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REVIEW

# An Overview of Renewable Hydrogen from Biomass Processes and Solar Energy Systems

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**ABSTRACT:** Renewable hydrogen has emerged as a promising energy carrier for achieving low-carbon and sustainable energy systems. Among the various production routes, biomass-based processes and solar energy–driven systems offer significant potential due to their renewable nature and wide resource availability. Biomass conversion pathways such as gasification, pyrolysis, and biological processes enable the utilization of agricultural residues, forestry waste, and organic by-products for hydrogen generation, while simultaneously addressing waste management concerns. These processes can be integrated with carbon capture techniques to further reduce greenhouse gas emissions. Solar energy systems, including photovoltaic-assisted electrolysis, solar thermochemical cycles, and photoelectrochemical water splitting, provide clean hydrogen production by directly harnessing solar radiation. The combination of biomass and solar routes enhances energy security by diversifying feedstocks and reducing dependence on fossil fuels. However, challenges related to conversion efficiency, system scalability, hydrogen storage, and economic viability remain critical for large-scale implementation. This overview examines the fundamental principles, recent technological developments, and key advantages of biomass-derived and solar-based hydrogen production pathways. Emphasis is placed on their role in supporting a sustainable hydrogen economy and contributing to global decarbonization goals.

**KEYWORDS:** Hydrogen; fuel cell; clean energy; solar energy; biomass process; environmental resource

## 1 Introduction

As the world moves toward low-carbon energy systems, hydrogen is emerging as a vital energy source that can decarbonize hard-to-electrify sectors and bridging the gap between variable renewable electricity generation and end-use applications [1]. As nations and regions, particularly the European Union, incorporate hydrogen into their climate mitigation strategies, renewable hydrogen production pathways have gained unprecedented attention [1,2]. Among these pathways, biomass-derived hydrogen offers unique

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advantages by providing dispatchable, continuous hydrogen supply that complements the intermittent nature of solar and wind-based electrolysis [1,3].

Biomass represents a versatile and widely distributed feedstock resource encompassing forest residues, agricultural waste, municipal solid waste, biogas, and dedicated energy crops [2,4]. Unlike other renewable hydrogen production methods that depend on weather conditions, biomass conversion processes can operate continuously, offering base load hydrogen production capacity while simultaneously addressing waste management and circular economy objectives [2,5]. When sustainably sourced and managed, when compared to traditional fossil fuel-based hydrogen generation by steam methane reforming (SMR), biomass feedstock's can dramatically lower lifetime Green House Gas (GHG) emissions [1,6]. Furthermore, if combined with technology for carbon capture and storage, biomass-to-hydrogen systems hold the potential to achieve carbon-negative hydrogen production, actively removing $CO_2$ from the atmosphere [1,7].

Combining solar energy with biomass processing represents an emerging frontier that exploits synergies between these renewable resources. Solar-biomass hybrid systems can utilize solar electricity for electrolysis, solar thermal energy for conversion processes, or full-spectrum solar radiation to drive thermochemical biomass conversion [8]. These hybrid configurations enhance system flexibility, improve overall energy efficiency, and reduce environmental footprints by leveraging the complementary characteristics of solar and biomass resources [9]. Recent techno-economic studies have demonstrated the viability of such integrated systems, with hydrogen-based hybrid renewable energy systems combining biomass supercritical water gasification and solar electrolysis showing promising economic performance [9]. Fig. 1 shows the various hydrogen supply chains types.

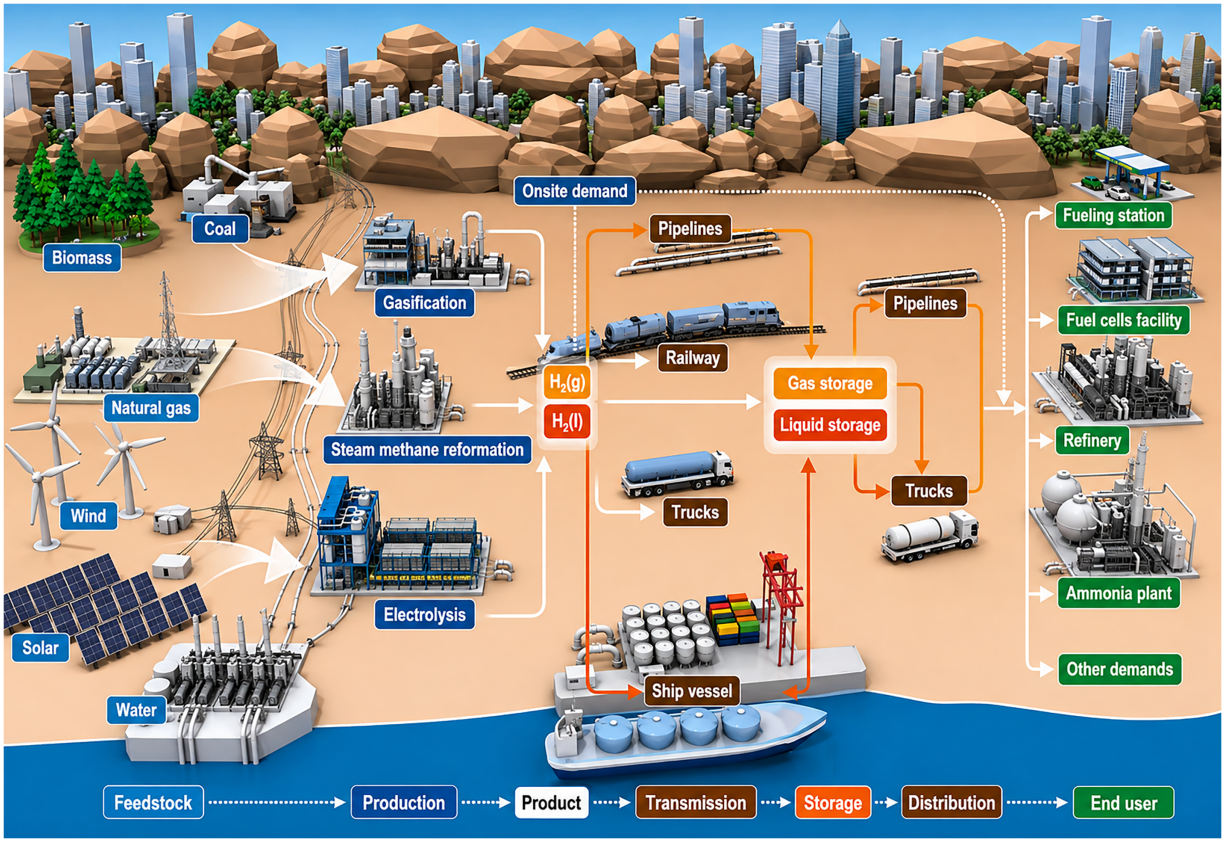



**Figure 1:** Different types of hydrogen supply chains (Riera et al., 2023) [Reprinted with permission from Riera, J. A.–2023].

