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Current Progress in Hydrogen Production Methods: A Short Review from 2020 to 2026

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ABSTRACT

Hydrogen is viewed as one of the most essential energy carriers for the future. There are many uses of hydrogen as a fuel for rockets; as a cooling medium in future clean energy systems; as a chemical feedstock for producing ammonia or methanol; and in healthcare products such as hydrogen-rich water with possible antioxidant and therapeutic properties. This review aims to provide a summary of current hydrogen production technologies and reviews four types of hydrogen production processes: steam methane reforming (SMR), water electrolysis, thermochemical processes, and biological methods. This review summarizes, compares, and analyzes the timeline of developments over the last six years for each of the four hydrogen production processes. This article is intended to researchers in hydrogen production and related fields, especially those working in sustainable energy research.

Keywords: Hydrogen Production, Steam Methane Reforming, Electrolysis of Water.

1. INTRODUCTION

In a low-carbon economy, hydrogen could be used as a clean fuel, especially in fuel cells, which use chemical reactions to generate electricity without harmful pollutants. This is the case for sustainable energy. In general, hydrogen generates fewer pollutants than other fuels. Hydrogen can also be used to provide energy to vehicles and to store energy on a large scale for manufacturing. However, the sustainability of hydrogen, from an environmental perspective, is highly dependent on the production method [1].

Hydrogen has been viewed as a potential source of renewable energy for a long time; however, the reason hydrogen is not currently being implemented on a large scale is due to the cost of implementing a technology to produce, store, and convert hydrogen into a usable energy form. Currently, most hydrogen production methods are fossil fuel-based and emit large amounts of carbon dioxide, creating environmental issues. Therefore, a complete evaluation of all aspects of hydrogen production pathways, storage technologies, supply chain, and economic feasibility must be conducted to support the transition to a sustainable hydrogen economy [2].

Hydrogen is also the most abundant element on Earth and is increasingly recognized for its potential as a feedstock for a wide range of applications across various industries. Hydrogen's availability as a naturally occurring substance is well known, and recent studies are exploring the

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potential to produce and commercialize naturally occurring underground hydrogen for industrial purposes. Low-carbon production techniques, such as carbon capture and storage (CCS) and electrolysis, can reduce emissions compared to conventional fossil fuel-based hydrogen production, although they cannot eliminate emissions [2, 3].

A green hydrogen economy is a necessary step toward a sustainable future, as the majority of hydrogen produced to date has been generated by fossil-fuel–based processes (gray hydrogen). The transition to green hydrogen is a crucial step toward achieving a significant reduction in greenhouse gas emissions by using renewable, clean energy sources for hydrogen production. Rapid advancements are being made in the deployment and integration of green hydrogen into existing infrastructure, and both governments and society must support this transition toward a hydrogen-based economy [4].

This review article offers valuable insight into what will shape hydrogen production in the coming years. To meet current industrial and energy demands worldwide, hydrogen production strategies will remain valid only if effective hydrogen production methods are available. This review paper will summarize previous research on hydrogen production by synthesizing and comparing information from each publication on hydrogen production. Moreover, this review article will describe the methodologies used to conduct the experiments & the final results obtained from each experiment.

2. METHODS OF HYDROGEN PRODUCTION

Hydrogen can be produced through several methods, including steam methane reforming (SMR), water electrolysis, thermochemical processes, and biological pathways. SMR is the most widely used method, while electrolysis and renewable-based techniques are gaining attention due to their potential for sustainable, environmentally friendly hydrogen production [5–7].

2.1 Steam Methane Reforming (SMR)

Steam methane reforming (SMR) [5-7] is a well-established method utilized for hydrogen production in industrial applications. The comprehensive chemical equation for the SMR process, encompassing both the first step that generates carbon monoxide and the water-gas shift reaction that transforms it into carbon dioxide, is

$$CH_4 + 2H_2O \rightarrow 4H_2 + CO_2 \tag{1}$$

The reactants are methane (CH_4) and water (in the form of steam). The products are hydrogen and carbon dioxide. Upon re-injection of CO_2 into the ground, the sole byproduct that persists is hydrogen. Natural gas is predominantly composed of approximately 94% methane, with the remainder primarily ethane (C_2H_6), which similarly converts to CO_2 and hydrogen through reforming processes [5].

Zheng et al. [6] conducted an experimental study on the effects of fin size on methane steam reforming for hydrogen production in a waste-heat-heated reactor. The study found that as the fin height increased from 34 mm to 46 mm, the outlet temperature of the steam generator decreased significantly, with a maximum reduction of 23.6 K and an average reduction of 18.9 K. This improvement contributed to greater steam production and enhanced the hydrogen production capacity of the system.

