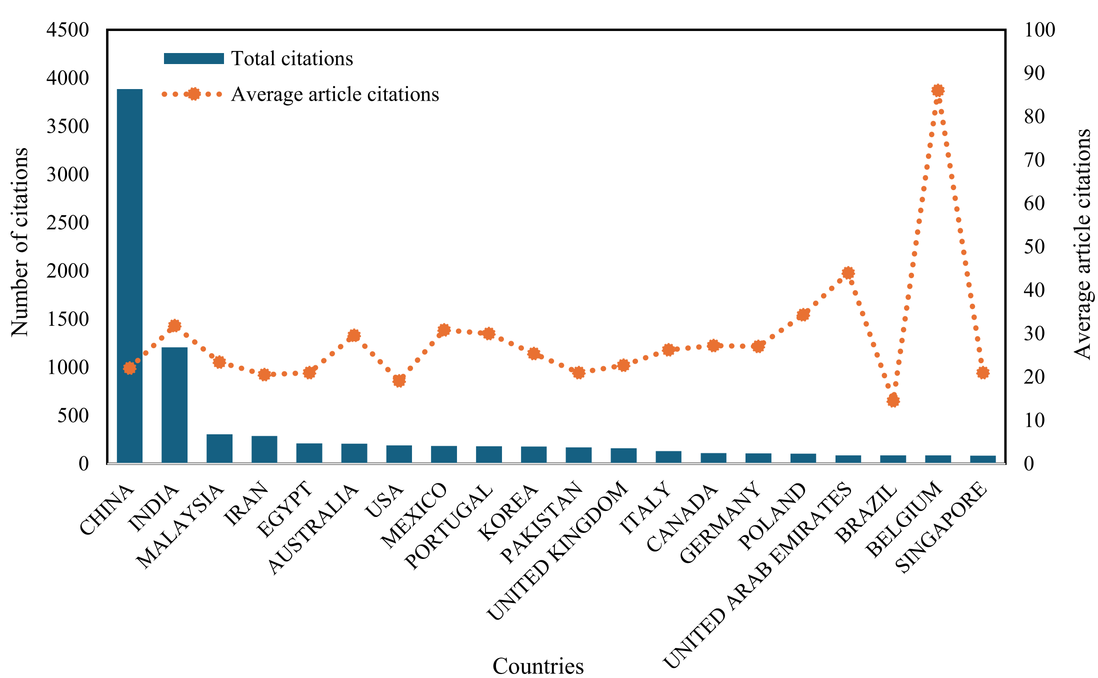

Fig. 17. Most cited countries.

impact.

3.5.5. Most globally cited papers

Table 1 presents the most cited papers on green hydrogen production from wastewater. The paper with the highest total citations is "GAUTAM S, 2020, with 259 citations, followed by "DAI L, 2018, with 177 citations. These papers have had a significant impact on the field. Several highly cited papers were published in recent years, such as "GAUTAM S, 2020″ (51.8 citations per year), "LIU C, 2020 (26.2 citations per year), and "REN W, 2020 (18.2 citations per year). This suggests that research in this area is active and growing, with new developments attracting substantial attention. The papers are published in various journals, including "Bioresource Technology," "Chemical Engineering Journal," "Applied Catalysis B: Environmental," and "International Journal of Hydrogen Energy." These journals appear to be prominent outlets for research on green hydrogen production from wastewater, indicating their importance in the field. Based on the titles and journal names, the papers cover diverse topics related to green hydrogen production from wastewater, such as catalytic processes, nanomaterials, bioprocesses, and environmental engineering aspects.

3.5.6. Most local cited

Table 2 presents the top 20 most locally cited authors and their respective number of fractionalized articles. It can be observed that the list is dominated by authors with common Chinese surnames like WANG, ZHANG, LI, LIU, CHEN, AND YANG. This highlights the significant contributions of Chinese researchers to this field. It is worth mentioning that authors such as WANG Y, ZHANG Y, LI Y, ZHANG H, ZHANG J, ZHANG X, LIU Y, and WANG X have the highest number of articles. This indicates the authors' significant research contributions and expertise in this area. On the other hand, the fractionalized article counts provide a more accurate representation of an author's contribution by considering the number of co-authors for each article. It can be seen that authors like WANG Y, ZHANG Y, LI Y, ZHANG H, ZHANG X, and WANG W have relatively high fractionalized article counts, suggesting their substantial individual contributions to the research in this field.

3.5.7. Three field plots

Fig. 18 presents the three-field plot analysis. The keywords related to the research topic are displayed on the left side. These include materials like malachite green, methylene blue, urea oxidation reaction, photocatalysts, and processes such as adsorption, hydrogen peroxide, hydrogen evolution reaction, and wastewater treatment. The countries involved in this research area are shown in the middle section. China appears to be the most prominent country, followed by Singapore and India.