Biomass-to-hydrogen conversion technologies span a diverse range of maturity levels and operational scales. Thermochemical conversion routes including gasification, pyrolysis, and steam reforming of bio-derived methane represent higher Technology Readiness Levels (TRL) suitable for centralized, large-scale production with relatively high hydrogen yields [2,10]. Gasification of forest residues with carbon capture has been estimated to produce hydrogen [6,11]. In contrast, biological conversion pathways like photo fermentation, dark fermentation, microbial electrolysis and bio photolysis operate at lower temperatures and offer decentralized production potential but currently face challenges related to low hydrogen productivity, limited yields, and early-stage technology development [2,12,13].

Advanced and hybrid technologies further expand the biomass-to-hydrogen landscape. Methane tri-reforming, which integrates $CO_2$ and $CH_4$ streams from biogas, Super Critical Water Gasification (SCWG), and solar-assisted thermochemical processes represent innovative approaches that require comprehensive Life Cycle Assessment (LCA) and techno-economic to validate their benefits [14]. These emerging technologies aim to address limitations of conventional routes while enhancing environmental performance and energy efficiency.

Biomass-derived hydrogen integration with fuel cell technologies creates complete renewable energy systems capable of power generation, transportation applications, and off-grid energy supply [9,15]. Fuel cells can utilize biomass hydrogen for distributed generation, energy storage, and load balancing, effectively linking biomass conversion systems with end-use applications [9]. Lifecycle studies consistently indicate that bio-hydrogen pathways reduce fossil energy demand and GHG emissions relative to fossil-derived hydrogen, though the magnitude of benefits depends critically on sustainable biomass sourcing, conversion efficiency, and system boundaries employed in assessments [1,6,16].

Despite these promising attributes, significant challenges impede the widespread deployment of biomass and solar-biomass hydrogen systems. Technical barriers include improving the productivity and scalability of biological conversion processes, optimizing energy integration in thermochemical routes, and managing the energy penalties associated with carbon capture systems [2,6]. Economic challenges encompass high capital costs for advanced conversion technologies, competition from established fossil-based hydrogen infrastructure, and uncertainties in biomass feedstock availability and pricing [6]. Environmental and resource considerations involve ensuring sustainable feedstock sourcing without land-use conflicts, minimizing water consumption, and developing harmonized LCA methodologies to enable robust comparisons across diverse hydrogen production pathways [1,16]. Methodological inconsistencies in existing techno-economic and life cycle assessments further complicate decision-making and policy development. Variations in system boundaries, functional units, allocation methods, and impact assessment approaches across studies hinder direct comparisons and obscure the relative merits of different biomass-to-hydrogen technologies [1,16]. Additionally, market inertia from incumbent fossil fuel industries, inadequate policy incentives, and underdeveloped hydrogen infrastructure present systemic barriers to commercialization.

This paper summarizes recent developments, present issues, and potential avenues for future research while offering a thorough overview of sustainable hydrogen generation from biomass processes and solar energy systems. The review is structured to cover fuel cell technologies and their integration with biomass systems, hydrogen production from biomass via thermochemical, biological, and hybrid conversion technologies, environmental and economic assessment of biomass-based low-carbon hydrogen including solar-biomass integration and feedstock considerations, detailed examination of biological biomass conversion pathways, environmental resource use including life cycle assessment and circular economy aspects, and key technical, economic, and infrastructural challenges facing hydrogen energy systems. By mapping technology readiness levels, environmental performance metrics, techno-economic indicators, and integration strategies, this review aims to guide research and development priorities, inform policy

frameworks, and accelerate the transition toward sustainable hydrogen production systems that leverage the complementary strengths of biomass and solar resources.

***Review Methodology***

This review was carried out through a structured literature search to identify recent studies on renewable hydrogen production from biomass processes and solar energy systems. Relevant publications were collected from major scientific databases, including Scopus, Web of Science, Science Direct, and Google Scholar. The literature search covered articles published between 2020 and 2025 using keywords such as renewable hydrogen, green hydrogen, biomass hydrogen production, bio hydrogen, solar hydrogen, photocatalytic hydrogen production, water splitting, and biomass gasification were used to refine the search and improve the relevance of the results. Only peer-reviewed journal articles published in English and directly related to renewable hydrogen production technologies were included in this review. Conference papers, book chapters, duplicate records, non-English publications, and studies outside the scope of biomass- and solar-based hydrogen production were excluded. The selected articles were carefully screened based on their titles, abstracts, and full-text content to ensure their relevance. The final set of publications was analyzed to summarize recent technological developments, compare different hydrogen production pathways, identify key challenges, and highlight future research directions for sustainable renewable hydrogen production.

## 2 Fuel Cells

Fuel cells represent critical technologies for hydrogen conversion into heat and electricity with minimal environmental impact and high efficiency. These electrochemical devices enable the practical use of hydrogen as a source of energy throughout diverse applications, from stationary power generation to transportation and portable electronics [17,18]. Fig. 2 shows the hydrogen fuel cell schematic diagram.

