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A systematic review on environmentally friendly hydrogen production methods: comparative analysis of reactor technologies for optimal efficiency and sustainability

Aisha Hamid [a,b], Raja Razuan Raja Deris [a], Siti Nur Amira Shaffee [c], Taufiq Yap Yun Hin [d], Divine Senanu Ametefe [e], Mohd Lokman Ibrahim [a,*]

[a] School of Chemistry and Environment, Faculty of Applied Sciences, Universiti Teknologi MARA, 40450, Shah Alam, Selangor, Malaysia
[b] Department of Chemistry, University of Turbat, Balochistan, Pakistan
[c] Petroliam Nasional Berhad (PETRONAS), Kuala Lumpur, Malaysia
[d] Catalysis Science and Technology Research Centre, Faculty of Science, Universiti Putra Malaysia, 43400, Serdang, Selangor, Malaysia
[e] College of Engineering, School of Electrical Engineering, Universiti Teknologi MARA (UiTM), 40450 Shah Alam, Selangor, Malaysia

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ABSTRACT

The transition to a hydrogen-based energy system is increasingly viewed as vital for achieving global sustainability and decarbonization goals. This systematic literature review (SLR) critically examines 37 peer-reviewed studies (2018–Q2 2024) on key hydrogen production methods: biomass gasification, auto-thermal reforming (ATR), photochemical water splitting, water electrolysis, and steam reforming. These technologies, while diverse in operational principles and efficiency, converge on the goal of delivering low-carbon hydrogen. Steam reforming remains the most commercially mature, yet it is constrained by high energy demands and catalyst degradation. Biomass gasification emerges as a renewable option, though hampered by cost and technical complexity. ATR offers improved energy efficiency but requires stringent process control. Photochemical water splitting, though promising in its solar-driven mechanism, is hindered by low conversion efficiency and material limitations. Water electrolysis, especially when powered by renewables, delivers high-purity hydrogen, albeit at elevated operational costs. The findings underscore that no single method can universally meet all economic, environmental, and technological criteria. Instead, context-specific hybridization and integration with renewable sources appear most viable. This review emphasizes the need for continued research in advanced catalysts, cost-effective materials, and scalable system designs. It also calls for cross-sectoral collaboration to tailor hydrogen strategies to local resource conditions and energy demands. By articulating the strengths, limitations, and future directions of current hydrogen production pathways, this study contributes to the evolving discourse on sustainable energy and supports informed decision-making toward a resilient, low-carbon future.

1. Introduction

The transition to a hydrogen-based energy system is increasingly recognized as a critical step towards achieving global sustainability and significant reductions in carbon emissions [28,63] Hydrogen, as an energy carrier, offers numerous advantages, including high energy density, versatility in various applications, and the potential for near-zero greenhouse gas emissions when produced through environmentally friendly methods [29]. It can be used in fuel cells to power vehicles, provide heat for buildings, and generate electricity, making it a versatile component in the energy landscape [75]. Additionally, its ability to be produced from a variety of sources, including renewable energy, adds to its appeal as an anchor of future energy systems. However, the success of hydrogen as a foundational element in future energy systems hinges on the efficiency and sustainability of its production processes. Central to this transition is the deployment of advanced reactor technologies that can optimize hydrogen recovery efficiency under diverse operational conditions. The efficiency of hydrogen production is not only a technical challenge but also an environmental imperative [37,65]. The selection of reactor types and the optimization of their operational parameters play a crucial role in determining the overall sustainability of hydrogen production processes. Efficient reactor technologies can minimize

* Corresponding author at: School of Chemistry and Environment, Faculty of Applied Sciences, Universiti Teknologi MARA, 40450, Shah Alam, Selangor, Malaysia.
E-mail address: mohd_lokman@uitm.edu.my (M.L. Ibrahim).

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energy input, reduce operational costs, and decrease the environmental footprint of hydrogen production [77]. This study aims to provide a comprehensive evaluation of five distinct hydrogen production methods, each chosen for their potential to minimize environmental impact. These methods include Gasification, Auto Thermal Reactors, Photochemical Water Splitting, Water Electrolysis, and Steam Reforming. By systematically analyzing existing literature, this review will compare the performance of these methods in terms of hydrogen recovery efficiency, energy consumption, operational stability, and environmental sustainability. The goal is to identify the most promising technologies that can support a sustainable hydrogen economy, ultimately contributing to the global effort to mitigate climate change and transition to a low-carbon energy system.

1.1. Overview of hydrogen production methods

Hydrogen production is a critical component in the transition to sustainable energy systems, and various methods have been developed to produce hydrogen efficiently and in an environmentally friendly manner. This section presents and discusses five distinct eco-friendly hydrogen production methods and their respective implementations. These methods include Biomass Gasification, Auto Thermal Reactor (ATR), Photochemical Water Splitting, Water Electrolysis, and Steam Reforming.

1.1.1. Biomass gasification

Biomass Gasification is a thermochemical process that converts carbonaceous materials, such as biomass, coal, or municipal solid waste, into hydrogen, carbon monoxide, and carbon dioxide [62]. This conversion occurs through high-temperature reactions with a controlled amount of oxygen and/or steam, typically at temperatures ranging from 800 to 1200 degrees Celsius. The process begins with the drying and pyrolysis of the feedstock, breaking it down into char, tar, and gases. The char then reacts with oxygen and steam in the gasification reactor to produce a mixture of gases known as syngas. Syngas primarily consists of hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), and methane (CH_4). To increase the hydrogen yield, the syngas can undergo a water-gas shift reaction, where carbon monoxide reacts with steam to produce additional hydrogen and carbon dioxide [54]. One significant advantage of gasification is its ability to utilize a wide variety of feedstocks, including renewable biomass and waste materials. This versatility makes it a valuable method for hydrogen production. Integrating Biomass gasification with carbon capture and storage (CCS) can substantially reduce its carbon footprint, enhancing its environmental friendliness [34]. However, the efficiency and sustainability of the gasification process heavily depends on feedstock quality, reactor design, and operational conditions. Key factors such as temperature, pressure, and the ratio of oxygen and steam are crucial for optimizing hydrogen yield and minimizing unwanted by-products. Advanced reactor technologies, such as fluidized beds and entrained flow gasifiers, offer improved mixing and heat transfer, enhancing the overall efficiency and output of the process. Thus, gasification is a robust method for hydrogen production that leverages high-temperature reactions to convert various carbonaceous materials into valuable gases. Its flexibility in feedstock uses and potential for integration with carbon capture technologies make it a promising approach for sustainable hydrogen production [1]. However, optimizing reactor conditions and managing feedstock variability is critical for maximizing its efficiency and environmental benefits. Fig. 1 illustrates a representative process of gasification.

1.1.2. ATR

ATR technology (*Fig. 2*) is an advanced method for hydrogen production. It combines partial oxidation and steam reforming within a single reactor to generate hydrogen efficiently under autothermal conditions [9]. This integrated approach enables the simultaneous oxidation of hydrocarbons with a controlled amount of oxygen and the reforming process involving steam. This significantly enhances overall energy efficiency. In an ATR, hydrocarbons such as natural gas are partially oxidized, generating heat that drives the subsequent endothermic steam reforming reactions [46]. The autothermal process balances the exothermic and endothermic reactions, eliminating the need for an external heat source and reducing operational energy requirements. ATRs operate at high temperatures, typically between 800 and 1000 °C. These high temperatures promote faster reaction rates and higher hydrogen yields. The resulting hydrogen-rich syngas contains lower levels of carbon monoxide compared to conventional steam reforming methods, making ATR a cleaner alternative [51]. Additionally, ATRs are compact and modular, allowing for scalability and integration into various industrial applications, from small-scale distributed hydrogen production systems to large-scale centralized plants. Moreover, the autothermal operation of ATRs ensures a stable thermal environment within the reactor. This stability reduces thermal stress and extends the lifespan of reactor components. The process also supports the incorporation of carbon capture and storage (CCS) technologies, further mitigating the carbon footprint of hydrogen production [52]. By efficiently utilizing the inherent energy within the feedstock and minimizing external energy inputs, ATR technology offers a promising pathway for producing hydrogen sustainably and economically. This aligns with global efforts to transition towards low-carbon energy

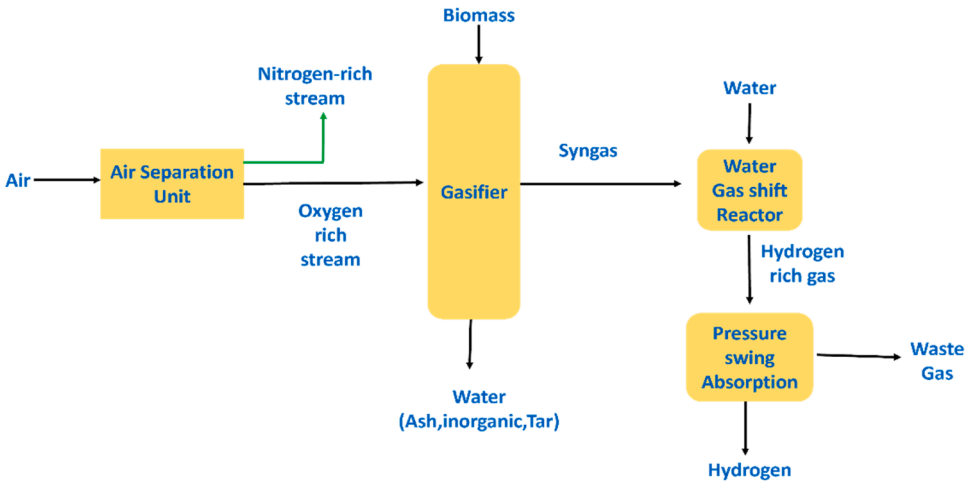

Fig. 1. Hydrogen production process via biomass gasification method.

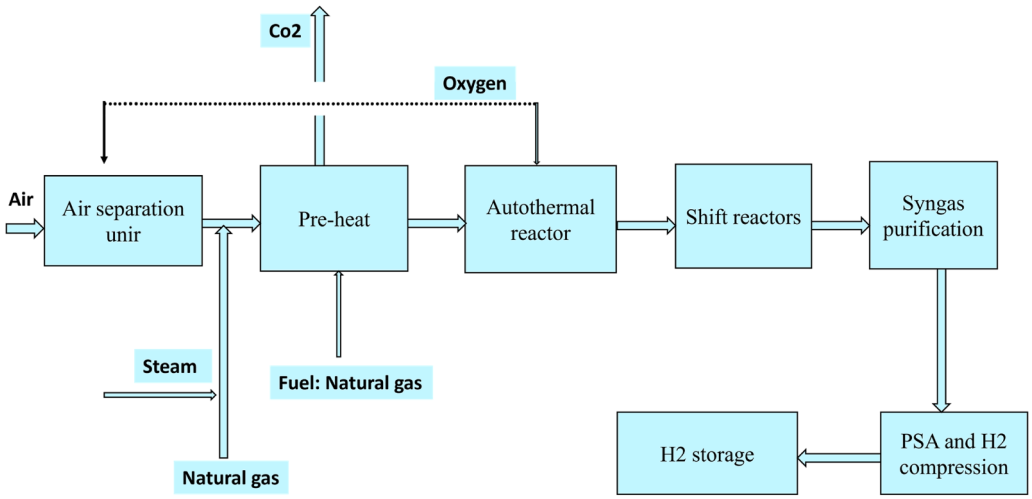

Fig. 2.. Hydrogen production process via auto thermal reactor method.

systems [55].