Other countries like Saudi Arabia, the United Kingdom, Malaysia, Portugal, Egypt, and Turkey are also represented. The right side of the plot displays the affiliations of the researchers working on green hydrogen production from wastewater. Several universities from China, such as Nanyang Technological University, Huazhong University of Science and Technology, Zhejiang University, and Northwest A&F University, are listed. Other notable affiliations include Central South University (China), Southwest Petroleum University (China), Dalian University of Technology (China), and Guangzhou University (China). The implications of these results suggest that research on green hydrogen production from wastewater is a globally pursued area, with significant contributions from countries like China, Singapore, and India. The involvement of various universities and research centers indicates the academic and scientific interest in this field. The diverse range of keywords highlights the multidisciplinary nature of this research, encompassing materials science, catalysis, water treatment, and hydrogen production technologies. The findings may have implications for developing sustainable and environmentally friendly processes for hydrogen production, utilizing wastewater as a resource.

Table 1
Top 50 globally cited papers.

Ranking	Author and source	Total citations (TC)	TC per year
1	GAUTAM S, 2020, J ENVIRON CHEM ENG	259	51.80
2	DAI L, 2018, BIORESOUR TECHNOL	177	25.29
3	SENTHIL KUMAR P, 2018, BIORESOUR TECHNOL	164	23.43
4	LUO L, 2016, BIORESOUR TECHNOL	155	17.22
5	MOHAMED MA, 2016, CHEM ENG J	150	16.67
6	PAN Z, 2018, APPL CATAL B ENVIRON	145	20.71
7	SACRISTÁN DE ALVA M, 2013, BIORESOUR TECHNOL	132	11.00
8	LIU C, 2020, CHEM ENG J	131	26.20
9	NAIR V, 2016, BIORESOUR TECHNOL	101	11.22
10	REN W, 2020, WATER RES	91	18.20
11	QIN P, 2018, NANOMATERIALS	90	12.86
12	KADIER A, 2015, INT J HYDROGEN ENERGY	89	8.90
13	MA X, 2016, BIORESOUR TECHNOL	87	9.67
14	FANG Y, 2017, ACS SUSTAINABLE CHEM ENG	87	10.88
15	ZUORRO A, 2014, DESALIN WATER TREAT	87	7.91
16	GHIMIRE A, 2017, BIORESOUR TECHNOL	86	10.75
17	MEERBERGEN K, 2018, J BIOSCI BIOENG	86	12.29
18	WANG T, 2019, CHEM ENG J	86	14.33
19	LIZZUL AM, 2014, BIORESOUR TECHNOL	86	7.82
20	NGUYEN V-H, 2018, APPL CATAL A GEN	84	12.00
21	GERCHMAN Y, 2017, BIORESOUR TECHNOL	82	10.25
22	MITTAL H, 2020, COLLOIDS SURF A PHYSICOCHEM ENG ASP	81	16.20
23	TAN X-B, 2016, BIORESOUR TECHNOL	80	8.89
24	CHEN Y, 2020, RSC ADV	79	15.80
25	SINGH HM, 2019, BIOFUELS	76	12.67
26	FERREIRA A, 2017, J CLEAN PROD	75	9.38
27	KHAFRI HZ, 2017, ULTRASON SONOCHEM	74	9.25
28	ZDARTA J, 2019, MATER SCI ENG C	73	12.17
29	ALJOHANI MM, 2023, PROCESS SAF ENVIRON PROT	71	35.50
30	SAMARI F, 2018, NEW J CHEM	71	10.14
31	GUAN Y, 2019, INT J BIOL MACROMOL	70	11.67
32	BANSAL M, 2018, INT J BIOL MACROMOL	70	10.00
33	GUO Z, 2023, CHEM ENG J	64	32.00
34	YIN K, 2018, CHEM ENG J	64	9.14
35	HAIDER Z, 2019, CATAL TODAY	64	10.67
36	SHEN Y, 2014, BIOPROCESS BIOSYST ENG	61	5.55
37	GE L, 2021, WATER RES	60	15.00
38	JAFFARI ZH, 2019, MATER SCI SEMICOND PROCESS	60	10.00
39	MANIVASAGAN P, 2015, INT J BIOL MACROMOL	59	5.90
40	ZHU S, 2020, J CLEAN PROD	58	11.60
41	DELPIANO GR, 2021, INT J MOL SCI	57	14.25
42	WANG R-F, 2020, CERAM INT	56	11.20
43	LIANG R, 2013, J NANOPART RES	56	4.67
44	DANOUCHE M, 2020, J ENVIRON CHEM ENG	55	11.00
45	ALI I, 2019, RSC ADV	55	9.17
46	PATRA AS, 2017, BIORESOUR TECHNOL	55	6.88
47	RAHIMI AQDAM S, 2021, J COLLOID INTERFACE SCI	54	13.50
48	FENG C, 2020, NEW J CHEM	53	10.60
49	ZHAO X-C, 2019, BIORESOUR TECHNOL	53	8.83
50	YUVARAJA G, 2019, INT J BIOL MACROMOL	52	8.67

Table 2
Ranking of the top 20 most locally cited authors.