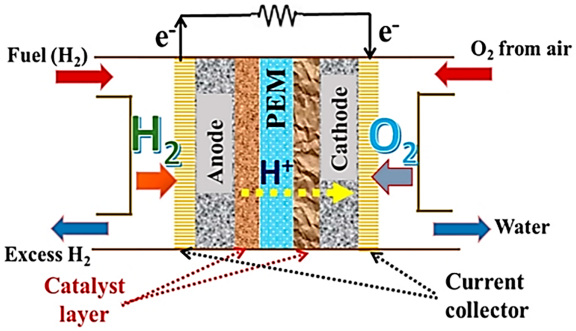



**Figure 2:** Schematic of hydrogen fuel cell [19] [Reprinted with permission from Olabi, A. G.–2023].

### *2.1 Fuel Cell Technologies and Applications*

Several fuel cell types have been developed for hydrogen utilization, with Proton Exchange Membrane Fuel Cells (PEMFCs) and Solid Oxide Fuel Cells (SOFCs) being particularly relevant for biomass-hydrogen systems. Solid oxide fuel cells operate at high temperatures (600°C–1000°C) can directly utilize syngas from biomass gasification, offering flexibility in fuel composition and high electrical efficiencies. Liu et al. [20] by using cooling, heating, and power system a novel hybrid fuel cell-combined integrating solar-driven biomass gasification with SOFC technology. The introduction of solar energy in this system increased the generating unit biomass capacity by 36.3%, 63.8% and usage rate compared to reference systems without solar integration.

Because PEMFCs need high-purity hydrogen and operate at lower temperatures (60°C–80°C), they are appropriate for applications where hydrogen is created through purification procedures [21]. Fard et al. investigated a biomass power system integrating PEMFC technology with the vanadium chlorine thermochemical cycle for hydrogen synthesis. The study revealed that biomass moisture content, PEMFC temperature, and current density are crucial parameters affecting system performance, with rising moisture content and PEMFC temperature improving performance indices while increasing current density negatively impacts performance.

### *2.2 Critical Analysis of Fuel Cell Integration*

Proton exchange membrane fuel cells (PEMFCs) and solid oxide fuel cells (SOFCs) offer distinct advantages for renewable hydrogen utilization. PEMFCs provide high efficiency and rapid response, suitable for transportation, yet their sensitivity to impurities increases purification costs [22]. Conversely, SOFCs exhibit superior fuel flexibility, directly utilizing biomass-derived syngas, though high-temperature operation accelerates material degradation [23]. While individual fuel cell technologies have reached TRL 7–9, fully integrated biomass-fuel cell systems remain at TRL 5–7 due to complex thermal and chemical interfacing [24]. Future research must prioritize durable materials and optimized syngas purification to ensure long-term pilot-scale stability.

## 3 Hydrogen as a Clean Energy Carrier

With just one proton and one electron, hydrogen is the most basic and prevalent element on Earth. Although hydrogen may store and supply useful energy, it is usually not found in nature on its own and must be created from chemicals that include hydrogen. Huge amounts of energy may be delivered or stored using hydrogen, which is an energy transporter rather than an energy source. Fuel cells may use hydrogen to produce power and heat or electricity. These days, the most popular uses of hydrogen are in fertilizer manufacturing and petroleum refining, with energy and transportation being developing areas. Hydrogen does not exist freely in nature and must be produced by breaking down compounds such as methane ($CH_4$) or water ($H_2O$). Consequently, hydrogen is not considered a fundamental energy source, but rather a clean energy carrier. A promising renewable energy source, hydrogen can help the world's efforts to reduce carbon emissions and establish sustainable energy sources. As an energy carrier, hydrogen enables the storage, transport, and utilization of energy produced from diverse primary sources, including renewable and low-carbon pathways. When hydrogen is used in fuel cells or combustion systems, the only direct by-product is water, making it an environmentally benign option at the point of use with no carbon dioxide, sulfur oxides, or particulate emissions. Hydrogen production technology is represented in Fig. 3.

One of the hydrogen main advantages is its high gravimetric energy density, which makes it suitable for applications ranging from transportation and stationary power generation to industrial processes. Hydrogen can be produced through several routes, such as water electrolysis, biomass conversion, and reforming of hydrocarbons. Among these, hydrogen generated via electrolysis using renewable electricity commonly referred to as green hydrogen offers a pathway for near-zero lifecycle emissions. Additionally, hydrogen provides an effective means of integrating intermittent renewable energy sources by enabling long-term energy storage and grid balancing.

Despite its potential, challenges remain in terms of storage, large-scale production efficiency, transportation, and infrastructure development. However, ongoing advancements in electrolyzer technologies, hydrogen storage systems and fuel cells are steadily addressing these limitations. Overall, hydrogen is expected to play a main part in transitioning toward a low-carbon energy system, particularly in sectors that are difficult to electrify directly, thereby contributing significantly to a cleaner and more sustainable energy

future. Its volumetric energy density is comparatively low, while having a gravimetric energy content that is two to three times higher than that of conventional fuels. There are several uses for hydrogen technology, including hydrogen-powered industries, hydrogen villages, and hydrogen-powered jet aircraft. It may be used to generate power and is appropriate for all home energy demands. With the use of fuel cells, hydrogen may be utilized to store energy as electricity.

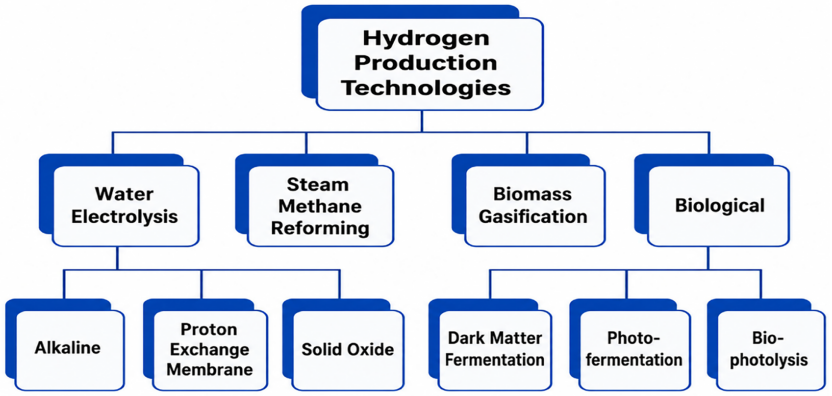



**Figure 3:** Hydrogen production technologies [25] [Reprinted with permission from Giakoumakis, G.–2025].

Green hydrogen has the potential to lower carbon emissions, according to the International Energy Agency (IEA), but doing so would need resolving important issues including production costs, safety, and infrastructure. Approximately 843 million metric tons of $CO_2$ are produced yearly by conventional hydrogen generation technologies, which is equal to the combined emissions of Indonesia and the United Kingdom. Between 2019 and 2024, the world's hydrogen consumption is expected to rise from 70 to 120 Mt. The advancement of hydrogen technology is essential to meeting this need and supporting the seventh Sustainable Development Goal (SDG) of "clean and affordable energy." Accordingly, it is anticipated that the largest green hydrogen plant in the world, capable of producing 237,250 t of hydrogen annually, would be operational by 2025. This project will greatly accelerate the transition to sustainable energy by producing 4 GW of renewable energy from solar and wind through electrolysis.