Madon et al. [7] conducted an experimental work regarding the effect of the steam to carbon ratio (S:C) on the steam methane reforming's yield over coated nickel aluminide (Ni_3Al) catalyst in a micro reactor. As shown in Figure 1, the PTL-MM01 Dip Coater was used for dip coating at 160 mm/min, with 304 stainless steel plates as substrates. The plates were immersed in a solution with an uncoated area at the top, then withdrawn at a set velocity. After dipping, the samples underwent a 30-minute evaporation process followed by isothermal annealing in a Carbolite RHF 14/3 box furnace at 500°C for 90 minutes. Meanwhile, the experimental setup is shown in Figure 2. The experimental setup involved a coated catalyst loaded into a micro reactor with a 200 µm channel depth, placed in a box furnace for endothermic reactions (Figure 3). The experiments revealed that to steam-to-carbon (S:C) ratio of 4 yielded the highest methane conversion of 65.56%, while S:C ratio of 3 yielded the highest hydrogen yield of 41.34%. Additionally, S:C 2 displayed a quicker stability trend, stabilizing by 180 minutes. However, S:C 3 was determined to be the optimal ratio for both methane conversion and hydrogen yield within a 300-minute reaction time, indicating its superiority for the developed catalyst.

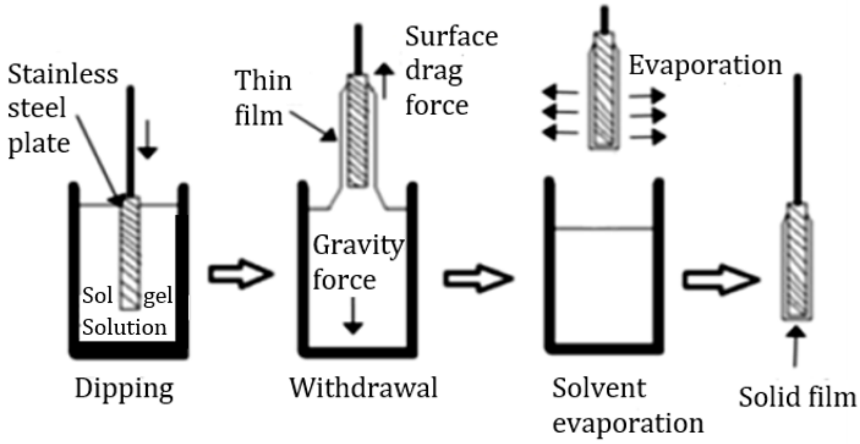

Figure 1: Schematic diagram of the (DIP) dip coating process [7].

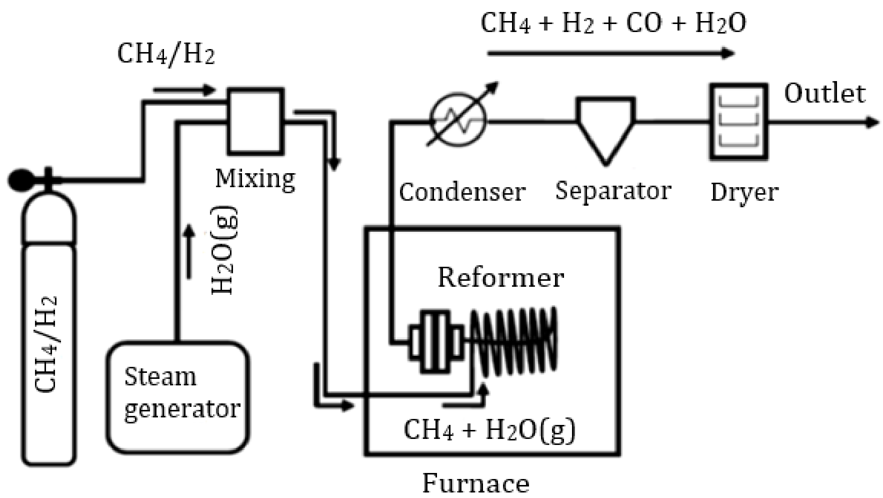

Figure 2: Schematic diagram of the steam methane reforming (SMR) setup [7].

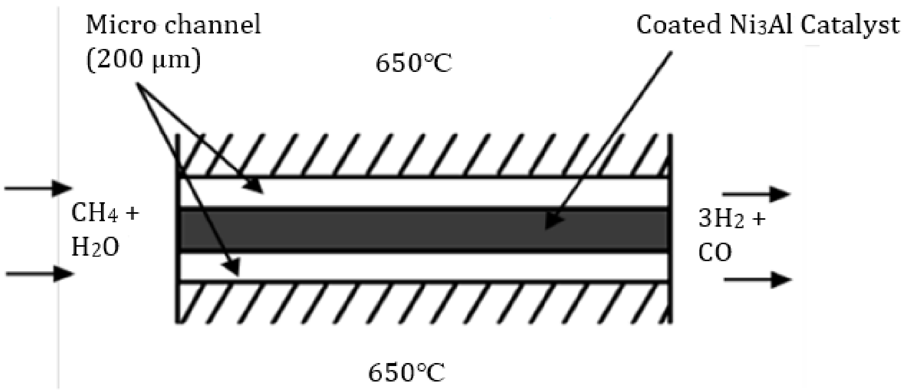

Figure 3: Schematic diagram of micro reactor with insert coated plate catalyst [7].