Ranking	Authors	Articles	Articles fractionalized
1	WANG Y	21	2.95
2	ZHANG Y	15	1.98
3	LI Y	13	1.83
4	ZHANG H	12	1.75
5	ZHANG J	12	1.51
6	ZHANG X	11	1.72
7	LIU Y	10	1.49
8	WANG X	10	1.17
9	WANG S	9	1.34
10	WANG Z	9	1.20
11	ZHANG L	9	1.07
12	HU J	8	1.19
13	LI H	8	1.08
14	WANG W	8	1.29
15	CHEN Y	7	0.97
16	CHEN Z	7	1.02
17	LI X	7	0.96
18	LIU X	7	1.21
19	YANG Y	7	0.87
20	CAO Y	6	1.14

3.6. Review of top-cited papers

This section presents the findings and recommendations from the top-cited papers in the study period. The top cited papers are grouped into the following areas for systematic review: (1) Photocatalysis and advanced oxidation processes, (2) biological treatment and microalgae cultivation, and (3) adsorption and adsorbents.

3.6.1. Photocatalysis and advanced oxidation processes

Photocatalysis involves using catalysts to accelerate chemical reactions using light energy [72,73]. In the context of hydrogen production, photocatalysis typically involves using photocatalysts like titanium dioxide (TiO_2), which can absorb photons from sunlight and initiate chemical reactions that result in the splitting of water molecules into hydrogen and oxygen [74]. This process is often termed "photocatalytic water splitting." On the other hand, advanced oxidation processes (AOP) comprise several techniques that utilize highly reactive oxygen species to degrade organic pollutants or facilitate chemical reactions [9]. In hydrogen production, AOPs can decompose water into hydrogen and oxygen. One common AOP used for this purpose is photocatalytic oxidation, where a semiconductor photocatalyst (such as TiO_2) generates reactive oxygen species under light irradiation. These species then react with water molecules, leading to the formation of hydrogen gas [75–77]. In view of this, authors that investigate the photocatalysis and advanced oxidation processes include Gautam et al. [78], who reviewed the properties, synthesis, structures, and applications of metal–organic frameworks (MOFs) and metal oxides, emphasizing their efficacy in wastewater photocatalysis. The authors highlighted that MOFs and metal oxides have high surface area and cost-effectiveness for diverse applications. Also, photocatalysis, especially with MOFs and metal oxides, efficiently treats wastewater by converting solar energy, aiding in contaminant removal. The authors proposed hydrogen generation via catalytic hydrolysis as a future research prospect for researchers. Mohamed et al. [79] developed green photocatalytic membranes using recycled newspapers, enhancing sustainability through phase inversion. The Fourier-transform infrared spectroscopy analysis revealed strong hydrogen bonding between cellulose and TiO_2 nanorods. Ultraviolet–visible spectroscopy and XPS confirmed enhanced visible light absorption due to nitrogen doping. In addition, membranes with 0.5 wt % TiO_2 exhibited optimal photocatalytic performance degrading phenol under ultraviolet and visible light.

Pan et al. [80] in their study introduced an economical activated graphite felt (AGF) material developed through a simple and low-cost activation method. The authors observed that the enhanced electrochemical performance of AGF for H_2O_2 production is attributed to its specific pore structure, high content of defects, and surface chemical transformations achieved through gaseous acetic acid activation. This advancement holds promise for cost-effective and efficient electrocatalysts in H_2O_2 synthesis, contributing to green chemical industries and environmental remediation efforts. Qin et al. [81] developed an efficient method for rapidly removing cationic dyes using monodispersed mesoporous silica nanoparticles as adsorbents. It was