1.1.3. *Photochemical water splitting*

Photochemical water splitting (*Fig. 3*) is an advanced method for hydrogen production that harnesses sunlight to drive the chemical reaction separating water (H_2O) into hydrogen (H_2) and oxygen (O_2) [6]. This process utilizes specialized materials known as photocatalysts, which absorb solar energy and use it to initiate and sustain the water-splitting reaction. The core principle involves the excitation of electrons in the photocatalyst when exposed to sunlight. These excited electrons participate in redox reactions necessary to break the chemical bonds in water molecules, producing hydrogen and oxygen gases. The efficiency of photochemical water splitting is highly dependent on the properties of the photocatalyst. Ideal photocatalysts should have a suitable band gap matching the solar spectrum, high stability in aqueous environments, and the ability to facilitate charge separation and transfer effectively [72]. Commonly explored materials for this purpose include titanium dioxide (TiO_2), cadmium sulfide (CdS), and various metal oxides and sulfides, often modified with co-catalysts to enhance their performance. One significant advantage of photochemical water splitting is its potential for sustainability. By utilizing sunlight, a virtually inexhaustible and clean energy source, this method can produce hydrogen without direct emission of greenhouse gases [74]. This aligns with the global imperative to transition towards renewable energy sources and reduce the carbon footprint associated with traditional hydrogen production methods, such as steam reforming of natural gas. Despite its promise, photochemical water splitting faces several technical challenges that must be addressed to realize its full potential. These include improving overall conversion efficiency, ensuring the long-term stability of photocatalysts, and scaling up the process for industrial applications [61]. Research is ongoing to develop novel photocatalyst materials, optimize reaction conditions, and integrate photochemical water splitting with other renewable energy technologies. In essence, photochemical water splitting is an innovative and environmentally friendly approach to hydrogen production that harnesses solar energy through advanced photocatalytic materials. While challenges remain, continued advancements in this field could make it a cornerstone of sustainable hydrogen energy systems in the future.

1.1.4. *Water electrolysis*

Water electrolysis (*Fig. 4*) is a prominent method for hydrogen production that uses electrical energy to split water molecules (H_2O) into

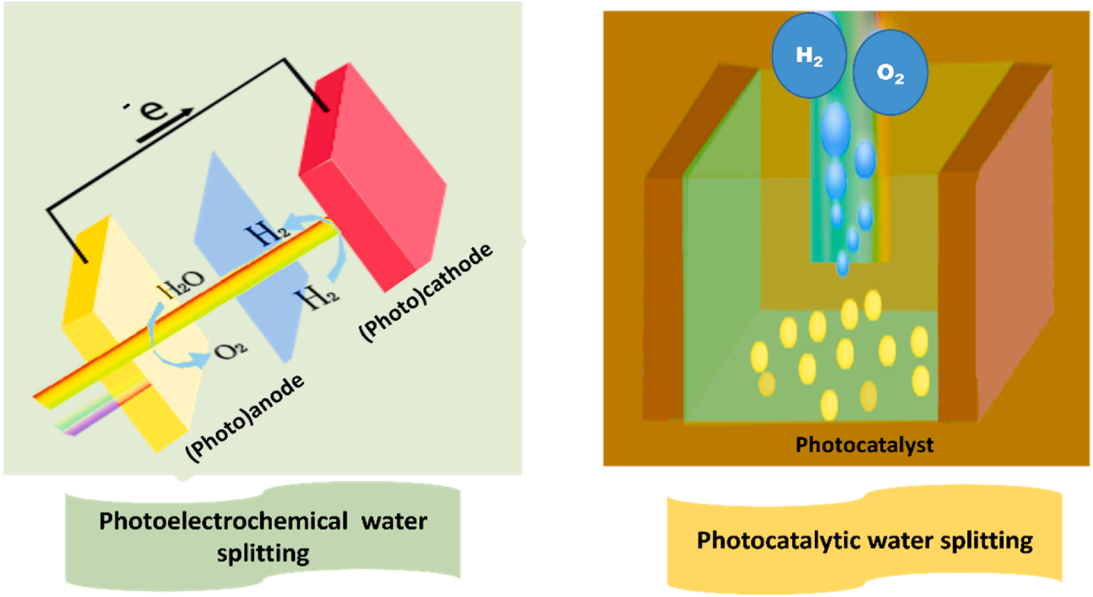

Fig. 3. Hydrogen production process via photochemical water splitting method.

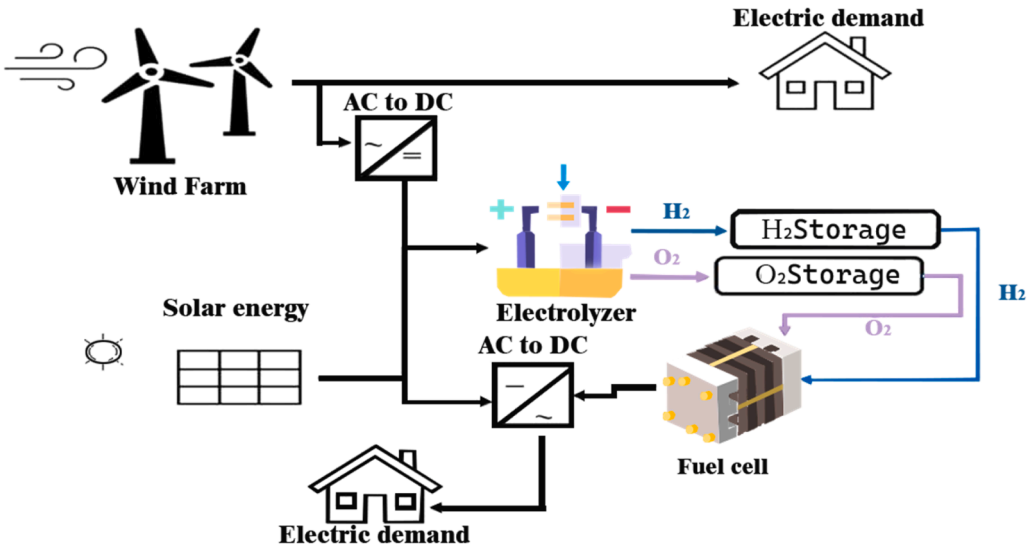

Fig. 4. Hydrogen production process via water electrolysis method.

hydrogen (H_2) and oxygen (O_2). This process occurs in an electrolyzer, a device with two electrodes, an anode and a cathode, immersed in an electrolyte solution [12]. When an electric current is applied, water molecules at the anode oxidize, producing oxygen gas, protons, and electrons. The protons move through the electrolyte to the cathode, where they combine with electrons to form hydrogen gas. The overall reaction is represented as $2H_2O \rightarrow 2H_2 + O_2$. The environmental friendliness of water electrolysis is significantly enhanced when the required electrical energy comes from renewable resources such as wind, solar, or hydroelectric power. By utilizing renewable energy, the hydrogen production process can achieve near-zero carbon emissions. This makes water electrolysis a highly sustainable option compared to traditional methods that rely on fossil fuels. Water electrolysis offers several operational advantages [27]. It is flexible and can be scaled to match supply and demand. This provides a valuable means of energy storage and helps stabilize the grid by absorbing excess renewable electricity during periods of low demand. Additionally, the hydrogen produced via electrolysis can be used in various sectors, including transportation, industrial processes, and residential heating. This versatility enhances its role in transitioning to a low-carbon economy. Despite these benefits, water electrolysis faces challenges related to energy efficiency and cost [12]. When an electric current is applied, water molecules at the anode oxidize, producing oxygen gas, protons, and electrons. The process requires a significant amount of electrical energy, and the efficiency of current electrolyzer technologies typically ranges between 60–80 %. Research and development efforts are focused on improving efficiency and reducing the cost of electrolyzers through advancements in materials, design, and manufacturing processes. Innovations such as proton exchange membrane (PEM) electrolyzers and solid oxide electrolyzers (SOE) are at the forefront of this progress, offering improved performance and durability. Therefore, water electrolysis stands out as a clean and versatile method for hydrogen production, especially when powered by renewable energy sources. Its ability to produce hydrogen without direct carbon emissions makes it a critical component in the pursuit of sustainable energy systems. Ongoing technological advancements are expected to address current limitations, paving the way for more widespread adoption and integration of water electrolysis in the global energy landscape.

1.1.5. Steam reforming

Steam reforming (*Fig. 5*) is a widely utilized method for hydrogen production, primarily involving the high-temperature reaction of

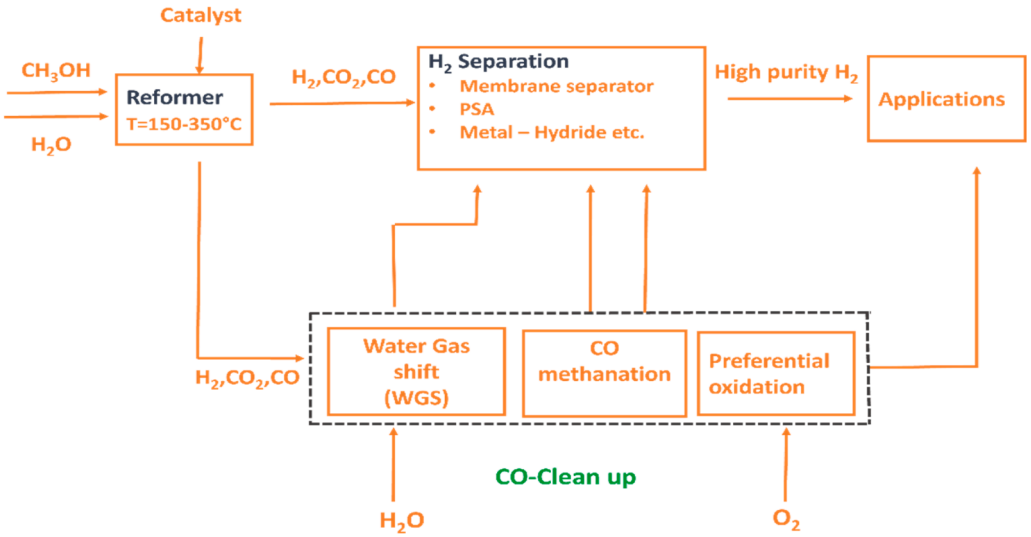

Fig. 5. Hydrogen production process via steam reforming method.

hydrocarbons, particularly natural gas, with steam [49]. The process begins with the endothermic conversion of methane (CH_4) and water (H_2O) into hydrogen (H_2) and carbon monoxide (CO) in the presence of a nickel-based catalyst. This reaction can be represented by the equation: $CH_4+H_2O \rightarrow CO+3H_2$. Following this, a secondary reaction known as the water-gas shift reaction occurs. In this reaction, carbon monoxide reacts with additional steam to produce more hydrogen and carbon dioxide (CO_2), as shown by the equation: $CO+H_2O \rightarrow CO_2+H_2$. The efficiency of steam reforming is influenced by factors such as temperature, pressure, and catalyst performance [3]. Typically, the process operates at temperatures ranging from 700 to 1100 °C and pressures between 3 and 25 bar. The high temperatures required for the reaction necessitate substantial energy input, often derived from fossil fuels, which can impact the overall sustainability of the method. To address the environmental concerns associated with CO_2 emissions from steam reforming, the integration of Carbon Capture and Storage (CCS) technologies is increasingly being adopted [92]. CCS involves capturing CO_2 produced during the reforming process and storing it in geological formations or utilizing it in other industrial processes. This significantly reduces the carbon footprint of hydrogen production. The integration of CCS enhances the environmental viability of steam reform by mitigating its greenhouse gas emissions. Moreover, advances in catalyst development and process optimization are ongoing to improve the efficiency and sustainability of steam reforming. Research efforts focus on developing more robust and active catalysts that can operate at lower temperatures and withstand longer operational cycles [42]. This reduces overall energy consumption and operational costs. Consequently, steam reforming remains a dominant method for hydrogen production due to its established technology and economic viability. However, its environmental impact necessitates the incorporation of CCS and ongoing advancements in catalyst and process technologies to align with global sustainability goals [95].

In summary, these hydrogen production methods encompass a broad range of techniques, each utilizing unique principles and processes to generate hydrogen efficiently. The operational mechanisms of these methods vary significantly, from high-temperature chemical reactions to the use of renewable energy sources. They exhibit substantial potential in scalability, environmental sustainability, and compatibility with existing energy infrastructures. The viability and efficiency of each method depend on several factors, such as feedstock availability, technological advancements, and carbon mitigation strategies. Together, these methods highlight the versatility and potential of hydrogen as a crucial element in the transition to a sustainable energy future.