Wu et al. [8] reported an innovative design for delivering hydrogen via steam reforming of methane using a CO_2-permselective membrane reactor, which will also reduce CO_2 emissions from this process. A membrane reactor is a type of reactor that contains both a dual-phase ceramic membrane and a carbonate membrane, both of which are supported by a two-layer asymmetric wall. The results of this research have demonstrated that using this asymmetrical thin ceramic-carbonate membrane reactor will provide sufficient removal of CO_2 from the feed, thereby producing a high concentration of H_2 at the exit of the single-stage reactor, while also lowering the levels of both CO and CO_2 in the retentate to extremely low concentrations.

Falco et al. [9] studied and modeled hydrogen production via solar steam methane reforming using molten salts as thermal energy carriers, using experimental testing and analysis. The experimental results showed that the average absolute error of the mathematical model, defined as the difference between the model predictions and the experimental data, was less than 2%. This result indicates that the mathematical model accurately simulates the newly developed hydrogen production system, which was tested and used in the model's development.

Huang et al. [10] investigated the interaction effects of key operating parameters, including material porosity, inlet gas temperature, steam-to-methane ratio, and inlet gas velocity, on methane conversion during methane steam reforming under concentrated irradiation. The study also aimed to determine the optimum operating conditions using the Response Surface Methodology (RSM). The findings indicated that material porosity, inlet gas temperature, and the steam-to-carbon (S/C) ratio positively influenced methane conversion, whereas inlet gas velocity had a negative effect. In addition, the analysis of variance (ANOVA) yielded an R^2 of 0.9914 for methane conversion, indicating high accuracy and reliability of the developed model.

Meanwhile, Yan and Cheng [11] conducted a systematic study based on both experimental and computational approaches to design a particle-based packed-bed membrane reactor and to explore its operational window and design challenges. The results showed that the membrane reactor achieved the maximum hydrogen flux per unit of methane consumed under the optimized operating conditions of a gas hourly space velocity of 1134 h^{-1} and a steam-to-carbon ratio of 2 (i.e.,2). On the other hand, the computational study indicated that the optimal operating window was approximately 30 atm and 773.15 K.

Based on the literature review above, studies on hydrogen production generally align with the goals of emission reduction and minimizing environmental impact. However, many studies remain either overly conceptual or narrowly focused, thereby limiting their practical applicability. For example, although the integration of steam methane reforming with carbon sequestration shows promising potential to reduce emissions, it still lacks sufficient experimental validation and practical feasibility, particularly regarding CO_2 handling and field implementation. Furthermore, studies on heat transfer enhancement through fin optimization have shown improvements in hydrogen production; however, these investigations are largely confined to small-scale validation and do not adequately address operational stability or system integration. Research on catalyst performance in microreactors has established ideal operating conditions, including suitable ratios of steam to carbon, but is restricted to specific operating windows and lacks a comprehensive evaluation of catalyst durability and deactivation. Also, advanced membrane reactor studies indicate significant potential for in-situ CO_2 removal and enhanced hydrogen yield; however, they are generally based on ideal laboratory conditions and often do not address challenges related to scalability, material stability and economic feasibility. Therefore, future research should focus on multi-scale validation, real operating conditions, long-term performance evaluation and techno-economic analysis to bridge the gap between theoretical advances and industrial applications. Important findings from the current literature [5–10] are summarized in Table 1.

Table 1: Summary of recent studies on steam methane reforming for hydrogen production.

Paper /Year	System/Application	Method/Technique	Key Findings
Andrews [5]/2020	SMR with CO_2 sequestration via fracking	Conceptual + process analysis	Enables hydrogen production with large-scale CO_2 sequestration and significant emission reduction.
Zheng et al. [6]/2020	SMR with a finned steam generator	Numerical + experimental	Triangular fins and a larger size improve heat recovery and hydrogen production.
Madon. Et al. [7]/2020	Microreactor SMR with Ni_3Al catalyst	Experimental	Optimal S:C≈3 yields the best methane conversion and hydrogen production.
Wu et al. [8]/2020	Membrane reactor SMR with CO_2 capture	Dual-phase membrane	In-situ CO_2 removal enhances water-gas shift (WGS), achieving ~90% hydrogen yield.
Falco et al. [9]/2021	Solar SMR with molten salts	Experimental + modeling	The average absolute error of the model is less than 2%.
Huang et al. [10]/2022	Optimized SMR under irradiation	RSM optimization	Results provided theoretical guidance for the application of methane steam reforming under concentrated irradiation.