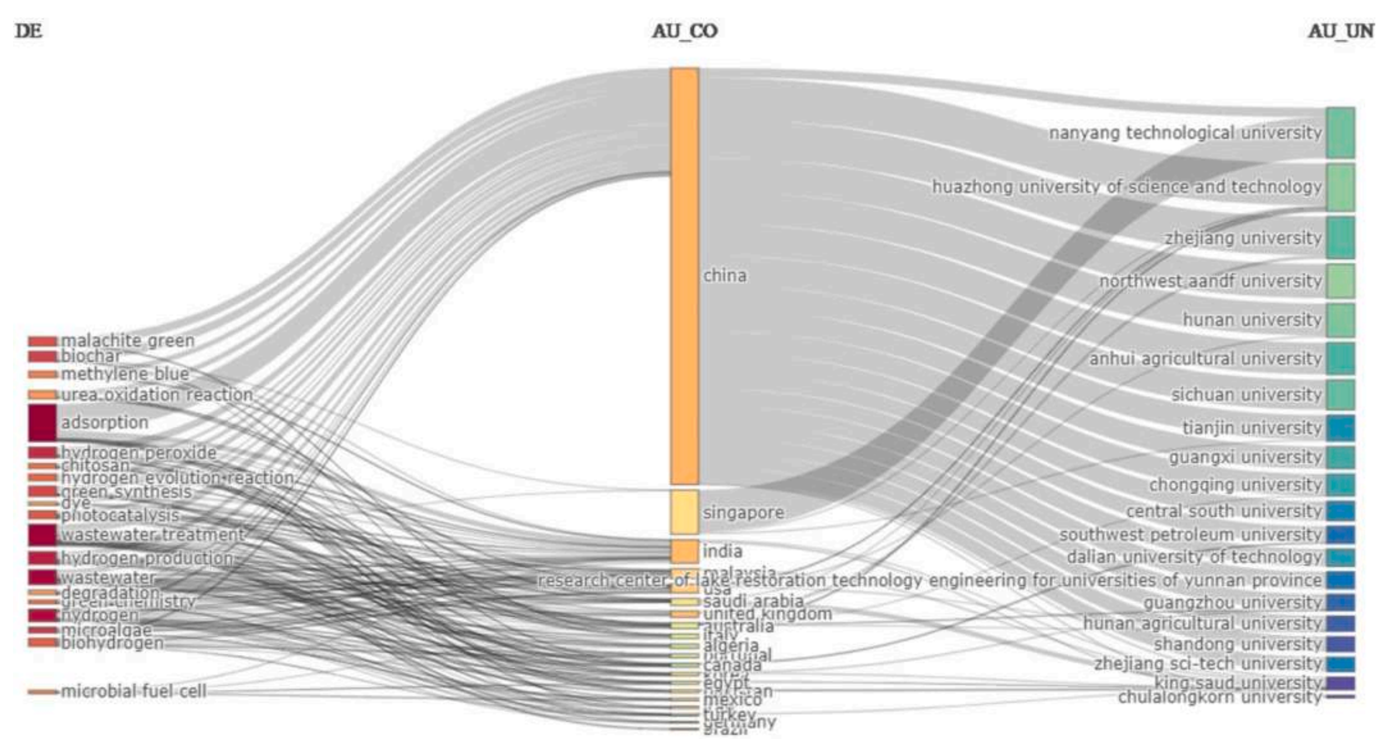

Fig. 18. Three-field plot. Left (keywords), Middle (country), and Right (affiliation).

observed that the mesoporous silica nanoparticles exhibited rapid and efficient adsorption of cationic dyes, including rhodamine B, methylene blue, methyl violet, malachite green, and basic fuchsin. Maximum capacities ranged from 14.70 mg/g to 34.23 mg/g under optimized conditions within 2 to 6 min. The adsorption mechanism involved electrostatic interactions and hydrogen bonding.

Ghimire et al. [82] reviewed recent advancements in converting microalgae biomass to produce bio-hythane, crucial for wastewater treatment and liquid biofuels. The authors indicated that biomass and by-product residues from microalgae processes can be utilized as feedstock for anaerobic fermentation to produce gaseous biofuels. Also, dark fermentation coupled with anaerobic digestion is highlighted as a potential technology for producing hydrogen and methane from residual algal biomasses. The combination of hydrogen and methane, known as hythane, is recognized for its superior characteristics and is increasingly considered an alternative to fossil fuels. Haider et al. [83] comprehensively reviewed the potential of polymeric carbon nitride (C_3N_4) as a photocatalyst for eco-friendly hydrogen peroxide (H_2O_2) production, replacing conventional methods. The study identified C_3N_4 as optimal due to simple synthesis, effective light absorption, and suitable conduction band position.

Shen et al. [84] optimized microalgae biofilm formation by comparing species' adhesion, evaluating substrates, and modeling culture parameters and found that glass fiber-reinforced plastic showed superior adhesion support for Chlorococcum sp. compared to nine other materials. Liang et al. [85] highlighted the effectiveness of UV/TiO2 AOPs in degrading pharmaceutical contaminants in wastewater effluents and suggested potential applications for hierarchical TiO_2 nanobelt membranes in water treatment processes. Danouche et al. [86] revealed the potential of S. obliquus for large-scale phycoremediation of heavy metal-polluted effluents, highlighting its ability to tolerate and mitigate the adverse effects of Pb(II) contamination through various antioxidant defense mechanisms. Feng et al. [87] developed eco-friendly composite aerogels with graphene oxide (GO) or graphene nanosheets (GNS) and waste-newspaper cellulose (WCE) for wastewater dye removal. The composite aerogels showed differing adsorption capacities for methylene blue (cationic) and Congo red (anionic) due to various electrostatic attraction, charge repulsion, and π–π interaction. Adding 0.5 w/v%, GO enhanced MB adsorption by 235.6 % in WCE, while CR adsorption increased by 70.2 %. Conversely, GNS/WCE showed superior CR adsorption compared to MB. Zhao et al. [88] investigated the combined effects of ammonium, temperature, and pH on Chlorella pyrenoidosa cultivation and lipid accumulation in anaerobic wastewater. The findings revealed that the highest lipid content (30.2 %) occurred at pH 8.3–8.5 and 25 °C with an ammonium concentration of 280 mg/L, 1.6-fold higher than neutral conditions. The percentage of unsaturated fatty acids (un-SFAs) increased to 74.8–77.9 % at pH 8.3–8.5 compared to 56.1–58.9 % at neutral pH. These findings suggest anaerobic wastewater could enhance lipid accumulation in microalgae, offering a potential method for algal lipid cultivation.