The primary objective of this study is to identify the most promising reactor technologies for sustainable hydrogen production by comparing their performance metrics. This comparison will provide insights into the relative strengths and weaknesses of each method. It will facilitate informed decisions for future research, development, and implementation in the hydrogen energy sector. Understanding these differences is crucial for optimizing hydrogen production pathways and guiding investments in technology development. In addition to evaluating the performance of these hydrogen production methods, this review will explore the broader implications of reactor technology choices on the sustainability of hydrogen energy systems. This includes assessing the lifecycle environmental impacts, the potential for integration with renewable energy sources, and scalability to meet future energy demands. By synthesizing findings from a wide range of studies, this systematic literature review aims to contribute to the development of more efficient, cost-effective, and environmentally friendly hydrogen production technologies. These technologies can support the global transition to a low-carbon energy future. This comprehensive analysis is crucial for guiding policymakers, industry stakeholders, and researchers towards the most effective strategies for hydrogen production. Therefore, ensuring that the shift to hydrogen-based energy systems can be achieved with maximum environmental and economic benefits requires a thorough understanding of the technological landscape and its implications. This study will serve as a foundational resource, highlighting the advancements and gaps in current knowledge, thereby promoting a more sustainable and resilient energy future.

The remainder of this paper is divided into five sections. Section 2 describes the methodological approach employed for the study. Section 3 provides a thorough review and synthesis of the pertinent literature. Section 4 presents and analyzes the key findings of the study. Section 5 critically assesses the study's limitations. Finally, Section 6 concludes the study by summarizing the main conclusions.

2. Methodology

To explore the efficiency and sustainability of various hydrogen production methods, this study employs a Systematic Literature Review (SLR) methodology. This approach is selected for its rigorous and structured process of collecting, analyzing, and synthesizing information from a wide range of scholarly sources. The study facilitates an exhaustive and impartial examination of the complex technological and environmental dimensions associated with hydrogen production. The review focuses on five key hydrogen production methods: biomass gasification, auto thermal reactors, photochemical water splitting, water electrolysis, and steam reforming. Each method is scrutinized through the lens of critical performance indicators such as hydrogen yield, energy efficiency, operational stability, and environmental impact. By systematically aggregating and evaluating existing academic research, the study aims to provide a clear comparative analysis of these reactor technologies. The methodology involves an extensive search of scientific databases to identify relevant studies, followed by a meticulous selection process to ensure the inclusion of high-quality, peer-reviewed articles. Data extraction and synthesis are conducted to aggregate findings and identify patterns and gaps in the current knowledge. This comprehensive analysis highlights the relative strengths and weaknesses of each hydrogen production method and examines the broader implications of hydrogen production technology choices on the sustainability of hydrogen energy systems. Through this rigorous synthesis of academic literature, the review aims to enhance scholarly understanding of hydrogen production technologies and inform future research, development, and policymaking in the field of sustainable energy. By providing a thorough and balanced evaluation, this study contributes to the ongoing discourse on transitioning to a low-carbon economy and supports the development of more efficient and environmentally friendly hydrogen production solutions.

2.1. Article selection method

In a comprehensive search for literature on environmentally friendly hydrogen production methods, a dual-database search strategy using Web of Science (WoS) and ScienceDirect was employed. The multidisciplinary research coverage in WoS and the extensive, high-quality academic collection in ScienceDirect [33] facilitated the thorough extraction of relevant scholarly articles. Following the PRISMA guidelines [8,44], this systematic review aimed to ensure clarity, comprehensiveness, and methodological rigor in the findings. Recognizing the dynamic and evolving landscape of hydrogen production technologies, the review focused on articles published from 2018 to the second quarter of 2024. This time frame was chosen deliberately to capture the latest innovations, research advancements, and perspectives on hydrogen recovery efficiency and reactor technologies. The field is rapidly advancing with emerging technologies and shifting energy policies, making this period critical for reflection on current trends, challenges, and opportunities. The keywords guiding the search included terms such as "hydrogen production," "environmentally friendly," "Biomass gasification," "Auto thermal reactor," "photochemical water splitting," "water electrolysis," "steam reforming," "hydrogen recovery efficiency," and "sustainable hydrogen." These terms were combined in various ways to retrieve the most relevant articles. To ensure scholarly rigor, stringent

inclusion and exclusion criteria were implemented. Inclusion criteria focused on studies that directly addressed the performance, efficiency, and environmental impact of the selected hydrogen production methods, ensuring alignment with research objectives. Conversely, exclusion criteria filtered out studies that were only tangentially related, did not meet academic quality standards or lacked empirical data pertinent to the review. This systematic approach allowed for a comprehensive assessment and comparison of the reactor technologies used in different hydrogen production methods. By synthesizing findings from a wide range of studies, the aim is to contribute to the development of more efficient, cost-effective, and environmentally friendly hydrogen production technologies that can support the global transition to a low-carbon energy future.

2.2. Inclusion and exclusion criteria

To ensure the highest relevance and academic rigor in the study on environmentally friendly hydrogen production methods, defined selection parameters were employed. Each chosen article needed to meet all inclusion criteria and avoid features falling under the exclusion benchmarks. This stringent approach guaranteed that the selected studies accurately highlighted the potential for sustainable hydrogen production technologies. The focus was on methods such as gasification, autothermal reactors, photochemical water splitting, water electrolysis, and steam reforming. By adhering to these parameters, the goal was to address existing gaps in the literature and provide valuable insights into the efficiency and sustainability of different hydrogen production methods. *Table 1* presents the summary of the inclusion and exclusion benchmarks.

By explicitly stating these criteria, the study aims to eliminate bias in article selection, ensuring the inclusion of only high-quality and relevant research in the review. This approach enhances the credibility and reliability of the findings, offering a clear pathway for potential replication and extension of the study. Such rigor ensures that the study provides a thorough and dependable evaluation of hydrogen production methods, highlighting the most promising technologies for achieving optimal efficiency and sustainability.

2.3. Article selection

As illustrated in *Fig. 6*, this review systematically investigates the comparative efficiency and sustainability of environmentally friendly hydrogen production methods. The initial selection process involved 126 articles: 95 from ScienceDirect and 31 from Web of Science (WoS). After removing duplicates, 114 articles remained and underwent a preliminary screening based on their titles and abstracts. This screening excluded 39 articles that did not explicitly address hydrogen production methods or reactor technologies. A thorough full-text assessment further excluded 34 articles that did not meet the strict inclusion criteria, as well as 7 articles that were inaccessible. This process resulted in a selection of 34 pivotal studies. To enhance the review's scope and depth, an expanded search using backward and forward citation tracking was conducted. This practice is recommended for comprehensive literature reviews [17,44,86]. Backward citation tracking involved examining the references of the initially identified studies to discover seminal works. Forward citation tracking aimed to find more recent studies that cited the initially selected articles since their publication. This dual approach enriched the search, leading to the inclusion of an additional 3 articles. In total, the study integrates findings from 37 peer-reviewed articles. Each article was selected to meet defined standards, ensuring the integrity and analytical rigor of the comparative analysis of reactor technologies for optimal efficiency and sustainability in hydrogen production.

3. Innovative technologies for sustainable hydrogen production

Hydrogen production technologies have undergone significant evolution, driven by the need for sustainable and efficient energy solutions. This section explores advancements and innovations in various hydrogen production methods, including gasification, ATR, photochemical water splitting, water electrolysis, and steam reforming. Each method features unique operational mechanisms, efficiency parameters, and environmental impacts, demonstrating diverse approaches to harnessing hydrogen as a clean energy carrier. By examining recent studies and breakthroughs, this review aims to provide a comprehensive understanding of how these technologies contribute to transitioning to a low-carbon energy future. The focus is on evaluating their comparative performance, technological challenges, and potential for integration with renewable energy systems.

Biomass Gasification as a method for hydrogen production has garnered significant attention due to its ability to utilize various feedstocks and enhance efficiency through innovative catalytic processes. A study by Xu et al. [90] explores the complexities of catalytic tar removal in biomass gasification, using a novel $TiO_2/NiWO_4$–Ni_5TiO_7 film. This multilayer system, synthesized through plasma electrolytic oxidation (PEO) followed by impregnation and annealing, shows remarkable efficiency in converting naphthalene, a model tar compound, at high temperatures. With a conversion rate of 63 % at 800 °C, this catalyst significantly outperforms traditional thermal cracking methods. This finding underscores the potential of advanced catalysts to improve the efficiency and stability of the gasification process for hydrogen production. In another relevant study, Theofanidis et al. [80] address the persistent issue of catalyst deactivation due to carbon deposition in reforming technologies. Their research elucidates the mechanisms of

Table 1
Inclusion and exclusion criteria.

Inclusion Criteria		Exclusion Criteria	
Criteria	Description	Criteria	Description
Relevance to Research Objectives	Articles should specifically address hydrogen production methods with a focus on sustainability, reactor technologies, and environmental impacts.	Irrelevance to Objectives	Articles that do not directly relate to hydrogen production methods, reactor technologies, or sustainability should be excluded.
Peer-Reviewed Publications	Only articles published in peer-reviewed journals will be considered, as they generally meet higher quality standards.	Non-Peer-Reviewed Materials	Grey literature, opinion pieces, and non-peer-reviewed publications will be excluded.
Language	Articles should be published in English to maintain consistency and accessibility in the review process.	Insufficient Detail	Articles that lack sufficient methodological or experimental detail, such as abstracts or brief summaries without comprehensive findings, should be excluded to ensure the quality of the review.
Publication Date	Articles should have been published between 2018 and the second quarter of 2024 to ensure the review covers the latest advancements and trends in the field.	Duplicate Publications	Articles that are duplicates or near-duplicates of previously identified articles should be excluded to avoid redundancy.
Geographic Scope	The study should include articles from a wide range of geographic locations to provide a global perspective on the topic.		

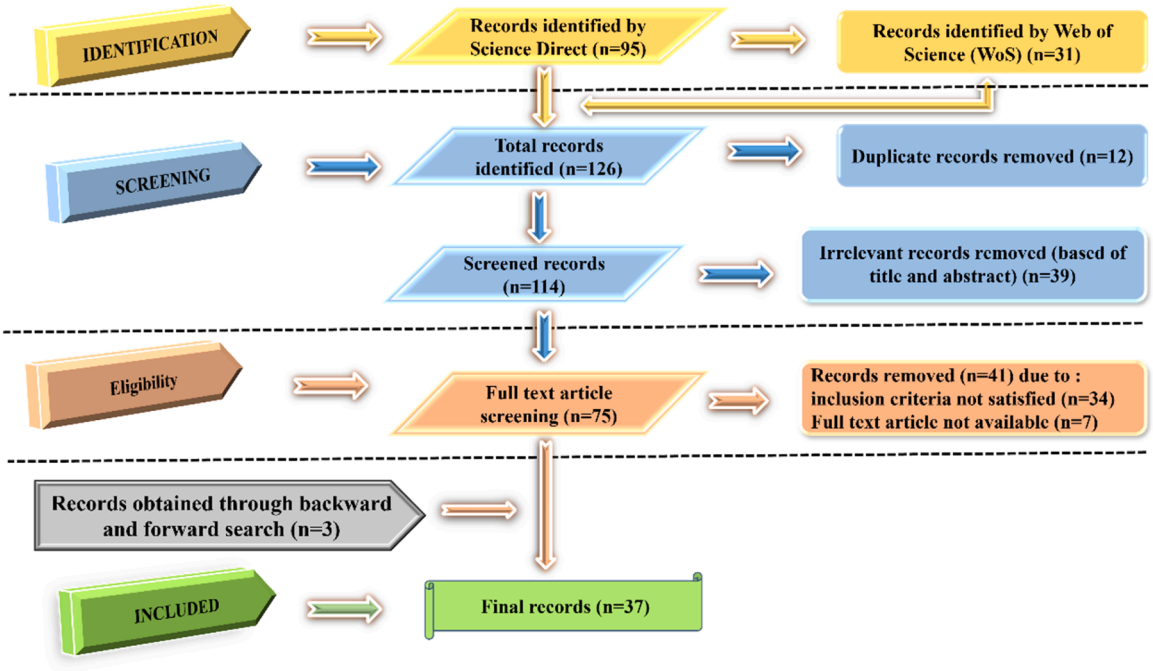

Fig. 6. Flowchart of the systematic review process based on PRISMA.