2.2 Electrolysis of water

Countries and societies are beginning to recognize that hydrogen energy can play an important role in achieving green development goals and can contribute significantly to global energy transition and decarbonization efforts [12]. The growing demand for hydrogen production technologies underscores hydrogen's crucial role in enabling low-carbon economic growth. Hydrogen can be produced using various techniques, such as water electrolysis [13–18], catalytic reforming of natural gas, photocatalytic hydrogen generation, and fossil fuel combustion. Among these methods, water electrolysis operates at relatively low temperatures and pressures. Therefore, it is considered an effective approach for utilizing wastewater resources as well as renewable energy sources. As a result, water electrolysis is regarded as one of the most suitable long-term methods for the hydrogen energy industry [12].

Dincer et al. [13] conducted a novel hybrid Q-learning algorithm and molecular-fuzzy-based modeling study. The results highlighted that the lifetime of electrolyzers and their hydrogen production capacity are important criteria for green hydrogen production. Proton exchange membrane (PEM) electrolyzers and alkaline water electrolysis were identified as promising technologies for future applications. In addition, improving the durability of electrolyzers was found to be essential for sustainability and for reducing long-term operational costs. Therefore, research incentives should focus on the development of advanced materials and technologies, while establishing quality standards is also important for extending the lifetime of electrolyzers. Qi et al. [14] investigated enhancing carbon oxidation via fluorine doping in carbon-assisted water electrolysis for hydrogen production. The study reported that the current density increased significantly from 37.2 to 123.2 mA/cm^2 at a potential of 1.6 V versus the reversible hydrogen electrode (RHE).

Farahat et al. [15] conducted a study on the design and performance evaluation of a solar-driven alkaline water electrolyzer under various operational and design parameters. The study revealed that square-shaped electrodes, with a height-to-width ratio of 1, provided optimal performance and increased hydrogen production by up to 25% compared to elongated electrode designs. Wirawan et al. [16] found that *Tectona grandis* (154.2 m^2/g) produced more hydrogen than banana leaves (50.72 m^2/g). In addition, *Tectona grandis* achieved a maximum current of 0.21 A at a particle size of 200 mesh. The study also reported that the inclusion of magnetite (Fe_3O_4) in a potassium hydroxide (KOH) solution enhanced electron transfer and reduced the cell potential, thereby improving hydrogen production performance.

Zhan et al. [17] proposed a coupled interfacial solar vapor generation–alkaline water electrolysis (ISVG–AWE) system that utilized a high-concentration KOH solution to absorb seawater vapor *in situ* while simultaneously serving as the electrolyte for alkaline water electrolysis (AWE). For the first time, the study demonstrated the direct use of water vapor produced by interfacial solar vapor generation (ISVG), thereby overcoming the efficiency limitations of the condensation process in conventional ISVG systems.

Du et al. [18] conducted an experimental investigation on the performance optimization of a photovoltaic/thermal module directly coupled with a proton exchange membrane (PEM) water electrolysis hydrogen production system. The results demonstrated that the 22-cell system achieved a daily average solar-to-hydrogen (STH) efficiency of 17.77%, approximately 4 times higher than that of the 5-cell system (4.4%).

Xiang et al. [19] conducted an experimental study on decoupled water electrolysis hydrogen production enabled by a Ni-based solid membrane for integrated systems. Their novel device represents a significant advancement in transitioning decoupled water electrolysis from laboratory-scale studies to industrial applications. The proposed system has the potential to fully leverage the advantages of high-pressure water electrolysis and renewable energy integration, while introducing a new concept for next-generation decoupled water electrolysis hydrogen production systems that are stable, high-performance, and cost-effective.

Goren and Dincer [20] developed newly designed biomass-based electrodes for water electrolysis to produce clean hydrogen. The hydrogen production experiments were conducted in a laboratory-scale, single-chamber, membrane-less cylindrical electrolysis cell. The study investigated the effects of applied voltage, electrolyte concentration, and graphite dosage on hydrogen production performance in biocathodes. The results indicated that hydrogen production increased with higher applied voltage, greater electrolyte concentration, and increased graphite content in the biocathodes.