## 4 Biomass Gasification

The demand for hydrogen is continuously increasing, reaching 97 Mt in 2023. This is a 2.5% increase over 2022 and a record high. Traditional industries like the chemical and petroleum refining sectors continue to be the principal users of hydrogen. The majority of hydrogen is still produced using fossil fuels, namely natural gas. Agricultural crop leftovers, forest residues, special crops produced for energy purposes, organic municipal solid trash, and animal wastes are all examples of biomass, a sustainable organic resource. Gasification of this natural resource can provide hydrogen and other byproducts. Hydrogen generation is a good fit for fluidized bed gasifiers. In fluidized bed gasifiers, steam, the oxidant gas, or combinations of these are introduced at the bottom to fluidize or entrain the sand-like bed material in the reaction region. Allothermal or indirect gasifiers employ steam without an oxidant being supplied to the gasifier portion, whereas autothermal or direct gasifiers require an oxidant. The largest biomass gasifier operating at atmospheric pressure, located in Vaasa, Finland, has a capacity of 140 MWth. They can also be pressurized up to 1–3 MPa to increase the single vessel capacity. Puig-Samper et al. (2024) [26] recently reviewed 100 LCA studies of various hydrogen production technologies, 12 of which were biomass gasification concepts. Fig. 4 shows the hydrogen renewable production from biomass gasification.

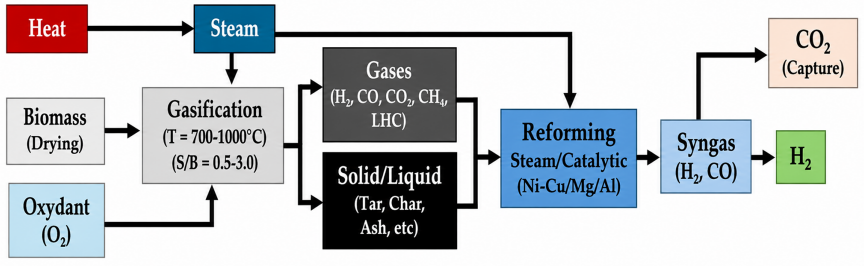



**Figure 4:** Renewable-$H_2$ production process from biomass gasification [27] [Reprinted with permission from Rey, J. R. C.–2024].

A green hydrogen plant with a 100 MW gasification input capacity and an on-site torrefaction plant is now being planned in the northern Netherlands by HyCarb, a development business owned by Torrgas. Prunings and demolition timber are examples of residual flows that provide the feedstock. The facility can produce about 15,000 t of green hydrogen a year. Haffner Energy, a French technological company, has announced intentions to build three smaller-scale green hydrogen production facilities in Europe: one in Montbélliard, France; one in Glovelier, Switzerland; and one in Alkmaar, the Netherlands. The first two will be able to produce 720 kg of hydrogen per day, and they are scheduled to begin operations in 2026. The third plant, located in France, may be a little bigger, with a start-up date of early 2027 and an objective of producing more than 1000 kg of hydrogen per day.

## 5 Hydrogen Production from Biomass

Biomass represents a sustainable and versatile feedstock for production of hydrogen, offering multiple conversion pathways with varying technological maturity, efficiency, and economic characteristics. This section examines the principal methods for converting biomass into hydrogen, including thermochemical processes, biological pathways, and emerging hybrid technologies. Biomass types with potential renewable production of hydrogen is shown in Fig. 5.

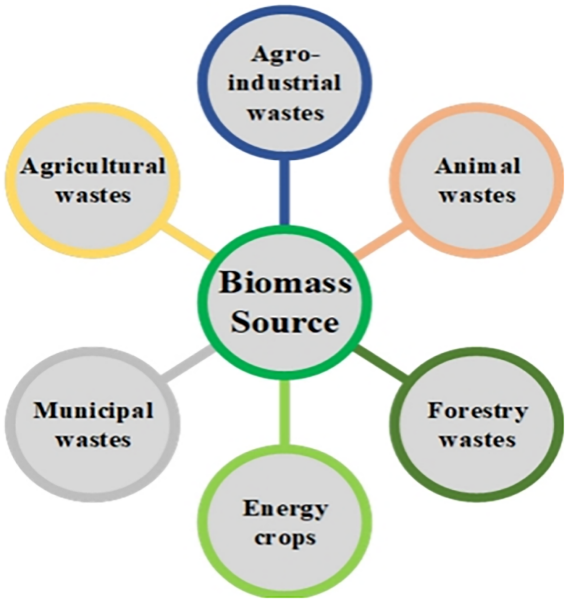



**Figure 5:** Types of biomass with potential to be used in renewable-$H_2$ production [27] [Reprinted with permission from Rey, J. R. C.–2024].

### *5.1 Thermochemical Conversion Technologies*

Biomass is broken down into hydrogen-rich products by thermochemical conversion processes, which use heat and chemical reactions. These methods generally achieve higher efficiencies and hydrogen yields compared to biological pathways and are more suitable for centralized, large-scale production [27].

#### *5.1.1 Gasification*

Gasification is the most mature and widely studied thermochemical process for production of hydrogen from biomass. This process converts solid biomass into syngas through partial oxidation at high temperatures (700°C–1000°C) in the presence of gasifying agents such as oxygen, air, carbon dioxide or steam [28–30]. Wolff Leal et al. [29] compared various gasification processes for green hydrogen production from lignocellulosic biomass, including steam gasification, conventional gasification, multi-stage gasification, chemical looping gasification and supercritical water gasification. The study emphasized that biomass composition, moisture content, ash content, and elemental composition directly influence gasification efficiency and syngas quality.