3.6.2. Biological treatment and microalgae cultivation

Biological treatment methods utilize microorganisms or plants to break down or remove contaminants from wastewater [89,90]. In the case of microalgae cultivation, certain species of microalgae can consume nutrients like nitrogen and phosphorus present in wastewater while producing biomass, including lipids [91,92]. These lipids can be converted into biodiesel or used for hydrogen production through anaerobic digestion or thermochemical conversion [93,94]. Studies in the section include Senthil et al. [95], who assessed the biosorption of malachite green dye from aquatic systems using nano zero-valent iron stacked activated carbon (NZVI-AC) prepared with a dual surface modification strategy. The results demonstrate that NZVI-AC is a promising material for treating dyes in industrial effluents due to its efficient biosorption properties, reusability, and applicability for multiple cycles. Luo et al. [96] investigated Coelastrella sp. QY01 from a local pond for treating anaerobically and aerobically treated swine wastewater (AnATSW). The study found that using 40 % AnATSW was optimal for QY01 cultivation. Under these conditions, nutrient removal and productivity of biomass and lipids were maximized.

Sacristán De Alva et al. [97] evaluated the nutrient removal and lipid accumulation potential of Scenedesmus acutus cultivated in pre- and post-treated municipal wastewater discharges compared to a nutrient-rich culture medium. The results indicate that S. acutus has potential for wastewater treatment, as it effectively removes nutrients while accumulating lipids suitable for biodiesel production. This suggests a sustainable approach to wastewater treatment and biofuel production simultaneously. Ma et al. [98] investigated cultivating Chlorella vulgaris in wastewater supplemented with waste glycerol from biodiesel production using scum-derived oil to enhance nutrient removal and lipid production by balancing the C/N ratio. It was observed that adding waste glycerol improved nutrient removal and lipid production of Chlorella vulgaris. Fang et al. [99] designed universal solvents to dissolve chitin to chitosan with different degrees of acetylation, constructing robust hydrogels through physical regeneration. The findings showed that KOH and LiOH interacted uniquely with chitin and chitosan, disrupting intermolecular hydrogen bonds and aiding dissolution. Also, the hydrogels displayed uniform network structures with nanofibers, boasting strong mechanical properties and transparency.

Meerbergen et al. [100] isolated and characterized bacterial strains from activated sludge systems capable of decolorizing and degrading Reactive Orange 16 and Reactive Green 19 azo dyes. The results suggest the potential use of these bacterial strains in treating industrial wastewater containing azo dyes, highlighting their effectiveness and versatility in addressing dye contamination issues. Nguyen and Wu [101] discussed the historical background, current status, and prospects of improving methods for solar energy conversion, particularly focusing on water splitting and CO_2 reduction for solar fuel development. The authors highlighted that the novel twin photoreactor systems show great potential for solar energy conversion from water splitting, which could mimic photosynthesis. The twin photoreactors offer a new approach to producing solar fuels while simultaneously degrading organic wastewater, indicating a promising green technology. Singh et al. [102] explored microbial fuel cells (MFCs) as alternative to fossil fuels, emphasizing wastewater treatment integrated with bio-electricity generation. The authors highlighted that MFCs present a clean and sustainable solution for energy production and wastewater treatment by utilizing microorganisms to convert wastewater into bio-electricity.

Ferreira et al. [103] investigated Scenedesmus obliquus microalgae for wastewater treatment, CO_2 fixation, and biomass production in a single process. The authors observed that treating brewery wastewater using S. obliquus in bubble-column photobioreactors (PBRs) with a 10 % brewery CO2 supplement improved performance. In addition, the S. obliquus biomass was evaluated for biohydrogen, yielding 67.1 mL H2 g − 1 (VS), and for bio-oil, bio-char, and bio-gas production, with yields of 64 %, 30 %, and 6 %, respectively, calculated over freeze dryer biomass basis. Khafri et al. [104] evaluated ZnS:Ni nanoparticles on activated carbon from apple tree wood for adsorbing Methylene Blue (MB) and Janus Green B (JGB) dyes. The findings suggest that ZnS:Ni-NPs-ACATW can efficiently remove MB and JGB dyes from contaminated water, making it a promising agent for wastewater remediation and environmental pollution control. Samari et al. [105] synthesized silver nanoparticles (AgNPs) with mango leaf extract, characterizing them and exploring their catalytic, biological, and sensing properties. The sensor exhibited a wide linear dynamic range from 0.2 to 103.7 ppm for Hg2 + ions with principal component analysis and an artificial neural network. The effective catalytic and mercury-detecting properties and low cost and toxicity make these AgNPs attractive for wastewater management systems.