In summary, the reviewed studies show significant and relevant progress in enhancing green hydrogen production through advanced electrolysis systems, renewable energy integration, and sustainable electrode materials. But there are still a number of limitations in their methods and findings. Many studies are based on laboratory-scale experiments, numerical simulations, or optimization models conducted in a controlled environment, which may limit the practical applicability and scalability of the reported performance. Some cases are mainly focused on short-term efficiency improvements, with little further investigation of long-term operational stability, degradation mechanisms, economic feasibility, or real industrial operating conditions. Moreover, some simulation-based studies rely on simplified assumptions that may overestimate hydrogen production efficiency and overall system performance. The electrochemical activity of biomass-derived and modified electrode materials looks promising. However, the issues of reproducibility, durability and potential for large-scale manufacturing have not yet been adequately addressed. Similarly, the efficiency of renewable-driven electrolysis systems has been enhanced, but their performance under variable environmental conditions and intermittent energy input necessitates further research. Hence, future studies should focus on pilot-scale validation, long-term durability testing, techno-economic analysis and integrated multi-physics modeling under realistic operating conditions to enhance the reliability, scalability and industrial feasibility of green hydrogen production technologies. Table 2 summarizes the principal findings of the current literature [13–20].

Table 2: Summary of recent studies on hydrogen production via water electrolysis.

Paper / Year	System / Application	Method/ Technique	Key Findings
Dincer et al. [13]/2024	Water electrolysis investment assessment for green hydrogen	Hybrid Q-learning algorithm with molecular fuzzy modeling	Electrolyzer lifespan and production capacity were identified as the most important criteria, while proton exchange membrane (PEM) and alkaline electrolysis were the most effective strategies.
Qi et al. [14] /2024	Carbon-assisted water electrolysis for hydrogen production	Experimental fluorine-doped biochar electrode development	Fluorine doping improved carbon oxidation activity and reduced energy consumption by enhancing the formation of active C–F bonds.
Farahat et al. [15]/2025	Solar-driven alkaline water electrolysis	Numerical and experimental investigation using Euler–Euler two-phase CFD model	Optimized electrolyte velocity, electrode geometry, and a smaller electrode gap improved hydrogen production efficiency and reduced ohmic resistance.
Wirawan et al. [16]/2026	Biomass-derived activated carbon for water electrolysis	Experimental synthesis of TGAC/BLAC with Fe_3O_4 nanoparticles	Tectona grandis activated carbon exhibited superior hydrogen evolution performance, owing to its higher surface area and enhanced electrochemical activity.
Zhan et al. [17]/2026	Seawater hydrogen production via ISVG-AWE coupling system	Interfacial solar vapor generation coupled with alkaline water electrolysis	The integrated system achieved stable, long-term hydrogen production with high vapor-collection efficiency while avoiding seawater corrosion and side reactions.
Du et al. [18]/2026	PV/T-driven PEM water electrolysis hydrogen production	Experimental optimization of PV/T-PEM coupled system	The 22-cell configuration achieved the highest solar-to-hydrogen efficiency, while high ambient and inlet water temperatures reduced system performance.
Xiang et al. [19]/2025	Decoupled water electrolysis hydrogen production	Nickel-based bipolar solid membrane electrolysis system	The novel decoupled electrolyzer achieved continuous cyclic hydrogen production with high Faraday efficiency and industrial-scale potential.
Goren and Dincer [20]/2025	Biomass-based bioelectrode for water electrolysis	Experimental graphite-loaded biocathode synthesis	Increasing the graphite dosage and applied voltage significantly improved hydrogen production performance.

2.3 Solar Thermochemical

The utilization of solar energy has emerged as a critical solution for achieving sustainable development in response to escalating global energy demand and severe environmental issues. One promising technology is the solar thermochemical cycle for hydrogen production, which utilizes solar energy to produce hydrogen. The solar reactor is the primary component that facilitates this process. Within the reactor, water undergoes a two-step or multi-step thermochemical cycle [21].

Li et al. [22] investigated a novel solar-driven multigeneration energy system that integrated a heliostat field with thermal energy storage. The study found that the thermal energy storage system significantly improved the reliability and flexibility of the overall system by enabling stable operation during periods of low or absent solar radiation. Gupta et al. [23] performed a numerical investigation on a modified conical solar thermochemical reactor for hydrogen production via steam methane reforming (SMR). The study demonstrated a significant correlation between structural and operational parameters in optimizing the thermal and chemical performance of the modified reactor geometry.

Zhao et al. [24] evaluated redox materials for solar thermochemical hydrogen production (STCH) through water-splitting reactions, with a focus on solar-to-hydrogen efficiency. The study found that the evaluated materials exhibited varying performance characteristics, providing important insights into their suitability for the STCH process. Chang et al. [25] introduced metal foam into the catalytic bed to improve the uniformity of heat and mass transfer. The results indicated that the metal foam significantly enhanced intra-bed heat transfer, leading to a 20 K reduction in the maximum temperature difference within the catalytic bed.