carbon removal from supported Ni catalysts, differentiating between supports with and without redox properties. They reveal that supports like Al_2O_3 and $MgAl_2O_4$, which lack redox properties, facilitate carbon removal through a two-step process involving Ni oxidation and subsequent migration. In contrast, supports with redox functionality, such as $MgFe0.09Al1.91O_4$ and $CeZrO_2$, enable direct carbon oxidation via lattice oxygen. This nuanced understanding of catalyst regeneration mechanisms is crucial for designing more resilient catalysts, thereby extending their operational life and enhancing the overall efficiency of hydrogen production via gasification. Ochoa et al. [68] contribute to this discussion by investigating the deactivation mechanisms of Ni-supported catalysts during the steam reforming of biomass pyrolysis volatiles. Their findings identify coke encapsulation and Ni sintering as primary deactivation pathways. Through detailed analyses using techniques such as XRD, N_2 adsorption-desorption, and various forms of microscopy and spectroscopy, they demonstrate that oxygenates, particularly phenols, play a significant role in coke formation. They also observe that as Ni particles become increasingly encapsulated, the rate of coke deposition slows, shifting towards the catalyst support. These insights are instrumental in developing strategies to mitigate catalyst deactivation, thereby optimizing the gasification process for hydrogen production. Advancing the field further,Qi et al. [73] conduct a comprehensive thermodynamic and techno-economic analysis of hydrogen production from different algae biomasses via plasma gasification. Their study reveals that Enteromorpha algae achieve the highest exergy efficiency (74.46 %) and overall process efficiency (33.92 %) compared to other algae such as Cyanobacteria and Sargassum. They identify significant exergy losses in the acid gas removal and plasma gasification units, which account for a substantial portion of the total exergy loss. Additionally, their economic analysis highlights the sensitivity of the process to feedstock and electricity prices, positioning Enteromorpha as a particularly promising feedstock for cost-effective hydrogen production through gasification. Finally, Sun et al. [78] explore the potential of a NiOOH—CuO nano-heterostructure in enhancing the ethanol oxidation reaction (EOR) within a hybrid water electrolysis setup. Their innovative approach aims to substitute the anodic oxygen evolution reaction with EOR, facilitating simultaneous biomass upgrading and hydrogen production. The NiOOH—CuO catalyst, anchored on a three-dimensional conductive Cu foam, demonstrates superior performance, significantly lowering the energy barriers for EOR. This method not only reduces the cell voltage required for hydrogen generation but also achieves high ethanol conversion rates, resulting in the efficient production of acetate. This study exemplifies the versatility and potential of integrating biomass upgrading with hydrogen production, paving the way for more sustainable and efficient gasification-derived hydrogen production processes.

The use of ATR in hydrogen production has been extensively explored in recent research, showcasing significant advancements and innovative methodologies. Hu et al. [41] developed NiYxZr0.85-xOy catalysts supported by a Y-Zr-O solid solution for the ATR of acetic acid. Their study demonstrates that the incorporation of oxygen vacancies, which enhance the mobility of oxygen species on the catalyst surface, significantly improves hydrogen yield and catalyst stability. Notably, the NiY0.2Zr0.65O1.75 catalyst achieved nearly complete conversion of acetic acid with a hydrogen yield of 3.0 mol-H_2/mol-HAc while mitigating issues related to coking. Furthering the field, Sun et al. [79] proposed a chemical looping oxidative steam reforming process utilizing $Cu_2O/Ca_2Fe_2O_5$ as a catalytic oxygen carrier for methanol ATR. This innovative approach leverages lattice oxygen to facilitate the partial oxidation of methanol, achieving a hydrogen production rate of 37.6 $\mu mol{\cdot}H_2{\cdot}g-1{\cdot}COC{\cdot}s-1$ at 240 °C. The study highlights the role of $Ca_2Fe_2O_5$ in tuning the redox activity, which is crucial for efficient hydrogen production via chemical looping pathways. The work by Cai et al. [16] on Pd/MoC catalysts represents a significant leap in methanol decomposition for ATR. Their research indicates that a 0.5Pd/MoC catalyst, characterized by highly dispersed Pd particles on α-MoC1$-x$, significantly surpasses traditional CuZnAl catalysts. It achieved a remarkable turnover frequency of 807 mol-H_2·molPd$-1{\cdot}h-1$ at 160 °C. The catalyst's stability across various temperatures is attributed to the robust interaction between Pd particles and the α-MoC1$-x$ phase, underscoring its potential for sustainable hydrogen production. Dudek et al. [25] explored an alternative pathway for naphtha conversion through redox oxidative cracking (ROC) using perovskite oxides in an ATR mode. Their findings reveal that Na_2WO_4-promoted $SrMnO_3$ and $CaMnO_3$ catalysts not only enhance olefin yields but also achieve efficient hydrogen combustion, thereby reducing CO_2 emissions and energy

consumption compared to conventional naphtha steam cracking methods. This approach presents a promising avenue for environmentally friendly hydrogen production. Gan et al. [36] synthesized Ni-Y-Ti-O catalysts featuring a $Y_2Ti_2O_7$ pyrochlore structure for the ATR of acetic acid. The N10YT catalyst demonstrated complete acetic acid conversion and a hydrogen yield of 2.62 mol-H_2/mol-HAc. Its high performance is attributed to the intrinsic oxygen vacancies and strong interactions between the Ni metal and the support. This study highlights the potential of pyrochlore structures in enhancing catalyst activity and stability for hydrogen production. The research by Zheng et al. [99] introduces a novel approach to optimizing methanol steam reforming micro-reactors for ATR through the design of a trapezoidal cavity. Their simulations and experimental results indicate that the F-type trapezoidal cavity significantly enhances reforming temperature performance, methanol conversion rates, and hydrogen yield. This innovative design offers a new method for improving the efficiency of ATR systems. Chen et al. [19]addressed the challenges of catalyst deactivation in the ATR of acetic acid by incorporating WO_2 into Ni-based catalysts. The Ni-$_2$W/-SiO_2 catalyst, with 2 wt% WO_2, exhibited stable performance with 100 % acetic acid Z sintering and carbon deposition, thereby maintaining catalyst stability and activity.

Water electrolysis, a cornerstone technology for sustainable hydrogen production, has garnered significant research interest due to its potential to generate clean energy. Recent studies have focused on various strategies to enhance the efficiency and durability of electrocatalysts used in this process. In their investigation, Li et al. [55] tackled the challenge of improving the longevity of platinum (Pt) nanoparticles, commonly employed in water electrolysis. They utilized atomic layer deposition (ALD) to apply an ultrathin silicon dioxide (SiO_2) layer on Pt/CB electrocatalysts. This approach significantly mitigated Pt agglomeration and detachment during the hydrogen evolution reaction (HER). Their findings revealed that just a few cycles of SiO_2 ALD substantially reduced the decline in current density after accelerated durability tests. This extended the catalyst's effective lifespan and maintained high catalytic activity. This approach underscores the potential of surface coatings to enhance the stability and efficiency of Pt-based catalysts in water electrolysis. Li et al. [57] introduced an innovative synthesis of nonconsecutive carbon-coated RuP_2 porous microsheets (RuP_2@InC-MSs), designed as bifunctional electrocatalysts for operation under neutral conditions. Their environmentally benign one-pot thermolysis method employed low-cost phosphorization agents. The resulting catalysts exhibited superior performance in both the hydrazine oxidation reaction (HzOR) and HER. Notably, these catalysts demonstrated significant energy-saving potential in hybrid water electrolyzers, achieving robust current densities and showcasing the viability of integrating solar energy for hydrogen production. This study highlights the importance of developing multifunctional catalysts that operate efficiently under mild conditions. Zhou et al. [102] focused on developing valence-variable metal-modified $CuCo_2S_4$ thiospinels to enhance the oxygen evolution reaction (OER) at large current densities, a critical factor in industrial-scale water electrolysis. By incorporating metals such as Mn, V, and Cr, the researchers facilitated the formation of an oxyhydroxide-like active phase, which improved OER kinetics by altering the Co-Co interatomic distances. Their optimized catalysts achieved remarkable overpotentials and turnover frequencies, far exceeding those of commercial RuO_2 catalysts. This study offers valuable insights into the design of high-performance catalysts for large-scale hydrogen production. Fu-Min Hassan et al. [40] explored the electronic structure modification of ultrathin MnFeOOH integrated with Ni_3S_2, aiming to develop bifunctional electrocatalysts for improved alkaline water splitting. By varying the Mn/Fe ratio, the researchers fine-tuned the adsorption properties of oxygen- and hydrogen-containing intermediates, thereby enhancing both OER and HER activities. Their optimized catalysts demonstrated excellent durability and efficiency, achieving significant current densities at low overpotentials. This research provides a strategic approach to designing hybrid catalysts with tailored electronic properties for efficient water electrolysis. The study conducted by Xie et al. [89] synthesized cobalt corrole complexes with varying numbers of cyano groups to investigate their electrocatalytic performance in hydrogen production. The presence of cyano-substituents notably enhanced the catalytic activity, with the complexes achieving high turnover frequencies and faradaic efficiencies in both organic and neutral aqueous media. This work underscores the significance of molecular structure in determining catalytic performance and offers a pathway for designing effective electrocatalysts for HER [14] examined the electrocatalytic activity of metal-free organic catalysts based on 1,10-phenanthroline for HER. Their study revealed that the efficiency and mechanism of the HER were influenced by the nature of the catalyst and the pKa of the acids used. The researchers provided the first evidence of HER occurring at different potentials through the same mechanism, identified key intermediates, and used DFT methods to elucidate the underlying processes. This research highlights the potential of metal-free catalysts in advancing the field of water electrolysis.

A study by Wang & Tang [81] delves into the electrocatalytic oxygen reduction reaction (ORR) using the rotating ring-disc electrode (RRDE) subtraction method. This innovative approach, coupled with chronoamperometric electrolysis, provides deeper insights into the intrinsic electrocatalytic activities of various homogeneous materials. The study emphasizes hydroxy anthraquinone derivatives and riboflavin, highlighting their potential for enhancing the ORR. This enhancement is crucial for water electrolysis, thereby improving overall hydrogen production efficiency. In a parallel investigation, Liu et al. [60] examined the oxygen evolution reaction (OER) on stainless steel (SS) electrodes. Their findings indicate superior selectivity and stability of SS compared to electrochemically deposited nickel oxide (EdNO). The formation of hexavalent chromium ions at the SS electrochemical interface is identified as a key factor contributing to this selectivity. These insights are instrumental in optimizing material properties for efficient hydrogen production via water electrolysis. Dolganov et al. [24] focused on the stability and decomposition pathways of the NiOOH phase in Ni-based electrocatalysts under open circuit potential. Their comprehensive study, employing both in situ and ex situ spectroscopies, reveals that NiOOH, the active phase during OER, rapidly degrades to $Ni(OH)_2$ outside operational conditions. This degradation underscores the necessity for in situ characterization methods to accurately capture the active phases of electrocatalysts. Such information is vital for improving the stability and efficiency of these materials in water electrolysis applications. Kerschbaumer et al. [50] proposed a novel approach utilizing a biochar sacrificial anode to assist in water electrolysis. This method leverages the carbon oxidation reaction to reduce the anode potential and energy consumption, thereby enhancing hydrogen production efficiency. The study demonstrates that using a combination of pinewood char, graphite, and coal liquefying residue as biochar anode components improves both activity and stability in high-concentration alkaline electrolytes. This innovative use of biochar not only offers a sustainable and scalable solution but also significantly reduces oxygen production compared to traditional platinum anodes, marking a substantial advancement in green hydrogen production technologies. Karthik et al. [48] explored the integration of renewable energy sources, specifically solar and wind, for large-scale green hydrogen production via alkaline water electrolysis. The study presents a detailed comparative analysis of electrolyzer capacities matched to the energy outputs of wind turbines and solar photovoltaic power plants. Findings indicate that solar photovoltaics offer a more cost-effective solution, producing hydrogen at a lower cost per kilogram compared to wind energy. This research provides a robust methodology for evaluating and standardizing performance assessments of renewable-based hydrogen production systems, highlighting the potential for large-scale applications and their economic feasibility. Gallenberger et al. [35] investigated the coupling of electrocatalytic oxidation of biomass derivatives with the hydrogen evolution reaction (HER) using a $Co(OH)_2$–CeO_2 catalyst. This

innovative approach aims to enhance hydrogen production while simultaneously converting biomass derivatives into high-value chemicals. The $Co(OH)_2$—CeO_2 catalyst achieved selective oxidation of 5-hydroxymethylfurfural (HMF) to 2-furancarboxylic acid (HMFCA) with remarkable selectivity, significantly boosting hydrogen production. This dual-function strategy presents a promising avenue for integrating biomass conversion with hydrogen production, enhancing the overall efficiency and sustainability of water electrolysis processes.