Gasification is considered one of the most promising thermochemical routes due to its high hydrogen yield and ability to produce hydrogen-rich syngas suitable for downstream purification and fuel cell applications. Tavares Borges et al. [30] conducted a comprehensive hydrogen production assessment through biomass gasification, calculating the potential for producing hydrogen worldwide from solid biomass in a 2050 ideal trends scenario at 45.03 EJ, with Brazil's potential at 6.5 EJ. The study highlighted that gasification technology offers significant potential for sustainable hydrogen production at industrial scales. Bengharbia and Younus [28] identified gasification as one of the most viable technologies, capable of meeting 20%–50% of regional hydrogen demand with reduced greenhouse gas emissions and improved energy efficiency.

Steam gasification, which uses steam as the gasifying agent, promotes the water-gas shift reaction to produce higher hydrogen concentrations in the syngas. Zhang et al. [31] noted that steam reforming of pyrolysis products can significantly enhance hydrogen yields from agricultural waste. The presence of steam facilitates the carbon monoxide to hydrogen conversion through the water-gas shift reaction, increasing overall hydrogen production.

#### *5.1.2 Pyrolysis and Reforming*

In pyrolysis, biomass is thermally broken down in the absence of oxygen at temperatures usually between 400°C and 600°C to produce syngas, biochar, and bio-oil [31,32]. While pyrolysis alone produces limited hydrogen, coupling pyrolysis with subsequent reforming processes significantly enhances hydrogen yields. Zhang et al. [31] shown that the pyrolysis and reforming of agricultural wastes produces a high output of hydrogen, with steam reforming being especially successful in encouraging water-gas shift processes to create additional hydrogen. Steam reforming significantly increases hydrogen generation by promoting secondary cracking and water-gas shift reactions. Fig. 6 represents the hydrogen renewable and activated charcoal production from biomass pyrolysis.

Altayib and Dincer [33] developed a hybrid integrated energy system combining solar-thermochemical processes with biomass pyrolysis for hydrogen production. The system utilized petroleum coke blend and biomass through hydro-gasification, followed by steam-methane reforming in a solar tower reactor. Solar energy integration enabled continuous operation, with the steam-methane reactor maintained in auto thermal mode during night-time.

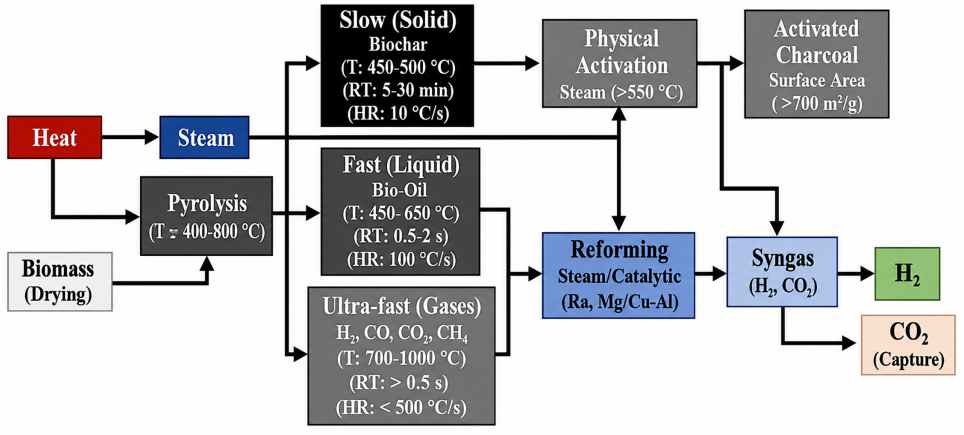



**Figure 6:** Renewable-$H_2$ and activated charcoal production process from biomass pyrolysis [27] [Reprinted with permission from Rey, J. R. C.–2024].

### *5.1.3 Supercritical Water Gasification*

Water has special qualities as a reactant and reaction medium at temperatures over 374°C and pressures above 22.1 MPa, when Super Critical Water Gasification (SCWG) takes place [29,34,35]. This process is particularly advantageous for wet biomass feedstocks, eliminating the need for energy-intensive drying [35]. The levelized cost of energy was 0.38 $/kWh, with a greenhouse gas emissions reduction potential of approximately 21 t of $CO_2$-equivalent per year. Abawalo et al. [34] highlighted hydrothermal gasification as particularly promising as food waste for wet biowaste streams. The process offers dual-purpose solutions for converting organic waste to clean hydrogen while reducing landfill reliance. SCWG is particularly attractive for hydrogen production from wet biomass due to enhanced hydrogen recovery and elimination of biomass drying requirements. Bio-based hydrogen pathways through hydrothermal gasification show significantly energy use, lower greenhouse gas emissions, and pollutant outputs compared to conventional methods.

### *5.1.4 Chemical Looping Processes*

Chemical looping represents an advanced thermochemical approach that uses metal oxide oxygen carriers to facilitate biomass conversion and hydrogen production while enabling inherent carbon capture [29,36]. Ghannadi and Dincer [36] used a combined power cycle with carbon capture and storage to assess iron-based chemical looping for the synthesis of hydrogen from biomass. Chemical looping enables efficient hydrogen production with inherent carbon capture, resulting in low-carbon or carbon-negative hydrogen systems. The integration of solar energy for thermal input and combined Brayton and Rankine cycles for power generation demonstrated the potential for sustainable, low-carbon hydrogen production with simultaneous carbon management.

## *5.2 Biological Conversion Pathways*

Biological hydrogen production methods utilize microorganisms to convert biomass into hydrogen through fermentation or photosynthetic processes. While generally exhibiting lower efficiencies than thermochemical routes, biological pathways offer advantages for decentralized production and processing of wet organic wastes [27,37]. Dark fermentation involves the anaerobic breakdown of organic substrates by bacteria in the absence of light, producing hydrogen and organic acids [28,32,34]. Abawalo et al. [34] identified dark fermentation as particularly promising for wet biowaste streams such as food waste, providing substantially reduced greenhouse gas emissions as comparison to traditional techniques. The process typically achieves

hydrogen yields of 1–3 mol $H_2$/mol glucose, with performance dependent on substrate composition, pH, temperature, and microbial community structure [37].