Zeng et al. [26] conducted experimental and numerical studies that successfully provided valuable guidance for the future development of hydrogen production systems integrated with practical heat sources, such as solar thermal power plants and nuclear reactors.

Yuan et al. [27] designed a helical flow channel solar thermochemical reactor based on the characteristics of a dish solar collector. The results suggested that a high steam-to-carbon (S/C) ratio was more favorable for methane conversion than for solar thermochemical conversion. In addition, the medium- and high-temperature solar-driven spiral-flow biogas reforming thermochemical reactor proposed in the study effectively minimized problems associated with non-uniform solar flux distribution, thereby promoting more uniform heating of the reactant gas.

In conclusion, research on solar thermochemical hydrogen production is focused on optimizing reactors, developing advanced redox materials, and integrating multigeneration systems, all with the potential to improve performance. However, most of these studies are based on thermodynamic analysis and numerical simulations. The lack of large-scale experimental validation may limit the practical application of the findings under realistic conditions. Most reactor optimization studies focus on thermal efficiency and methane conversion and neglect crucial parameters like long-term operational stability, material degradation, economic viability and scalability. Improvements in reactor geometries and heat-transfer enhancement methods have been developed to improve methane conversion and hydrogen yield.

However, many assessments are still conducted under idealized conditions that do not accurately reflect fluctuating solar irradiation or industrial operating environments. Moreover, material-based studies usually focus on thermodynamic performance but pay less attention to cyclic durability, corrosion resistance, and manufacturability. Hence, future studies should include integrated multi-physics modeling, transient solar conditions, long-term material stability and techno-economic assessment through pilot-scale experimental studies to enhance the industrial feasibility and reliability of solar thermochemical hydrogen production systems. The important findings from the literature [21–27] are summarized in Table 3.

Table 3: Summary of recent studies on solar thermochemical reactors for hydrogen production.

Paper /Year	System / Application	Method / Technique	Key Findings
Kong et al. [21]/2025	Solar thermochemical hydrogen production using coal-based reductants	Thermodynamic analysis of reductant–oxygen carrier pairs	Coal-based reductants reduced the reduction temperature and improved solar-to-fuel conversion efficiency up to 60.3%, with hydrogen production efficiency reaching 65.9%.
Li et al. [22]/2026	Solar-driven multigeneration system with desalination and hydrogen production	Thermodynamic-economic optimization using artificial neural network-generic algorithm (ANN-GA)	The optimized system achieved 25.56% exergetic round-trip efficiency, 18.56 kg/h hydrogen production, and 2.18 kg/s freshwater generation.
Gupta et al. [23]/2026	Modified conical solar thermochemical reactor for SMR hydrogen production	CFD simulation with Local Thermal Non-Equilibrium (LTNE) and Discrete Ordinate (DO) radiation models	Optimized porosity, cell size, and CH_4/H_2O ratio improved methane conversion to 84.95% and enhanced hydrogen yield.
Zhao et al. [24]/2025	Solar thermochemical H_2 production using redox materials	Coupled reactor–system modeling framework	Ceria (CeO_2) exhibited a superior overall solar-to-H_2 efficiency compared to perovskite materials.
Chang et al. [25]/2025	High-temperature heat pipe-based thermochemical reactor	Experimental and numerical heat/mass transfer enhancement using metal foam	Metal foam reduced temperature gradients and increased methane conversion by 11%, enhancing hydrogen production performance.
Zeng et al. [26]/2026	Sulfur–iodine thermochemical cycle for hydrogen production	Material selection, CFD simulation, and pilot-scale experiment	The optimized H_2SO_4 decomposition system achieved 67% conversion efficiency with strong corrosion resistance and stable operation.
Yuan et al. [27]/2024	Solar-driven thermochemical reactor with helical flow channels	Numerical simulation of spiral-flow reactor design	The helical flow structure achieved methane conversion of 94.76%, hydrogen yield of 1.54 mol/mol, and energy conversion efficiency of 32.52%.

2.4 Biological

Biological hydrogen production is an emerging alternative that utilizes renewable feedstocks and mild operating conditions. Microorganisms produce hydrogen through various metabolic pathways, such as fermentation, biophotolysis, and microbial electrolysis, often by breaking down complex organic materials and releasing hydrogen along with organic acid intermediates. Integrating these microbial processes into multi-stage biorefineries enables the conversion of waste streams into valuable products, thereby minimizing waste disposal requirements and reducing greenhouse gas emissions [28–29].

Fu et al. [30] studied the effects of biological carrier optimization on hydrogen production and biofilm formation in a dark-fermentation anaerobic circulating fluidized bed reactor. The study found that acid treatment produced the maximum reactor biomass of 38.95 g. Meanwhile, silane treatment achieved the greatest average biofilm thickness of 4.12 μm and the highest biofilm density of 0.579 g/cm^3.