Photochemical water splitting has emerged as a promising method for sustainable hydrogen production by leveraging solar energy to drive chemical reactions. Recent research highlights various innovative strategies and advancements aimed at enhancing the efficiency and effectiveness of this process. A study by Shi et al. [76] investigated the photoelectrochemical (PEC) activation of methane to methyl radicals at ambient temperature and pressure using a proton exchange membrane system. The authors demonstrated that both water splitting and steam reforming of methane could be induced over oxide photoanodes, specifically titanium oxide (TiO_2) and tungsten trioxide (WO_3), under ultraviolet light irradiation. Notably, the study revealed that visible light further enhances methane activation and promotes the formation of ethane ($C2H_6$) over the WO_3 photoanode. Under optimized conditions, the selectivity of $C2H_6$ reached 57 % on a carbon basis, indicating significant potential for PEC systems to optimize hydrogen production through photochemical activation processes. In another significant contribution, Dang et al. [22] developed a Z-scheme photocatalyst composed of Pt/GaP-TiO_2-SiO_2 (PGTSR) for hydrogen evolution from photocatalytic seawater splitting. The PGTSR heterojunction exhibited high photoactivity, achieving substantial hydrogen and oxygen evolution rates under simulated sunlight. This study also employed a twin photoreactor divided by a Neosepta membrane, which facilitated the separated evolution of hydrogen from oxygen in artificial seawater splitting. The findings underscore the potential of Z-scheme photocatalysts in advancing artificial photosynthesis systems, thereby enhancing hydrogen production efficiency. Fu et al. [34] presented a novel p-type gallium indium zinc oxynitride (GaInZnON) homojunction photocatalyst with a core-shell structure for overall water splitting. This photocatalyst demonstrated impressive hydrogen and oxygen evolution rates, attributed to the facilitated charge transfer resulting from the ideal type-I band alignment between the GaInZnON core and the GaInON shell. The study's detailed characterizations and DFT calculations provided insights into the efficiency of the core-shell structure in solar-driven overall water splitting, emphasizing its potential in developing stable and efficient photocatalysts for hydrogen production. Yao et al. [94] introduced a ternary CdS/$ZnFe_2O_4$/Cu_2O core/shell heterojunction nanorod array (NRA) photoanode, designed to enhance bias-free visible-light-driven hydrogen generation. The novel stair-like type-II band alignment in the CdS/$ZnFe_2O_4$/Cu_2O core/shell NRA significantly improved photocurrent density and hydrogen generation rates compared to CdS/$ZnFe_2O_4$ and CdS NRAs alone. The study highlighted the efficient charge transfer and separation achieved by this band alignment, resulting in superior photostability and hydrogen production efficiency. This work illustrates the potential of core/shell NRA photoanodes in optimizing photochemical water splitting processes for hydrogen production.

Recent breakthroughs in photocatalytic and electrolysis technologies have significantly improved the potential for sustainable hydrogen production. In the field of photochemical water splitting, the development of perovskite-based photocatalysts has demonstrated remarkable improvements in light absorption, charge separation efficiency, and stability under solar irradiation. Notably, newly engineered perovskite heterojunction systems have achieved hydrogen production rates surpassing those of conventional oxide photocatalysts, as evidenced in recent works [69]. Similarly, in water electrolysis, anion exchange membrane (AEM) electrolyzers have emerged as a promising alternative to traditional proton exchange membrane (PEM) electrolyzers. AEM electrolyzers operate efficiently under alkaline conditions, reducing the need for expensive noble metal catalysts. Recent studies [31] have shown that novel AEM electrolyzers achieve high current densities with improved durability, offering a cost-effective pathway for green hydrogen production. Furthermore, innovative catalyst designs have enhanced the oxygen evolution reaction (OER) and hydrogen evolution reaction (HER) kinetics, further advancing electrolyzer performance [39]. These technological advancements address the primary bottlenecks of low efficiency and high cost associated with traditional photochemical and electrochemical hydrogen production. As such, they present promising routes for large-scale, economically viable, and environmentally sustainable hydrogen generation.

The exploration of steam reforming for hydrogen production has led to significant advancements, showcasing the breadth and depth of research in this domain. Li et al. [57] focused on overcoming the economic and environmental challenges associated with commercial reforming catalysts by developing a recyclable NiCaOx/NaCl catalyst. Their study achieved an impressive near 100 % hydrogen yield and complete ethanol conversion at temperatures between 650 and 700 °C. The catalyst's ability to be regenerated and maintain high performance after 50 hours of operation demonstrates its potential for sustainable hydrogen production. The roles of NaCl and CaO in enhancing the adsorption and activation of ethanol molecules were crucial in achieving these results, highlighting the importance of innovative catalyst design in steam reforming processes. In a different approach, Wei et al. [84] investigated methanol steam reforming using a ZnCeZrOx catalyst. The incorporation of cerium into the catalyst structure significantly improved both activity and stability by creating oxygen vacancies that facilitated water activation. This enhancement is critical for sustaining high hydrogen production rates over extended periods. The findings from this study underscore the potential of cerium-doped catalysts to provide robust and long-term solutions for hydrogen production via methanol steam reforming. Further advancements were made by Zheng et al. [97], who optimized the design of self-thermal methanol steam reforming microreactors (MSRM) to enhance hydrogen production. By refining the structure of the combustion catalyst support and optimizing the flow direction between reactants, they achieved a remarkable 100 % methanol conversion and substantial hydrogen output. This study emphasizes the significance of reactor design in improving the efficiency and efficacy of steam reforming processes, paving the way for more effective hydrogen production systems. Brito et al. [15] explored the steam reforming of biomass gasification gas, offering a comprehensive analysis from thermodynamic simulations to experimental validation. Their work demonstrated that steam reforming conditions at 725 to 850 °C, 1 bar pressure, and a steam-to-carbon ratio of 3 were optimal for enhancing hydrogen content and achieving nearly complete hydrocarbon conversion. This research highlights the viability of converting biomass-derived syngas into hydrogen, presenting a sustainable pathway for hydrogen production from renewable sources. The integration of renewable energy in steam reforming processes was further explored by Zhang et al. [96] through the development of a reflux solar methanol steam reforming reactor (SMSRR) system. By utilizing solar thermal energy, the SMSRR system significantly improved energy conversion rates and hydrogen yield. The optimized design, which included the use of reflux tubes to recycle heat, demonstrated a marked increase in methanol conversion efficiency. This study underscores the potential of integrating solar energy into hydrogen production processes, contributing to the development of more sustainable and efficient reforming technologies. Xu et al. [91] investigated the production of hydrogen from phenol using novel Ni/Al_2O_3-ash catalysts. The study revealed that a 50 % fly ash mixing ratio and an operational temperature of 450 °C, combined with an optimal steam-to-carbon ratio, achieved a maximum hydrogen yield of 83.8 %. The stability of the catalyst over prolonged periods further demonstrated its viability for continuous hydrogen production. This innovative approach highlights the potential for utilizing waste materials in steam reforming, offering both economic and environmental benefits.

Conducted a kinetic study on the steam reforming of light hydrocarbon mixtures derived from waste resources Woo et al. [87]. They utilized a commercial Ni-based catalyst to investigate two simulated gas compositions. The study generated kinetic data across various temperatures, space velocities, and steam-to-carbon ratios. The results indicated that higher hydrocarbon chains reduced methane conversion. However, these chains also promoted methanation, thereby increasing the hydrogen production rate. Interestingly, despite a decrease in methane fraction, a 10 % methane fraction in the hydrocarbon mixture boosted hydrogen production by 4 %. This finding suggests that direct reforming of waste-derived light hydrocarbons, without pre-reforming, is both feasible and effective. Furthering the field, Zheng et al. [100] optimized the design of an auto-thermal methanol steam reforming micro-reactor (ATMSRM) for better hydrogen production performance. Numerical simulations revealed that an F-type trapezoidal cavity significantly improved reforming temperature performance. The optimized ATMSRM exhibited a smaller temperature difference per degree Celsius, higher methanol conversion rates, and increased hydrogen yields compared to non-optimized designs and those with different cavity shapes. This innovative design proposes a promising method for enhancing the efficiency and output of ATMSRMs in hydrogen production. In another study, [98] optimized the integration design of self-thermal methanol steam reforming microreactors to enhance hydrogen production capabilities. This research examined the structural configuration of combustion catalyst supports (CCSs), the number of CCSs, the flow direction of reactants, and the amplification mode of the microreactor. The findings indicated that using an optimized CCS structure at the front-end, integrating two non-optimized CCSs at the back-end, and adopting opposite flow directions for reactants significantly improved hydrogen production. Under these conditions, the microreactor achieved a methanol conversion rate of 100 %, with hydrogen production reaching 2.519 mol/h and a CO selectivity of 4.43 %. These results underscore the critical role of structural and operational optimizations in maximizing the efficiency and output of steam reforming microreactors. Collectively, these studies highlight the viability and potential of steam reforming for hydrogen production. They emphasize the importance of optimizing catalyst composition, reactor design, and operational conditions to enhance hydrogen yield and purity. Through kinetic modelling, thermodynamic analysis, and innovative reactor designs, significant advancements have been made in improving the efficiency and scalability of steam reforming processes. These contributions support the broader goal of sustainable hydrogen production.

The exploration of hydrogen production methods reveals significant advancements and diverse challenges. Innovative catalytic processes in gasification have demonstrated efficiency in converting various feedstocks into hydrogen. However, issues such as catalyst deactivation and carbon deposition persist. ATR have shown improvements in hydrogen yields and catalyst stability through advanced designs and optimized conditions. Water electrolysis is notable for its clean hydrogen production. Ongoing research aims at enhancing the durability and efficiency of electrocatalysts. Photochemical water splitting, which utilizes solar energy, offers a sustainable option but requires further efficiency improvements in photocatalysts. Steam reforming remains a prominent method, with innovations in catalyst development and reactor design enhancing its efficiency and sustainability. These advancements underscore the importance of continuous innovation and optimization in addressing the inherent challenges of each method. Future research should prioritize integrating renewable energy sources, developing more robust catalysts, and scaling up technologies to meet the increasing demand for sustainable hydrogen production. Collectively, these efforts are essential for advancing towards a sustainable hydrogen economy and achieving global environmental and energy objectives.

In summary, exploring hydrogen production methods reveals a complex landscape of technological innovation and practical challenges. Gasification, ATR, photochemical water splitting, water electrolysis, and steam reforming each offer distinct advantages and face specific obstacles. Advances in catalyst development, process optimization, and integrating renewable energy sources are critical in enhancing the efficiency and sustainability of these methods. No single technology currently provides a perfect solution, but a synergistic approach tailored to regional resources and conditions holds promise. Continued research and investment in diverse hydrogen production technologies are essential to meet future energy demands and achieve global sustainability goals. This comprehensive analysis underscores the importance of innovation, flexibility, and collaboration in pursuing efficient and environmentally friendly hydrogen production systems. Table 2 provides a comprehensive summary of the key findings from these pertinent studies.

4. Findings and discussion

This discourse undertakes a comprehensive examination of recent advancements and challenges in environmentally friendly hydrogen production methods. The review focuses on five distinct methods: gasification, ATR, photochemical water splitting, water electrolysis, and steam reforming. Each method represents a unique approach to hydrogen production, characterized by varying efficiencies, energy consumption, operational stability, and environmental sustainability. By synthesizing the latest peer-reviewed studies, this discussion provides a panoramic view of technological breakthroughs and methodological innovations in hydrogen production. Through meticulous content analysis, the review elucidates emergent themes and enduring challenges across these methods. The synthesis draws on diverse methodologies, highlighting unique insights that contribute to enhancing the efficiency and sustainability of hydrogen production systems. The qualitative and quantitative analyses converge to reveal a nuanced landscape where technological innovation intersects with practical implementation challenges. This integrated approach unpacks the complexities of optimizing hydrogen recovery efficiency while minimizing energy consumption and environmental impact. Moreover, the studies underscore the importance of achieving a balance between high efficiency and sustainability in hydrogen production systems. This balance is crucial for their real-world deployment and scalability. By exploring these varied facets, from methodological advancements to practical deployment challenges, the study paints a holistic picture of the current state and future trajectories in hydrogen production. It underscores the intricate interplay of technological prowess, algorithmic ingenuity, and practical applicability that collectively chart the course for the next generation of sustainable hydrogen production technologies.