#### *5.2.1 Photofermentation and Biophotolysis*

Photofermentation utilizes photosynthetic bacteria to convert organic acids (often produced by dark fermentation) into hydrogen using light energy [17,32]. However, the technology remains at laboratory scale with challenges in efficiency and scalability. Green algae and cyanobacteria are examples of photosynthetic microorganisms that directly divide water into hydrogen and oxygen during biophotolysis [32,38]. Li et al. [38] noted that biophotolysis systems currently exhibit low system efficiency (less than 10%) and remain at lower technology readiness levels compared to thermochemical processes. Despite these limitations, biophotolysis represents a potentially sustainable pathway for solar-driven hydrogen production from water using biological catalysts.

#### *5.2.2 Anaerobic Digestion*

Anaerobic digestion is a well-established biological process that converts organic matter into biogas through microbial action in oxygen-free conditions [27,28,32]. While traditionally focused on methane production, anaerobic digestion can be optimized for hydrogen production or coupled with subsequent reforming of biogas to produce hydrogen. Rey et al. [27] that anaerobic digestion offers a best-case hydrogen production cost of 1.28 EUR/kg$H_2$, making it economically competitive with conventional steam methane reforming.

Bengharbia and Younus [28] identified anaerobic digestion as one of the most viable technologies for biomass-to-hydrogen conversion, capable of meeting 20%–50% of regional hydrogen demand. The process benefits from technological maturity, established infrastructure, and ability to process diverse organic feedstocks including food waste, agricultural residues, and wastewater sludge [35].

#### *5.2.3 Microbial Electrolysis Cells (MECs)*

MECs represent an emerging electrochemical-biological hybrid technology that uses electroactive bacteria to oxidize organic matter while producing hydrogen at the cathode with applied electrical potential [17]. Yagmur Goren et al. [17] evaluated MECs as an environmentally friendly biomass-based hydrogen production method, though the technology remains at laboratory scale. Abawalo et al. [34] included MECs among promising electrochemical methods for biowaste-to-hydrogen conversion, noting the need for further research in process integration and catalyst development.

### *5.3 Hybrid and Advanced Technologies*

Emerging hybrid technologies combine multiple conversion processes or integrate renewable energy sources to enhance efficiency and sustainability of biomass-to-hydrogen systems. Solar-biomass hybrid systems improve renewable hydrogen production efficiency while reducing carbon emissions.

#### *5.3.1 Solar-Biomass Hybrid Systems*

Integration of solar energy with biomass conversion processes offers synergistic benefits, including enhanced efficiency, reduced fossil fuel inputs, and improved sustainability metrics [33,39,40]. Xin et al. [40] developed a biomass-solar hybrid gasification system combining solar pyrolysis with photovoltaic-solid oxide electrolysis cells. The system achieved carbon efficiency from biomass to fuel of 66.81%, and total energy conversion efficiency of 73.06% representing increases of 10.45% and 54.25%, respectively compared

to conventional biomass gasification. Aminov et al. examined integrated power and hydrogen generation systems using biomass and solar thermal energy [39]. The integration of concentrated solar power significantly enhanced exergoeconomic and exergoenvironmental performance.

Moharamian et al. [41] proposed a novel solar-based externally fired biomass combined cycle with hydrogen production, integrating PhotoVoltaic/Thermal (PVT) solar collectors with biomass combustion. The study found that increasing PVT area decreased cycle energy and exergy efficiencies while increasing investment costs, but significantly decreased $CO_2$ discharge rates, demonstrating the environmental benefits of solar integration.

#### *5.3.2 Sequential and Multi-Stage Processes*

Sequential fermentation combines dark fermentation and photofermentation to maximize hydrogen yields from organic substrates [34]. Dark fermentation first converts carbohydrates to hydrogen and organic acids, followed by the organic acids photofermentation to produce additional hydrogen. This two-stage approach can theoretically achieve higher overall hydrogen yields than either process alone, though practical implementation faces challenges in process integration and optimization [37].

Multi-stage gasification processes employ multiple reactors operating at different temperatures and conditions to optimize biomass conversion and hydrogen production [29]. Wolff Leal et al. [29] reviewed multi-stage gasification as an advanced process for green hydrogen production from lignocellulosic biomass, noting that each stage can be optimized for specific reactions, potentially improving overall efficiency and product quality.

#### *5.3.3 Advanced Gasification Technologies*

Advanced gasification technologies including plasma gasification, microwave-assisted gasification, and solar thermal gasification, represent emerging approaches for enhanced biomass-to-hydrogen conversion [29]. Solar thermal gasification uses concentrated solar energy as the heat source for endothermic gasification reactions, reducing fossil fuel inputs and enabling carbon-negative hydrogen production when combined with carbon capture [33]. Microwave-assisted gasification employs microwave radiation for rapid, selective heating of biomass, potentially improving energy efficiency and product quality. Plasma gasification operates at extremely high temperatures (above 1200°C) using plasma torches, enabling complete conversion of biomass and contaminants into syngas with minimal tar formation [29].

These advanced technologies remain largely at research and development stages, with challenges in scalability, cost-effectiveness, and technical complexity requiring further investigation [29,37]. However, they represent promising pathways for next-generation biomass-to-hydrogen systems with enhanced performance and sustainability characteristics.

### *5.4 Critical Analysis of Biomass Hydrogen Production Technologies*

Thermochemical conversion, notably gasification, demonstrates superior commercial maturity [24]. However, tar formation and catalyst deactivation remain persistent technical bottlenecks [42]. Biological routes, including dark fermentation and Microbial Electrolysis Cells (MEC), offer environmentally benign alternatives but suffer from lower productivity and TRL (3–5) Biomass-powered Solid Oxide Fuel Cells Biomass-powered Solid Oxide Fuel Cells Experimental and Modeling Studies Biomass-powered Solid Oxide Fuel Cells. Process inconsistencies across studies often stem from variations in feedstock and reactor configurations [23]. Advancing these technologies requires hybridizing thermochemical and biological processes, alongside AI-driven optimization and carbon capture integration to improve overall sustainability and scalability.