Ge et al. [106] developed an H_2O_2 activator for antibiotics removal in wastewater by synthesizing transition-metal-free MgNCN/MgO nanocomposites. The results demonstrate that the MgNCN/MgO nanocomposites synthesized via a simple calcination process showed excellent catalytic ability for tetracycline (TC) degradation across a wide pH range without external energy input. Additionally, the Mg-N coordination facilitated H2O2 activation, generating singlet oxygen and hydroxyl radicals responsible for TC degradation. Ali et al. [107] found that synthesized BMMCs demonstrate significant potential as efficient adsorbents for removing cationic pollutants, contributing to environmental applications and water/wastewater treatment processes. Yuvaraja et al. [108] highlighted the potential of ACSSB@ZnO as an effective adsorbent for the removal of Pb(II) ions from aqueous environments, offering a promising solution for addressing the environmental and health risks associated with heavy metal contamination.

3.6.3. *Adsorption and adsorbents*

Adsorption includes the attachment of pollutants to a solid material's surface (adsorbent) [109,110]. Various adsorbents can remove contaminants from wastewater streams, including dyes and heavy metals [111,112]. In green hydrogen production, the emphasis may be on developing adsorbents that can effectively remove specific pollutants from wastewater, thereby improving the water quality for subsequent hydrogen production processes. Additionally, some adsorbents may have catalytic properties that could aid hydrogen generation. In this regard, authors who investigated adsorption and adsorbents in this study include Dai et al. [113], who investigated the potential of calcium-rich biochar (CRB) derived from crab shells for low-cost dye removal from wastewater. The authors observed that the CRB showed high adsorption capacities and fast adsorption rates for dyes. Also, hydrogen bonding, electrostatic attraction, and π-π interactions played significant roles in adsorption. Due to its simple synthesis process, cheap source, and exceptional adsorption performance, CRB was identified as promising for dye removal from wastewater.

Nair and Vinu [114] prepared mesoporous-activated biochar from Prosopis juliflora biomass char, optimizing activation to enhance the adsorption capacity for commercial dyes. The study activation was achieved via H_2O_2 treatment followed by microwave pyrolysis. Likewise, the optimization resulted in nanostructured biochar with a high specific surface area and narrow, deep pores. In addition, the adsorption parameters, such as initial pH and adsorbent dosage, were optimized. Ren et al. [115] developed metal-free materials as green catalysts for wastewater purification, targeting plasticizer degradation using peroxymonosulfate as an oxidizing agent. The study revealed that the carbon nanotubes show non-radical pathway efficacy and boron oxide self-cleans to regenerate boron activity. Tan et al. [116] studied the pH effects on Chlorella pyrenoidosa cultivation using anaerobically digested activated sludge effluent. It was seen that the pH variations affect algal growth and lipid accumulation, with high pH reducing contamination but promoting lipids. The results emphasize the significance of pH management techniques in algal wastewater systems, particularly where ammonia is the primary nitrogen source.

Mittal et al. [117] investigated the viability of zeolite-Y incorporated hydrogel composite (ZHC) of gum karaya (GK) as an adsorbent for cationic dye (Brilliant Green) wastewater treatment. They revealed that the ZHC shows good regeneration and reusability for dye adsorption up to six cycles. Zdarta et al. [118] findings demonstrate the potential of immobilized laccase enzymes on poly(l-lactic acid)–co-poly(ε-caprolactone) nanofibers for the efficient biodegradation of pharmaceutical pollutants, leading to reduced toxicity in wastewater. This approach offers a green solution for removing toxic pollutants and holds promise for industrial applications due to immobilized enzymes' enhanced stability and reusability. Bansal et al. [119] developed an environmentally-friendly material for removing mercury ions from wastewater using cellulose nanofibers extracted from bagasse esterified with l-cysteine to yield thiol and amine functionalized green material (Cys-CNFs). The results suggest that Cys-CNFs have potential applications as efficient and selective adsorbents for the removal of Hg^{2+} ions from wastewater, addressing the serious environmental hazard posed by the presence of mercury ions. Guo et al. [120] proposed an innovative zinc recovery from steel dust, preparing iron-carbon micro-electrolysis for wastewater treatment and addressing environmental and economic challenges. Zhu et al. [121] developed efficient Cr(VI) removal materials using corn straw, attapulgite, zeolite, starch, and iron oxide via pyrolysis. The results indicate that the hematite-coated hierarchical graphitic carbon materials (HGCs) exhibit mesoporous structure, adsorbing Cr (VI) effectively (19.51 mg/g at pH 5.0). The adsorption kinetics conform to pseudo-first and pseudo-second-order models involving various mechanisms. The study findings demonstrate the potential of utilizing agricultural waste materials and other compounds to create efficient adsorbents for heavy metal removal, contributing to waste management and environmental sustainability.