4.1. Statistical analysis

Based on the relevant literature in this study, the analysis of environmentally friendly hydrogen production methods reveals a significant disparity in research contributions across different regions (*Fig. 7*). This highlights both advancements and gaps in global engagement. Notably, in Asia, China emerges as a leader with 24 studies. This reflects an intensive focus on hydrogen technology, driven by rapid urbanization and escalating energy demands. China's strategic commitment to sustainable solutions addresses both environmental and economic challenges. In Europe, Germany contributed 2 studies, while Belgium, Spain, The Netherlands, Russia, Austria, and Italy each contributed 1 study. This indicates Europe's steady yet diverse interest in optimizing hydrogen production for sustainable energy transitions. South Korea also shows notable interest in 2 studies, suggesting a growing focus on hydrogen as a key component of its energy strategy. Other regions like Japan and Iraq each contribute 1 study, showcasing their emerging involvement in this crucial research area. The uneven distribution of studies underscores a significant limitation in the global research effort. Many countries, particularly in regions like Africa, South America,

Table 2
Summary of relevant literature on the environmentally friendly hydrogen production methods Note: Hydrogen Recovery Efficiency refers to the amount of hydrogen produced per unit mass of feedstock (kg) or per unit of energy input (kWh), based on the methodology used in each referenced study. All values for energy consumption, operational stability, and environmental sustainability are directly extracted from the cited sources under the reported experimental conditions.

Authors & Year	Method	Hydrogen Recovery Efficiency	Energy Consumption	Operational Stability	Environmental Sustainability
[90]	Catalytic tar removal using TiO_2/$NiWO_4$–Ni_5TiO_7 films	Higher efficiency than thermal cracking, 63 % naphthalene conversion at 800Å °C	N/A	Long-term stability towards catalytic steam reformation of naphthalene	Promising for future tar removal from biomass gasification
[80]	Mechanism of carbon deposits removal from supported Ni catalysts	Investigated isothermal regeneration at 993 °C; efficiency dependent on support material's redox properties	Significant economic cost reduction by catalyst regeneration	Carbon removal does not require particle migration with redox support; stable performance	Catalyst regeneration reduces waste and cost
[68]	Steam reforming of biomass pyrolysis volatiles	Deactivation due to coke encapsulation; reduced formation rate with time	N/A	Coke encapsulation and Ni sintering reduce stability	Valorization of biomass for hydrogen production
[73]	Plasma gasification of algae biomass	Exergy efficiency of 74.46 % for Enteromorpha; total efficiency 33.92 %	High exergy loss in acid gas removal and plasma gasification unit (80.14 %- 83.53 %)	High stability for Enteromorpha process compared to Cyanobacteria and Sargassum	Better economic benefits and efficiency with Enteromorpha
[78]	Ethanol oxidation by NiOOH—CuO nano-heterostructure	High ethanol conversion rate: low cell voltage required for H_2 generation	Energy-saving due to favorable ethanol oxidation	Stable high ethanol conversion rate and H_2 generation	Simultaneous biomass upgrading and hydrogen production
[41]	ATR of acetic acid using Ni-based catalysts	Near 100 % acetic acid conversion, 3.0 mol-H_2/mol-HAc	Balanced reaction heat with oxygen	High stability, no significant coking	Utilizes bio-oil, potentially reducing waste impact
[79]	Chemical looping oxidative steam reforming of methanol	37.6 $\mu mol \cdot H_2 \bullet g - 1 \cdot COC \cdot s - 1$ at 240 °C	Optimized through Cu↔Cu_2O looping	Enhanced by $Ca_2Fe_2O_5$ for oxygen mobility	Promotes efficient low-temperature methanol conversion
[16]	Methanol decomposition using Pd/MoC catalysts	High, with 807 $molH_2 \cdot molPd - 1\ h - 1$ at 160 °C	Low-temperature operation	Very stable, strong interaction between Pd and MoC	Produces clean hydrogen fuel
[25]	Redox oxidative cracking of n-hexane	Enhanced olefin yield (55–58 %)	Significantly reduced COx yield	High stability over 25 cycles	Lower CO_2 emissions compared to traditional methods
[36]	ATR of acetic acid using Ni-Y-Ti-O catalysts	100 % HAc conversion, 2.62 mol-H_2/mol-HAc	Intrinsic oxygen vacancies enhance performance	High stability, restrains sintering and coking	Utilizes bio-oil, promoting renewable biomass use
[100]	Auto-thermal methanol steam reforming micro-reactor	Higher hydrogen yield with optimal trapezoidal cavity	Enhanced reforming temperature performance	Long-term stability improved	New method for high-efficiency hydrogen production
[20]	ATR of acetic acid with Ni–W/SiO_2 catalysts	Stable at 100 % conversion, 2.8 mol-H_2/mol-HAc	WO_2 promotes efficient process	High stability, reduced sintering and carbon deposition	Enhanced catalyst performance, reduced carbon footprint
[56]	Pt/CB nanoparticles coated with ultrathin SiO_2 layers using ALD	High (significant reduction in Pt agglomeration and detachment)	Low (maintains high current density with minimal over-thick coating)	High (minimal decrease in current density after ADT)	Positive (prevents catalyst deactivation and reduces material loss)
[58]	Nonconsecutive carbon-coated RuP_2 porous microsheets	High (efficient bifunctional electrocatalyst for HER and HzOR)	Low (operates under neutral conditions)	High (excellent performance under neutral electrolyte)	Positive (environmentally benign synthesis method)
[102]	Valence-variable metal-modified $CuCo_2S_4$ thiospinels	Very High (efficient at large current densities)	Low (promotes oxyhydroxide-like active phase)	High (stable at high current densities)	Positive (uses abundant spinel materials)
[40]	Hybridization of ultrathin MnFeOOH with Ni_3S_2	High (excellent bifunctional performance)	Low (optimized electronic structure)	High (durable with optimal Mn/Fe ratios)	Positive (effective water splitting with bifunctional catalysts)
[89]	Electrocatalytic hydrogen production using CN-substituted cobalt triaryl corroles	High (efficient in both organic and aqueous media)	Low (high turnover frequencies)	High (efficient at various proton sources)	Positive (synthesis method enhances performance)
[14]	Metal-free organic catalyst based on 1,10-phenanthroline	Moderate (dependent on catalyst and acid type)	Low (different potentials for the same mechanism)	High (stable performance with specific acids)	Positive (metal-free catalysts reduce environmental impact)
[81]	Rotating ring-disc electrode (RRDE) and chronoamperometric electrolysis	Not specified	Not specified	Significant background activity with conventional electrode materials investigated	Enhanced understanding of electrocatalytic ability to improve OER
[24]	Electrocatalytic oxygen evolution reaction (OER) on stainless steel	High selectivity towards OER	Cost-effective	Stable and sustainable electrocatalyst with no interaction with methanol under equilibrium conditions	Stainless steel as a sustainable and efficient electrocatalyst
[60]	NiOOH OER active phase of NiOx electrocatalysts	Decomposes to Ni (OH)2	Requires in situ methods	NiOOH phase degrades quickly at open circuit potential, necessitating operando characterization approaches	Highlights the need for in situ characterization to understand catalyst behavior

(*continued on next page*)

Table 2 (*continued*)

Authors & Year	Method	Hydrogen Recovery Efficiency	Energy Consumption	Operational Stability	Environmental Sustainability
[50]	Biochar sacrificial anode-assisted water electrolysis	Improved with biochar	Reduced (60–76 % of Pt anode)	High stability and activity in high concentration alkaline electrolyte	Industrially clean, scalable, and sustainable approach for green hydrogen production
[48]	Alkaline water electrolysis using solar and wind energy	High, varying by energy source	Cost-effective (6.33–8.87 $/kg)	Adaptable method for large-scale applications with high hydrogen production rate from renewable sources	Reduces carbon footprint and adapts to various environmental conditions for large-scale hydrogen production
[35]	Electrocatalytic conversion of biomass derivatives with Co $(OH)_2$–CeO_2 catalyst	High (selectivity of 89.4 %)	Boosted hydrogen production (4.1 times water splitting)	Stable electrocatalytic conversion under regulated pH and potential	Potential for developing clean energy through selective biomass conversion coupled with hydrogen production
[76]	Photoelectrochemical activation of methane	Not specified; implied by C_2H_6 formation	Not specified	Operational under ambient temperature and pressure	Uses methane, a potent greenhouse gas
[22]	Z-scheme photocatalyst Pt/GaP-TiO_2-SiO_2: Rh	HER: 80.1 $^{\mu m}$ol/g in pure water, 94.0 $^{\mu m}$ol/g in artificial seawater	4-hour simulated sunlight irradiation	Stable performance with high Ti_3+ defects and oxygen vacancies	Uses seawater; potential for large-scale solar energy conversion
[34]	Core-shell GaInZnON@GaInON homojunction	H_2 evolution rate of 603 $^{\mu m}$ol/h/g	Apparent quantum efficiency of 3.5 % at 430 nm	Stable with facilitated charge transfer due to band alignment	Solar-driven process with efficient photocatalyst
[94]	CdS/$ZnFe_2O_4$/Cu_2O core-shell nanorod array	H_2 generation rate of 134 $^{\mu m}$ol/h	Bias-free visible light irradiation	Good photostability with continuous light irradiation of 2 hours	Bias-free visible-light-driven process; efficient charge transfer
[57]	NiCaOx/NaCl catalysts	Approximately 100 %	Operates at 650–700 °C	Sustained operation for 50 hours at 650 °C	Catalyst is recyclable and reprocessable
[84]	ZnCeZrOx catalyst	93.6 % to99.8 %	Operates at 400 °C	Stable solid solution structure induced by Ce doping	Enhanced activity due to oxygen vacancies and stable structure
[97],	Self-thermal methanol steam reforming microreactor (MSRM)	100 % CH_3OH conversion	Operates with 48 mL/h methanol-water compound and 3.2 mL/min methanol	High HP capability with optimized CCS structure	Optimized design for improved efficiency
[15]	Steam reforming of biomass gasification gas	48.7 % to 61.8 %	Operates at 725 to 850 °C, 1 bar, S/C ratio of 3	High hydrogen yield and purity, particularly with lignin-derived streams	Mitigates coke formation, high hydrogen purity
[96]	Reflux solar methanol steam reforming reactor (SMSRR)	Increased by 5.96 %	Improved energy conversion rate by 19.5 %	Methanol conversion increased by 6.43 %	Utilizes solar thermal energy, reduces outlet temperature
[91]	Steam reforming of phenol over Ni/Al_2O_3-ash catalysts	83.80 %	N/A	>20 hours at 450Â °C	Utilization of fly ash-based catalysts
[87]	Steam reforming of light hydrocarbon mixture from waste resources	Increased by 4 % with 10 % methane fraction	N/A	N/A	Feasibility of direct reforming without pre-reforming
[99]	Auto-thermal methanol steam reforming micro-reactor with trapezoidal cavity	Higher with optimal trapezoidal cavity	Optimized for lower consumption	Improved long-term performance	Enhanced efficiency reducing carbon emissions
[98]	Self-thermal methanol steam reforming microreactor	100 % CH_3OH conversion, 2.519 mol/h H_2	Optimized for lower consumption	High stability with optimal conditions	Reduced CO selectivity (4.43 %)

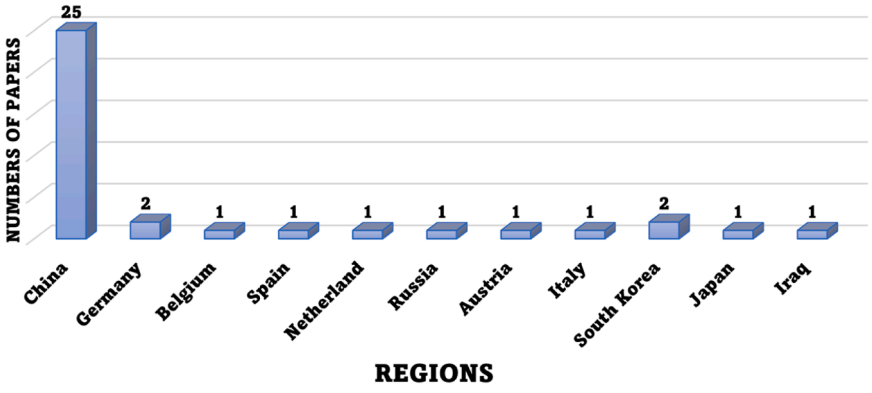

Fig. 7. Geographical distribution of empirical studies on the hydrogen production.