## 6 Biomass for Low-Carbon Hydrogen Production

The utilization of biomass for hydrogen production offers significant potential for achieving low-carbon or carbon-negative energy systems. This section examines the environmental and economic dimensions of biomass-based hydrogen production, solar-biomass integration strategies, feedstock considerations, and future perspectives for advancing sustainable hydrogen economies.

### *6.1 Environmental and Economic Assessment*

#### *6.1.1 Life Cycle Environmental Impacts*

Comprehensive life cycle assessments demonstrate that biomass-based hydrogen production pathways offer substantially lower environmental impacts compared to fossil fuel-based methods. Yagmur Goren et al. [17] conducted a comparative environmental analysis revealing that biomass-based methods (photofermentation, dark fermentation, microbial electrolysis cells) exhibit significantly lower acidification potential (AP) and global warming potential (GWP) than fossil fuel-based processes. Fig. 7 shows the life cycle using renewable electricity.

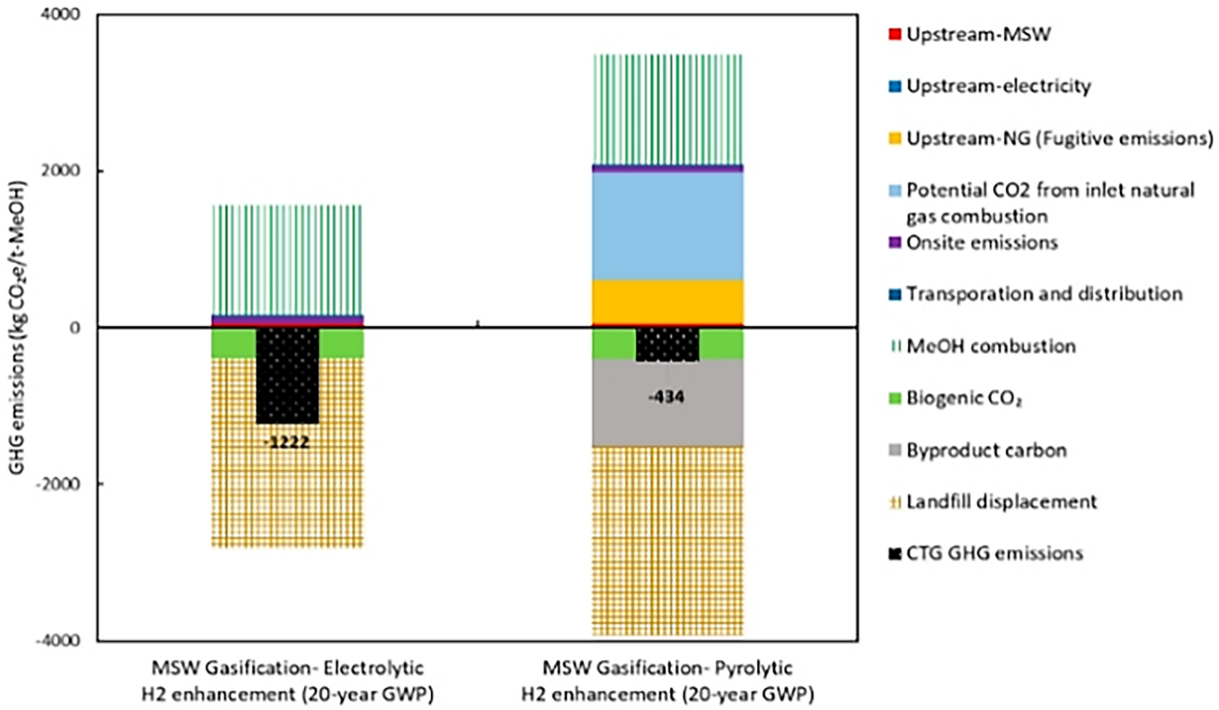



**Figure 7:** Life cycle emissions using renewable electricity (Ostadi et al., 2024) [Reprinted with permission from Ostadi, M.–2024].

Abawalo et al. [34] emphasized that bio-based hydrogen pathways show significantly pollutant outputs, lower energy use, and greenhouse gas emissions compared to conventional methods. Life cycle analysis by Bengharbia and Younus [28] highlighted reduced greenhouse gas emissions and energy efficiency benefits of gasification and anaerobic digestion for biomass waste conversion to hydrogen. The environmental benefits extend beyond carbon emissions to include waste valorization, reduced landfill reliance, and decreased methane emissions from organic waste decomposition [32,34].

Aminov et al. [39] exergo-environmental impact factors ranging from 66.2% to 73.9% with environmental impact rates of 5.4–7.1 Pts/MWh for solar-biomass hybrid systems, demonstrating significant improvements compared to conventional fossil-based systems. The integration of solar energy further enhances environmental performance by reducing fossil fuel inputs and associated emissions [39,40].

Life cycle assessment (LCA) is standard for evaluating biomass-based hydrogen production, yet environmental impacts vary significantly due to methodological inconsistencies [43]. Key uncertainties stem from the selection of functional units such as mass-based vs. energy-based metrics and varying system boundaries, which can alter greenhouse gas estimates significantly [44]. Furthermore, addressing multifunctionality through different allocation methods for co-products like biochar or heat leads to markedly different results [45]. The treatment of biogenic carbon and land-use change remains another critical source of variability, as assuming carbon neutrality often overlooks cultivation and sequestration delays [46]. Consequently, direct comparisons of reported carbon footprints require caution. To improve reliability, future studies must adopt harmonized guidelines, transparently report assumptions, and utilize standardized system boundaries for better comparability across the hydrogen landscape.