Santos et al. [31] conducted an evaluation of the acid pretreatment of Residual Fermented Solid (RFS) for sequential biological hydrogen and methane production. The proposed strategy resulted in a 3.3-fold increase in hydrogen production compared to untreated RFS, as it successfully recovered 53% of the principal sugars from the RFS after acid pretreatment. Furthermore, the energy potential of the two-step methane production process was found to be 2.2 times greater than that of the one-step process after 21 days.

Namdarimonfared et al. [32] conducted an experimental study on biological hydrogen production from paper mill effluent via dark fermentation. The study found that hydrogen, as a biofuel, and volatile fatty acids (VFAs), as valuable byproducts, could be successfully produced from carbohydrate-rich wastewater using dark fermentation. Shui et al. [33] conducted an investigation to elucidate the relationship between hydrogen production and the application of an external static magnetic field (SMF) during the photo-fermentation of giant reed. The study found that, compared to conditions without an external magnetic field, the cumulative hydrogen yield increased by 26.1%, while the latency time for hydrogen production was reduced by 56.7% in the presence of an SMF of 20 mT.

Ekwenna et al. [34] found that pretreated (PT) digested cattle slurry (DCS) was utilized in batch cultures for hydrogen fermentation using glucose and sucrose as substrates. The study revealed that the pretreated DCS exhibited a higher daily volumetric hydrogen production (VHP) than untreated DCS at 55 °C and pH 5.5. In addition, the results indicated that agro-industrial waste has the potential to support hydrogen-producing microorganisms in DCS while simultaneously inhibiting hydrogen-consuming microorganisms. Castro et al. [35] proposed a process strategy for the valorization of residual biomass, involving the chemical conversion of solubilized sugars into furfural and the biological conversion of cellulosic glucose into hydrogen. Their work contributes to developing a circular economy model by producing green energy from residual biomass.

The literature review above reveals progress in biological hydrogen production with limitations in methodology. Major limitations include using only a few operating conditions (i.e., temperature and pH), a short experimental duration, and a single type of microbe, all of which limit the ability to apply the results to the production of hydrogen on a commercial scale. Furthermore, the low Chemical Oxygen Demand (COD) removal efficiency relative to increased levels of hydrogen production indicates that there has not been complete conversion of the substrates and that there are limits to the fermentation of these substrates. In addition, many studies do not perform comprehensive analyses of the microbial community, the reactor hydrodynamics, or the inhibitory compounds that may have developed as a result of pretreating the biomass. In addition, the energy required for these pretreatment techniques, the use of magnetic fields, and thermal treatment have not been evaluated in the literature; thus, it is difficult to assess the overall sustainability and economics of the solution.

Further studies on mixed microbial communities and continuous operation of the reactor for longer periods are required to improve process stability and hydrogen yield. In addition, the studies should employ more advanced analytical techniques such as microbial sequencing, metabolomics, and surface analysis to gain deeper insight into the reaction substrates and their interactions with the microorganisms in these systems. In addition, optimizing hydraulic retention times, organic loading rates, substrate pretreatment methods, and carrier materials will improve substrate utilization efficiency and reduce the inhibitory effects of these substrates on mixed culture systems. Table 4 summarizes all the major research findings from the literature [30-35].

Table 4: Summary of recent studies on biological hydrogen production.

Paper/Year	System/Application	Method/Technique	Key Findings
Fu et al. [30]/2025	Biological hydrogen production in an anaerobic circulating fluidized bed reactor (ACFBR)	Surface optimization of polyamide 6 (PA6) biological carriers using acid, activated carbon, graphite, silane coupling agent, and quaternary ammonium salt.	Acid-treated carrier achieved the best hydrogen yield (0.921 mol-H_2/mol-glucose), highest hydrogen production rate (0.138 L-H_2/(L·h)), and Chemical Oxygen Demand (COD) removal efficiency (32.15%).
Santos et al. [31]/2025	Sequential biological hydrogen and methane production from residual fermented solid (RFS)	Sulfuric acid and oxalic acid pretreatment of biomass followed by dark fermentation and anaerobic digestion	Oxalic acid pretreatment (5.5 wt%, 170 °C, 25 min) produced the best results, achieving 567 ± 23 N-mL H_2/L and 3779 ± 49 N-mL CH_4/L with 80% Chemical Oxygen Demand (COD) reduction and improved energy recovery.
Namdarimonfared et al. [32]/2023	Hydrogen production from paper mill effluent in a packed-bed biofilm reactor	Continuous dark fermentation in an anaerobic packed bed biofilm reactor (APBR) at various hydraulic retention times (HRTs)	Maximum hydrogen concentration reached 41.5% at Hydraulic retention time (HRT) 4 h, while the highest hydrogen production rate was 6.21 L H_2 d^{-1} L^{-1} at HRT 2 h.
Shui et al. [33]/2023	Photo-fermentative biological hydrogen production from giant reed	Application of static magnetic field (SMF) during photo-fermentation	20 mT SMF increased cumulative H_2 yield by 26.1%, enhanced nitrogenase activity by 94.52%, and improved energy conversion efficiency to 27.27%.
Ekwenna et al. [34]/2023	Biological hydrogen production using agro-industrial waste pretreated seed sludge	Pretreatment of digested cattle slurry using potash extract, cassava-steep wastewater, and corn-steep liquor	Pretreated sludge improved H_2 production compared to untreated sludge. Potash extract pretreatment achieved the highest daily hydrogen production with the sucrose substrate.
Castro et al. [35]/2023	Integrated biological hydrogen and furfural production from vine shoots	Steam explosion pretreatment, enzymatic hydrolysis, microwave-assisted furfural production, and fermentation using *Clostridium butyricum*	Optimized steam explosion improved sugar recovery and enabled biohydrogen production of 830.7 mL/L. Microwave-assisted conversion achieved furfural production of 15 g/L with 73% yield.