Delpiano et al. [122] revealed the potential of Fe-BTC MOF as an efficient adsorbent for removing synthetic organic dyes from water, highlighting its suitability for environmental remediation applications. Wang et al. [123] found that combining sugarcane bagasse (SCB) and calcium oxide to produce an SCB-calcium carbonate (SCB–$CaCO_3$) is an efficient, low-cost, green, and recyclable material for the removal of organic dyes from wastewater, providing insights into its adsorption mechanism and potential application in environmental remediation. Patra et al. [124] developed a biodegradable h-GG/SiO_2 nanocomposite using anionically modified guar gum, and sol–gel deposited silica nanoparticles. The study demonstrated that h-GG/SiO_2 nanocomposite possesses high adsorption capacities for cationic dyes and metal ions, with notable Q_{max} values: 781.25 mg/g for malachite green, 281.69 mg/g for safranin, 645.16 mg/g for Pb^{2+}, and 709.21 mg/g for Cd^{2+}. It also selectively removed cationic malachite green from dye mixtures and exhibited promising regenerative efficacy, suggesting economic viability for wastewater management applications. Rahimi et al. [125] explored a green remediation approach for aquatic dye pollutants using whey protein concentrate and montmorillonite nanofibrils. It was seen that Nanofibrils from whey protein concentrate dispersed montmorillonite, enhancing the nanocomposite structure. It effectively adsorbed various dyes, especially cationic ones like Chrysoidine-G, with promising potential in wastewater treatment.

3.7. *Advantages and disadvantages of some techniques used in hydrogen production using wastewater*

The study and technology of producing hydrogen from wastewater is developing, employing a number of methods to produce hydrogen gas. The advantages and disadvantages of some common techniques are listed in Table 3. The primary benefit is that the majority of the procedures are eco-friendly, resulting in zero or minimal carbon emissions that may be linked to material transportation or construction. However, the low yield of hydrogen production and the low chemical oxygen demand (COD) removal efficiency are the primary drawbacks of the majority of the techniques, specifically biological treatment (both light-dependent and light-independent methods), anaerobic membrane bioreactor (AnMBR), and advanced oxidation process (AOP). Consequently, a number of studies have various ways of optimizing these two parameters [15,126,127]. For example, optimizing reactor design, microbial culture immobilization, pH, temperature, organic loading rate, hydraulic retention time, sludge retention time, and biofilm sludge can all boost the production of biohydrogen. When used in conjunction with traditional processes or other AOP techniques such as biological processes, UV/sonication, and microwave, they can be more effective for process acceleration, wastewater treatment, and hydrogen production improvement. But this combination uses more energy, which may be avoided by choosing the best methods for maximizing technological efficiency and consuming the least amount of energy [15,128]. Numerous factors, such as operating costs, maintenance costs, administrative expenses, and installation costs in anaerobic membrane bioreactors, have a substantial impact on the cost and commercialization of hydrogen. The cost of renewable electricity and existing electrolyzers

Table 3
Merits and demerits of some techniques.

Biological hydrogen production (Dark Fermentation)		Electrochemical water splitting (Electrolysis)		Photo-fermentation		Anaerobic digestion (AD)		Microbial electrolysis cells (MECs)	
Merit	Demerit	Merit	Demerit	Merit	Demerit	Merit	Demerit	Merit	Demerit
Low energy requirements [130].	Low hydrogen yield [131,132]	High efficiency [26]	Costly [133–135]	Purple non-sulfur bacteria can achieve a high substrate to hydrogen ratio [136]	Low hydrogen production rate [137]	Waste-to-Energy	Low hydrogen yield [138,139]	Lower energy requirement than traditional electrolysis methods [140–142]	Electrode fouling [140,143]
Sustainable and requires simple setup	Slow kinetics [144,145]	Renewable energy compatible [146,147]	Electrode degradation due to harsh conditions in wastewater [15,23,148]	Expensive energy inputs are not required	Low conversion efficiency [137]	Sustainable	In order to produce hydrogen more efficiently than methane, ideal conditions must be met, which calls for more process control [149,150]	There are available pilot-scale studies	MECs can be costly, particularly for large-scale systems [137]
Low material costs [21]	Pretreatment of wastewater is necessary [151].	Scalable [152]	High energy demand, i.e., 55 kWh per kilogram of hydrogen produced [153]	Eco-friendly procedure with minimal energy consumption	The enzyme hydrogenase is extremely sensitive to oxygen [21].	Co-production of biogas [154,155]	Slow process [156,157]	Concurrent production of hydrogen and wastewater treatment [158]	High energy requirements are a major concern, including energy losses and external energy requirements
	Low conversion efficiency [137]				Genetic and metabolic engineering are necessary [21].			High rate of hydrogen production [15]	Limited hydrogen production [140]
					Light dependency [159]			Moderate to high removal of COD [15]	

continue to be the primary obstacles to water electrolysis, while the oxygen needed for bio-oxidation in wastewater treatment facilities makes up 50 %–60 % of the total power requirement [15,49,129].