North America, and parts of Asia, are underrepresented. This disparity highlights the need for broader international collaboration and increased investment in hydrogen research. Enhanced participation from underrepresented countries could drive innovation, address unique local energy challenges, and contribute to a more sustainable global energy future.

In a comprehensive review of environmentally friendly hydrogen production methods, 37 studies were meticulously analysed and categorized into five key thematic clusters (*Table 3*). This framework provides a clear understanding of current research trends. The review

Table 3
Systematic content analysis of studies on hydrogen production methods.

Study	Gasification	ATR	Photochemical Water Splitting	Water Electrolysis	Steam Reforming
[90]	✓				
[80]	✓				
[68]	✓				
[73]	✓				
[78]	✓				
[41]		✓			
[79]		✓			
[16]		✓			
[25]		✓			
[36]		✓			
[100]		✓			
[19]		✓			
[55]				✓	
[57]				✓	
[102]				✓	
[40]				✓	
[89]				✓	
[14]				✓	
[81]				✓	
[24]				✓	
[60]				✓	
[50]				✓	
[48]				✓	
[35]				✓	
[76]			✓		
[22]			✓		
[34]			✓		
[94]			✓		
[57]					✓
[84]					✓
[97],					✓
[15]					✓
[96]					✓
[91]					✓
[88]					✓
[99]					✓
[97]					✓

reveals a significant focus on photochemical water splitting, with 12 studies dedicated to this method. This highlights its potential as a promising approach for hydrogen production. Steam reforming follows closely with 9 studies, indicating its continued relevance despite environmental concerns. ATR technology is the subject of 7 studies, reflecting ongoing interest in optimizing this method for better efficiency and sustainability. Gasification is discussed in 5 studies, showcasing its role in converting organic materials into hydrogen. Water electrolysis, another crucial method, is examined in 4 studies, emphasizing its importance in producing hydrogen using renewable energy sources. This detailed thematic analysis highlights concentrated research efforts in specific hydrogen production technologies while also identifying gaps in the literature. Notably, regions with fewer studies suggest a need for broader international research collaboration and increased investment. This would ensure a more balanced and comprehensive understanding of efficient and sustainable hydrogen production methods. Enhanced involvement from countries with limited studies could foster innovation and address unique local energy challenges, thereby contributing to a more sustainable global hydrogen production landscape.

To visually summarize the key focus areas in environmentally friendly hydrogen production methods, *Fig. 8* presents a pie chart that represents the percentage distribution of various technologies identified in the selected studies. By visually representing these technologies, the chart offers insight into the academic emphasis placed on each method, enhancing the understanding of the current research landscape.

The chronological analysis from 2018 to the second quarter of 2024 (*Fig. 9*) highlights the evolving research focus on environmentally friendly hydrogen production methods. This timeline showcases the growing interest and advancements in hydrogen production technologies over the years. In 2018, two studies initiated the exploration into sustainable hydrogen production, marking the beginning of this research trajectory. The interest grew steadily with three studies each in 2019 and 2020, indicating increasing recognition of hydrogen's potential as a clean energy source. The years 2021 and 2022 saw significant surges in research activity with eight studies each, reflecting a

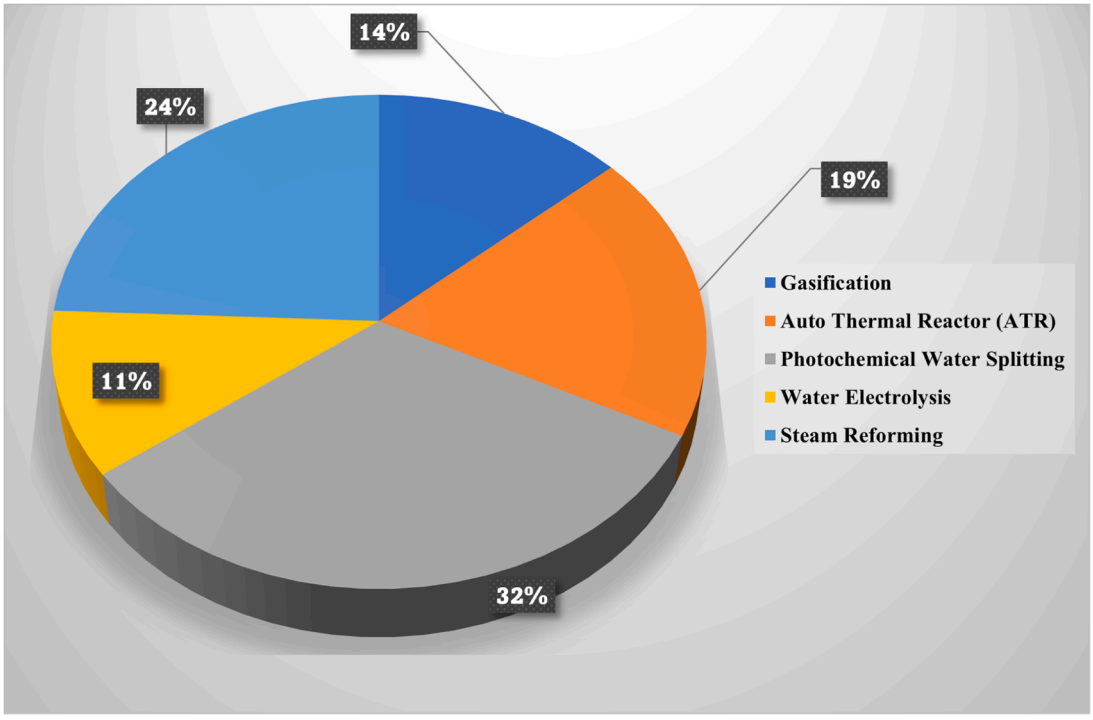

Fig. 8. Chart depicting the distribution of environmentally friendly hydrogen production methods based on the systematic analysis of 37 peer-reviewed studies published between 2018 and the second quarter of 2024. Data extracted through systematic literature review methodology.

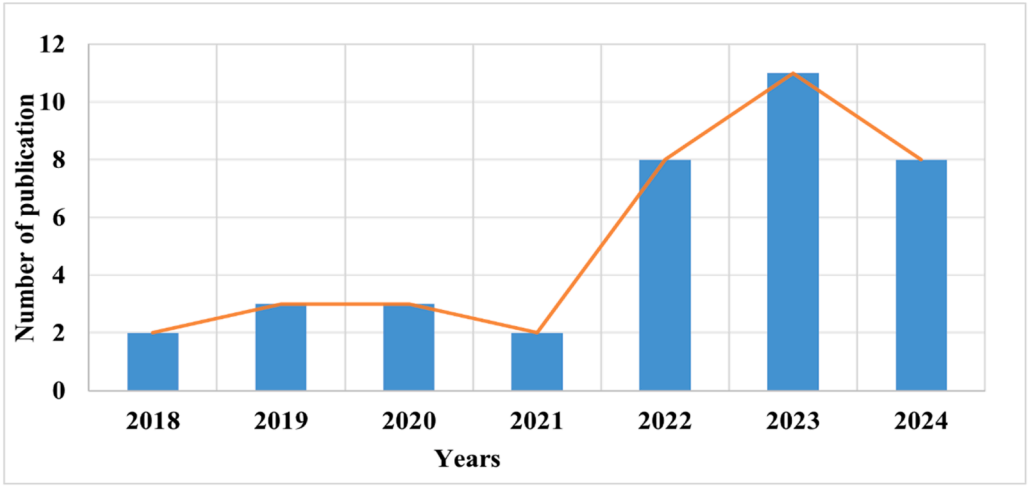

Fig. 9. Trend analysis of academic publications on environmentally friendly hydrogen production methods (2018–Q2 2024), based on data synthesized from 37 systematically reviewed articles. The statistical trend was analyzed through content analysis and chronological mapping.

heightened global commitment to developing efficient and sustainable hydrogen production methods. The peak came in 2023 with eleven studies, showcasing the culmination of intensive research efforts. In 2024, despite being only the second quarter of the year, the research activity has maintained its momentum with eight studies, indicating a continued strong focus on this field. This chronological pattern underscores the dynamic progression of research on hydrogen production. It evolved from initial explorations to more concentrated and impactful studies. This reflects an academic field that is increasingly attuned to the challenges and opportunities of sustainable hydrogen production, emphasizing the need for ongoing innovation and research to address the complexities of this vital energy source. In sum, this analysis highlights the critical importance of continued efforts in developing environmentally friendly hydrogen production methods to support global sustainability goals.

4.2. Challenges, solutions, and impact of hydrogen production methods

Hydrogen production plays a crucial role in advancing sustainable energy systems. It offers a clean and versatile energy carrier capable of significantly reducing carbon emissions. However, each hydrogen production method encounters unique challenges that affect its efficiency, cost-effectiveness, and environmental sustainability. This section examines the specific challenges associated with five prominent hydrogen production methods: gasification, ATR technology, photochemical water splitting, water electrolysis, and steam reforming. It also explores innovative solutions developed to address these challenges and evaluates their impacts on hydrogen production. By understanding these aspects, it becomes possible to appreciate the complexities and advancements driving the evolution of hydrogen production technologies towards a more sustainable future.

4.2.1. Biomass gasification

Biomass gasification is a well-established method for hydrogen production that involves converting carbonaceous materials, such as coal, biomass, and waste, into hydrogen and other valuable gases through a series of thermochemical processes [45]. Despite its potential, gasification faces several significant challenges. One of the primary issues is the production of tar and other contaminants during the gasification process. These impurities can hinder the efficiency of hydrogen extraction and lead to operational difficulties [47]. To ensure the purity of the hydrogen produced, complex and costly gas cleaning systems are required. Another challenge is the high energy consumption associated with the gasification process, which can offset the environmental benefits of using renewable feedstocks. To address these problems, advanced gasification technologies have been developed. These include plasma gasification and integrated gasification combined cycle (IGCC) systems, which aim to improve efficiency and reduce emissions. Additionally, the use of catalysts and optimization of operating conditions can significantly enhance the gasification process [88] . These improvements reduce tar formation and improve hydrogen yield. The implementation of these solutions has shown promising results, with increased hydrogen production efficiency and lower environmental impact. However, the economic viability of gasification remains a concern due to substantial initial investment and operational costs. Gasification's positive impact lies in its ability to utilize a wide range of feedstocks, including waste materials [32]. This contributes to waste management and reduces reliance on fossil fuels. Moreover, gasification can be integrated with carbon capture and storage (CCS) technologies to further mitigate its environmental footprint. In summary, while gasification presents notable challenges, ongoing advancements and solutions are enhancing its feasibility and sustainability as a method for hydrogen production. This makes gasification a crucial component of the transition to a cleaner energy future.

4.2.2. ATR

ATR technology for hydrogen production faces several challenges, primarily related to operational efficiency and environmental impacts [66]. One significant issue is the precise control of the reaction temperature and the air-to-fuel ratio. Optimizing these parameters is crucial for maximizing hydrogen yield and minimizing unwanted by-products such as carbon monoxide and carbon dioxide. Variations in these parameters can lead to incomplete reactions, reducing overall efficiency and increasing greenhouse gas emissions. To address these issues, advanced control systems and sensors have been developed [30]. These technologies monitor and adjust reaction conditions in real-time, ensuring optimal performance. Another solution involves integrating catalysts that enhance reaction rates and selectivity towards hydrogen production. This improvement increases efficiency and reduces by-product formation. The implementation of ATR technology offers several benefits [18]. It has the potential for higher hydrogen yields compared to traditional steam reforming methods due to the exothermic nature of the reactions, which provide additional energy to sustain the process. Additionally, ATR can utilize a wide range of feedstocks, including natural gas, biogas, and other hydrocarbons, making it a versatile option for hydrogen production [43]. However, there are negative impacts to consider. High operational costs are associated with advanced control systems and catalysts. Moreover, the need for

significant energy input can offset the environmental benefits if the energy is sourced from non-renewable resources. Hence, ATR technology presents promising advancements in hydrogen production [101]. However, addressing its challenges is crucial for maximizing its potential benefits and minimizing its environmental footprint.