3. CONCLUSION AND FUTURE DIRECTION

From the results of the study and review above, several important conclusions can be drawn as follows:

1. Steam methane reforming (SMR) is still considered to be a very efficient and viable method for producing hydrogen from natural gas, especially when used in combination with high-efficiency heat recovery technologies (e.g., heat exchangers), novel membranes, solar energy, and optimized catalyst design. Enhancements in fin geometry, steam to carbon ratios, porous catalyst supports, and the utilization of membranes for CO_2 separation resulted in higher

methane to hydrogen conversion efficiency and hydrogen yield, along with a decrease in the quantity of carbon captured from the reforming process.

2. The use of advanced electrode materials (e.g., biomass-based activated carbons or bioelectrodes of graphite and nickel-based solid membranes) can improve the performance of water electrolysis systems. The integration of renewable energy technologies in the design of electrolyzers (e.g. PV/T-PEM, ISVG-AWE) can be improved. Systems can be designed in innovative ways to take advantage of seawater. Decoupled alkaline electrolysis also reduced gas crossover, thereby providing enhanced operational flexibility for renewable energy applications.

3. Optimizing reactor design, developing advanced redox materials, enhancing heat and mass transfer, and integrating renewable energy systems can substantially improve solar thermochemical hydrogen production. Methods such as helical flow channels, porous media modification, metal foam integration, sulfur–iodine cycles, and coupled reactor–system modeling effectively improved hydrogen yield, thermal efficiency, temperature uniformity, and energy utilization. Moreover, the hybridization of solar energy, waste heat recovery and thermochemical cycles highlights the promising potential of sustainable large-scale green hydrogen production with reduced carbon emissions and improved system performance.

4. The benefit of biological methods is that it can turn organic waste such as food processing wastewater, dairy waste and agricultural waste into hydrogen. It also provides renewable energy production and cuts waste disposal and treatment costs. Overall, literature studies indicate the possibility of improving biological hydrogen production through optimization of the reactor, biomass pretreatment, biofilm engineering, and external stimulation techniques. Acid pretreatment, magnetic field application and integrated fermentation systems have been shown to increase hydrogen yield and microbial activity. The use of industrial and agricultural waste as a feedstock indicates the possibility of sustainable biohydrogen production, with an emphasis on the importance of process optimization and efficient substrate conversion for large-scale development.

NOMENCLATURE

CCS	Carbon capture and storage
SMR	Steam methane reforming
H_2	Hydrogen
H_2S	Hydrogen sulfide
C_2H_6	Ethane
CH_4	Methane
CO_2	Carbon dioxide
K	Kelvin
Al-Cl	Aluminium-chloride
PPY	Polypyrrole
DIP	Dip coating process
CNN	Convolutional neural network
LSTM	Long Short-Term Memory
Cu	Copper
COD	Chemical oxygen demand
APBR	Anaerobic packed bed biofilm reactor
ISVG	Interfacial solar vapor generation
PV/T	Photovoltaic/Thermal
PEM	Proton exchange membrane
SMF	Static magnetic field

STH Solar-to-hydrogen
RFS Residual fermented solid
PA6 Polyamide 6
ACFBR Anaerobic circulating fluidized bed reactor
DCS Digested cattle slurry
VHP Volumetric hydrogen production
RFS Residual fermented solid
HRT Hydraulic retention time
PT Pretreated
LTNE Local thermal non-equilibrium
WGS Water-gas shift
AWE Alkaline water electrolysis

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