4. Conclusion and future research directions

Energy recovery through wastewater management has shown to be an effective and affordable strategy for a circular economy in addressing the serious environmental risks associated with the discharge of wastewater into aquatic systems. Wastewater is a potential source of hydrogen, a feedstock chemical, clean energy vector, and fuel that is widely acknowledged to play a role in the decarbonization of the future energy system. In order to present a sustainable and clean energy production approach, this paper offers a unique review of hydrogen production from wastewaters. The systematic and bibliometeric review approach were employed to assess the trend, evolution and potential future research directions for the production of hydrogen from wastewater. The analysis covered the period from 2013 to 2023. The following conclusions can be drawn from the review:

- The research saw an average annual growth of 32.88 %, with 1,883 authors contributing and 27.95 % involving international collaboration, resulting in 415 papers with 1,362 keywords.
- The field of research has seen a significant surge in recent years, with a notable increase in publications since 2020. Technological advancements in wastewater hydrogen production could be the reason behind the boost in publications, contributing to global efforts to address environmental challenges and promote sustainable practices.
- Research on industrial wastewater, including olive mill wastewater and activated carbon, suggests potential for integrating advanced hydrogen production processes with wastewater treatment methods or adsorption and electrochemical techniques to address practical applications and treatment challenges.
- The top sources for high-impact journals include Bioresource Technology, Chemical Engineering Journal, Journal of Environmental Chemical Engineering, Journal of Cleaner Production, and International Journal of Hydrogen Energy.
- The study reveals a global collaboration in green hydrogen production from wastewaters, highlighting the growing interest and research in this field and the potential benefits of international cooperation.
- The study reveals numerous regional collaborations across Asia, Europe, and the Middle East, including China-India, China-Malaysia, India-Thailand, Germany-Austria, Germany-Poland, France-Finland, and Saudi Arabia-Kuwait.
- China, India, Malaysia, Iran, and Egypt are leading research hubs in green hydrogen production from wastewater, with established programs, dedicated resources, and a critical mass of researchers.

The study identified the following potential research directions: firstly, there is increasing interest on the production of hydrogen from wastewaters, recycled water electrolysis using renewable energy is one method of lowering carbon emissions. On the other hand, little is known about how contaminants in recycled water impact the design and functionality of water electrolysers. These factors should be evaluated in future research. Secondly, although electrolysis and electrodialysis are commercially established techniques, there is the need for more research on their use in treating wastewater to produce hydrogen. Microbial photoelectrochemical cell, a recent energy generation technology, has gained interest due to its ability to treat various pollutants. However, due to lower H_2 rate, these systems are still in lab stages, and further development that focuses on increasing its durability and efficiency is required. Also, microbial electrolysis, a promising future technology, aims to produce hydrogen and remove chemical oxygen demand. However, it faces energy barriers and requires higher voltages. Further research that aims to overcome this issue and overcome the slightly high energy input of the microbial electrolysis cell process should be looked at going into the future. Furthermore, the bibliometric analysis shows that a number of additional studies are necessary for the production of hydrogen from wastewater particularly when it comes to a thorough assessment of process stability, and its economic viability. Finally, electrochemical water splitting with wastewater as a feedstock for green hydrogen production has a bright future, but there are still technical, financial, and environmental challenges to overcome. Improving electrolyte conductivity, boosting electrode performance, and streamlining system integration are some solutions that can be employed going into the future. This could propel sustainable futures in the water and energy sectors as technologies advance, whiles interdisciplinary research and policy development support them.

Among the study's drawbacks are its emphasis on English-only publications and the possible absence of studies in other languages. The fact that not all studies on the subject may be included in Scopus, which is the biggest scientific database, is also acknowledged as a limitation. There maybe some studies in the Web of Science database which are missed in this analysis. Although such limitations exist in this study, the study offers a thorough grasp of the most recent developments and trends in the field.

CRediT authorship contribution statement

Flavio Odoi-Yorke: Methodology, Investigation, Funding acquisition. **Ephraim Bonah Agyekum:** Software, Resources, Project administration. **Mustafa Tahir:** Validation, Supervision, Resources. **Agnes Abeley Abbey:** Writing – original draft, Visualization, Validation. **Pradeep Jangir:** Writing – review & editing, Writing – original draft, Visualization, Validation. **Farhan Lafta Rashid:** Visualization, Validation, Supervision, Software. **Hussein Togun:** Validation, Supervision, Software. **Wulfran Fendzi Mbasso:** Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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