4.2.3. Photochemical water splitting

Photochemical water splitting is an innovative method for hydrogen production that utilizes solar energy to drive the chemical reactions necessary for splitting water molecules into hydrogen and oxygen [26]. A significant challenge of this method is the low efficiency of photon-to-hydrogen conversion. This inefficiency is primarily due to the limited absorption spectrum and poor quantum efficiency of the photocatalysts used [64]. Many photocatalysts struggle to effectively utilize visible light, which constitutes a large portion of the solar spectrum, and there is also the rapid recombination of photogenerated charge carriers. To address these challenges, advanced photocatalysts with broader absorption spectra and higher quantum efficiencies are being developed [4]. Examples include photocatalysts doped with transition metals or constructed with heterojunction structures that facilitate better charge separation and utilization. Additionally, optimizing the surface area and morphology of the photocatalysts can significantly enhance light absorption and reaction kinetics. Photochemical water splitting has substantial positive impacts, particularly in terms of environmental sustainability. By harnessing abundant solar energy, this method offers a clean and renewable pathway for hydrogen production, reducing reliance on fossil fuels and minimizing greenhouse gas emissions. However, scalability and economic feasibility of large-scale photochemical water splitting remain critical issues [2]. Advancements in material science and engineering are essential to overcome these barriers. With these advancements, photochemical water splitting has the potential to become a viable and sustainable solution for hydrogen production. This would contribute significantly to global efforts in mitigating climate change and advancing renewable energy technologies.

4.2.4. Water electrolysis

Water electrolysis is a well-established method for hydrogen production, known for its simplicity and ability to generate high-purity hydrogen [70]. However, it faces several challenges that hinder its widespread adoption [59] . A significant issue is the high energy consumption required for the electrolysis process, which affects its overall efficiency and cost-effectiveness. This energy-intensive nature arises from the need to split water molecules into hydrogen and oxygen using electrical energy. If this energy is sourced from non-renewable resources, the environmental benefits are negated [21]. Moreover, the durability and cost of the electrolyzer materials, particularly catalysts and membranes, present significant obstacles. These materials often degrade over time, leading to increased maintenance costs and reduced operational stability [5]. To address these challenges, research has focused on improving the efficiency of electrolyzers through advanced catalyst development and the integration of renewable energy sources such as solar and wind power. For instance, developing low-cost, high-efficiency catalysts, such as transition metal alloys, and using proton exchange membrane (PEM) electrolyzers, has shown promise in reducing both costs and energy consumption [67]. Implementing renewable energy sources to power electrolysis significantly enhances its sustainability profile by ensuring that the hydrogen produced is truly green [10]. The positive impacts of these solutions include a reduction in greenhouse gas emissions and a move towards a more sustainable energy system. However, transitioning to renewable energy-powered electrolysis also presents challenges, such as the intermittency of renewable energy sources, which can affect the continuous operation of electrolyzers [71]. Despite these challenges, the successful integration of advanced materials and renewable energy sources in water electrolysis systems holds great promise [13]. This approach can lead to large-scale, environmentally friendly hydrogen production, contributing positively to global energy sustainability efforts.

4.2.5. Steam reforming

Steam reforming is a widely utilized method for hydrogen production, particularly valued for its efficiency in converting hydrocarbons, such as natural gas, into hydrogen [23]. However, this method faces several significant challenges. One of the primary issues is the high energy requirement. The process operates at elevated temperatures, typically between 700–1100 °C, necessitating substantial energy input. This energy is often derived from fossil fuels, contributing to greenhouse gas emissions [82]. Another significant challenge is catalyst deactivation due to coking, which reduces the efficiency of the process over time. Solutions to these challenges have been extensively explored. For instance, advancements in catalyst design have shown promise [19]. The development of Ni-based catalysts with enhanced resistance to coking and sintering has been particularly effective in maintaining high catalytic activity and longevity. Moreover, integrating renewable energy sources for process heating can mitigate the carbon footprint associated with steam reforming [83]. Implementing these solutions has notable impacts. Improved catalyst longevity reduces operational costs and enhances the overall efficiency of hydrogen production. Utilizing renewable energy for the process can significantly lower greenhouse gas emissions, aligning steam reforming with environmental sustainability goals. However, these solutions also present challenges [7]. The initial investment for advanced catalysts and renewable energy infrastructure can be substantial, potentially posing economic barriers to widespread adoption. Additionally, while the integration of renewable energy is beneficial, it requires a stable and reliable supply, which can be variable and intermittent [93,11]. Despite these challenges, steam reforming remains a pivotal technology for hydrogen production. Ongoing innovations are continually improving its environmental and economic feasibility.

4.3. Mass production feasibility, cost, and carbon footprint comparison

An evaluation of hydrogen production methods would be incomplete without considering their scalability, cost, and environmental impacts. This section summarizes recent techno-economic analyses and life cycle assessments (LCA) to assess the mass production potential, production cost, and carbon footprint of each method reviewed.

4.3.1. Mass production potential

varies across technologies. Steam reforming and ATR are the most mature and industrially scalable, benefiting from established infrastructure. Water electrolysis is increasingly scalable with modular designs, particularly when powered by renewable energy. Biomass gasification and photochemical water splitting, while promising, require further technological development for cost-effective mass production [85].

4.3.2. Cost analysis

reveals substantial differences among methods. Steam reforming remains the most cost-effective option, with production costs typically ranging between 1 and 2 USD/kg H_2, particularly in regions with inexpensive natural gas. ATR shows similar cost ranges. Water electrolysis, depending heavily on renewable electricity prices, exhibits higher costs between 4 and 6 USD/kg H_2. Biomass gasification costs are estimated at 2.5–5 USD/kg H_2. Photochemical water splitting remains in the research phase, with costs exceeding 10 USD/kg H_2 [85].

4.3.3. Carbon footprint assessments

highlight that electrolysis powered by renewable energy achieves near-zero emissions (~0 kg CO_2-eq/kg H_2). In contrast, steam reforming and ATR without carbon capture generate significant emissions (~9–12 kg CO_2-eq/kg H_2). Biomass gasification offers a lower or even negative carbon footprint if integrated with carbon capture and storage (CCS)

technologies. Photochemical water splitting, though limited by low efficiency, offers a theoretically low-carbon pathway if solar-driven systems can be scaled effectively [53].

(Table 4) Summary of mass production potential, production cost, and carbon footprint of hydrogen production methods. This comparative evaluation reinforces the importance of both technological innovation and policy incentives to drive the cost reductions and emission mitigations necessary for a sustainable hydrogen economy

5. Limitation of the study

Reflecting on the study's limitations is crucial for understanding its scope and implications. Although this review comprehensively analysed studies published up to the second quarter of 2024, it is important to recognize that the field of environmentally friendly hydrogen production is evolving at an accelerated pace. As such, the temporal boundary, spanning from 2018 to mid-2024 may have led to the exclusion of seminal earlier contributions and emerging innovations beyond this cut-off point. Future reviews should aim to incorporate the most recent studies beyond mid-2024 to ensure continued relevance and currency in assessing technological advancements. Moreover, the review identified a discernible geographical imbalance in the literature analysed, with the majority of studies originating from Asia, Europe, and North America, and relatively sparse contributions from Africa and South America. This uneven distribution could introduce regional biases, potentially skewing the findings toward practices prevalent in more extensively researched regions while underrepresenting context-specific innovations or challenges from underexplored areas. Addressing this geographical asymmetry in subsequent studies would not only enhance the representativeness of the review but also promote a more globally inclusive understanding of hydrogen production technologies.

In addition, the review's restriction to English-language sources may have inadvertently excluded significant research published in other languages, thereby limiting access to diverse epistemological perspectives and innovative approaches emanating from non-English-speaking regions. The study's focus on five main hydrogen production methods, while methodologically coherent, poses a risk of selection bias, as it may prioritize specific technologies or operational paradigms at the expense of alternative and potentially transformative practices. Furthermore, the reliance on well-established academic databases may favour prominently published research, thereby overlooking grey literature or emerging yet underrepresented contributions that could offer novel insights into the field. Finally, the exclusive emphasis on peer-reviewed publications might obscure the practical realities of hydrogen production, such as real-world implementation challenges or context-specific adaptations, which are often inadequately captured in academic literature. As such, integrating industrial reports, government white papers, and field-based evidence could provide a more comprehensive and praxis-oriented understanding. In sum, while this review offers critical insights into the current landscape of hydrogen production technologies, addressing these methodological, linguistic, geographic, and epistemic limitations in future work will be essential for constructing a more holistic and equitable framework. Such efforts would ultimately contribute to the development of globally relevant, sustainable, and context-sensitive hydrogen energy solutions.

6. Conclusion

This study provides a comprehensive analysis of environmentally friendly hydrogen production methods, revealing key findings across various technologies such as gasification, ATR, photochemical water splitting, water electrolysis, and steam reforming. Steam reforming, while recognized for its efficiency and widespread usage, encounters significant challenges including high energy requirements and catalyst deactivation. Proposed solutions such as the development of advanced Ni-based catalysts and the integration of renewable energy sources for heating have shown promise in enhancing the efficiency and sustainability of this method. On the other hand, gasification, particularly of biomass and waste materials, offers a sustainable alternative with recent advances in gas-cleaning technologies that improve hydrogen yield and purity. However, the complexity and high cost associated with biomass processing remain substantial barriers. ATR technology, which combines partial oxidation and steam reforming, presents a balanced approach with relatively lower energy consumption. Nevertheless, it demands precise control of operational conditions to prevent catalyst deactivation, posing a significant technical challenge. Photochemical water splitting, driven by solar energy, represents a highly sustainable method; however, it is hindered by low efficiency and the necessity for advanced materials to enhance light absorption and catalytic activity. Water electrolysis, powered by renewable electricity, stands out due to its environmental benefits and the production of high purity hydrogen. Despite its advantages, it faces limitations due to high operational costs and energy consumption. The collective implications of these findings suggest that no single hydrogen production method currently offers a perfect solution. Instead, a combination of methods, tailored to specific regional and resource conditions, may prove to be the most effective strategy. For instance, regions with abundant solar or wind resources could optimize steam reforming with renewable energy, while areas rich in biomass waste might find gasification more suitable. Future research should focus on developing advanced catalysts and materials to enhance efficiency and reduce costs across all methods. Furthermore, integrating these hydrogen production technologies with renewable energy systems and developing hybrid approaches could significantly enhance sustainability. Collaborative global efforts and substantial investment in diverse hydrogen production technologies are crucial for meeting future hydrogen demands and achieving climate goals. This review underscores the importance of continuous innovation and flexibility in the pursuit of efficient and sustainable hydrogen production.

Table 4
Summary of mass production potential estimated cost, and carbon footprint of various hydrogen production methods.

Hydrogen Production Method	Mass Production Potential	Cost Estimate (USD/kg H_2)	Carbon Footprint (kg CO_2-eq/kg H_2)	Reference
Steam Reforming	High	1–2	9–11	[85]
Auto Thermal Reactor	High	1.5–2.5	8–10	[31]
Water Electrolysis	Moderate to High (with renewables)	4–6	~0 (with renewable)	[38,85]
Biomass Gasification	Moderate	2.5–5	0–3 (with CCS)	[47]
Photochemical Water Splitting	Low (currently)	>10	~0 (projected)	(pidjoe, n. d.)

CRediT authorship contribution statement

Aisha Hamid: Writing – original draft. **Raja Razuan Raja Deris:** Writing – review & editing. **Siti Nur Amira Shaffee:** Writing – review & editing. **Taufiq Yap Yun Hin:** Writing – review & editing. **Divine Senanu Ametefe:** Writing – review & editing, Writing – original draft. **Mohd Lokman Ibrahim:** Supervision.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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Data availability

No data was used for the research described in the article.

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