### *6.1.2 Economic Viability and Cost Analysis*

Economic assessments indicate that mature biomass-to-hydrogen technologies are approaching cost competitiveness with conventional hydrogen production methods. Rey et al. [27] best-case production costs of 1.28 EUR/kg$H_2$ for anaerobic digestion and 1.79 EUR/kg$H_2$ for conventional gasification, comparable to natural gas steam reforming costs of 0.92–2.8 EUR/kg$H_2$. These findings suggest that biomass-based hydrogen can be economically viable, particularly as carbon pricing mechanisms increasingly favor low-carbon production pathways [17]. The study emphasized that addressing process efficiency and cost reduction in solar concentrators and receivers is crucial for improving competitiveness.

The economic viability of biomass-based hydrogen production depends on multiple factors including feedstock costs, technology maturity, scale of operation, policy incentives, and carbon pricing [27,38]. Li et al. [38] noted that while biological conversion technologies currently have higher costs and require significant development, thermochemical processes like biomass gasification with system efficiencies of 40%–50% offer more immediate economic potential. Rising carbon costs are expected to reduce the competitive advantage of fossil-based hydrogen and promote cost-competitiveness of biomass-based renewable hydrogen [17].

Techno-Economic Assessment of Biomass-Based Hydrogen Production Technologies

The economic viability of biomass-based hydrogen depends on complex interactions between feedstock costs, conversion efficiency, and capital investment. While diverse methodologies often complicate direct comparisons, this consolidated assessment identifies key commercial drivers. Thermochemical routes currently lead in cost-effectiveness at scale due to high maturity and efficiency, though intensive gas-cleaning and capital requirements remain significant burdens. Conversely, biological pathways benefit from milder operating conditions but suffer from higher unit costs driven by low productivity and limited industrial scaling. Hybrid solar–biomass systems offer superior environmental profiles but necessitate higher initial investment in thermal storage and integration. Beyond technology, economic performance is highly sensitive to economies of scale, feedstock logistics, and regional carbon pricing. Future competitiveness hinges on process intensification, catalyst innovation, and supportive policy frameworks to offset investment risks. Ultimately, large-scale deployment and optimized logistics are essential to achieving a cost-competitive renewable hydrogen economy. Table 1 shows the Comparative Techno-Economic Assessment of Renewable Hydrogen Production Technologies.

**Table 1:** Comparative techno-economic assessment of renewable hydrogen production technologies.

| S. No. | Technology | Capital Cost | Operating Cost | Major Cost Drivers | Cost Sensitivity | Commercial Feasibility |
|---|---|---|---|---|---|---|
| **1.** | Gasification | High | Moderate | Gasifier, gas cleaning, biomass preprocessing | Biomass price, plant scale | High |
| **2.** | Pyrolysis | High | Moderate | Reactor system, catalyst, reforming | Catalyst cost, biomass quality | Moderate–High |
| **3.** | SCWG | Very High | Moderate | High-pressure reactor, materials | Equipment cost, energy demand | Moderate |
| **4.** | Dark Fermentation | Moderate | Moderate | Bioreactor, substrate preparation | Feedstock quality, microbial efficiency | Low–Moderate |
| **5.** | Photofermentation | Moderate | Moderate | Photobioreactor, illumination | Solar availability | Low |
| **6.** | MEC | High | Moderate | Electrodes, electricity | Electricity price | Moderate |
| **7.** | Solar–Biomass Hybrid | Very High | Moderate | Solar collectors, storage, integration | Solar irradiance, capital investment | Moderate |

#### *6.1.3 Technology Readiness and Scalability*

Technology readiness levels vary significantly across biomass-to-hydrogen pathways, influencing deployment timelines and investment priorities. Thermochemical processes, particularly gasification and pyrolysis, have reached higher technology readiness levels with demonstrated industrial-scale applications [27,28,30]. Tavares Borges et al. [30] highlighted that biomass gasification technology has matured sufficiently for industrial-scale hydrogen production, with global potential estimated at 45.03 EJ by 2050.

Biological conversion technologies generally remain at lower technology readiness levels, with most applications at laboratory or pilot scale [37,38]. Li et al. [38] that biological pathways like biophotolysis exhibit system efficiencies below 10% and require substantial development before commercial deployment. However, anaerobic digestion represents an exception, with established infrastructure and commercial applications for biogas production that can be adapted for hydrogen generation [27,28].

Bengharbia and Younus [28] identified challenges in technological efficiency and economic scalability as key barriers to widespread deployment of biomass-to-hydrogen technologies. Future priorities include catalyst development for tar reduction in gasification, process optimization for biological pathways, and AI-driven supply chain optimization for feedstock logistics [28,34].

### *6.2 Solar-Biomass Integration Systems*

#### *6.2.1 Hybrid System Configurations*

Solar-biomass hybrid systems integrate solar thermal or photovoltaic energy with biomass conversion processes to enhance efficiency, reduce carbon intensity, and enable continuous operation. Multiple configuration strategies have been demonstrated, each offering distinct advantages and challenges.

Altayib and Dincer [33] developed a multigeneration plant combining solar-thermochemical processes with biomass pyrolysis, producing 148.6 t/day of hydrogen with average energy efficiency of 61.3% and exergy efficiency of 58.1%. The system utilized concentrated solar energy for steam-methane reforming atop a solar tower, with autothermal operation during nighttime maintaining continuous production. This configuration achieved heat cogeneration of 1.28 MW, dried product output of 121 t/day, and power generation of 931.2 kW.

Xin et al. [40] proposed a biomass-solar hybrid gasification system integrating solar pyrolysis with photovoltaic-solid oxide electrolysis cells. The system achieved exceptional performance with total carbon efficiency from biomass to fuel of 66.81% and energy conversion efficiency of 73.06%. The integration of SOECs with waste heat recovery reduced electricity consumption during electrolysis by 19.30%, demonstrating the benefits of thermal integration and energy cascading.

Wei et al. [47] investigated hydrogen injection into biomass-solar integrated systems using PEM electrolyzers powered by photovoltaic panels. The study demonstrated that additional green hydrogen injection can enhance environmental performance of solar-biomass integration.

#### *6.2.2 Performance Enhancement through Solar Integration*

The integration of solar energy with biomass conversion processes provides multiple performance benefits including enhanced efficiency, reduced fossil fuel consumption, and improved environmental metrics. Aminov et al. [39] demonstrated that solar-biomass hybrid systems achieve exergy efficiencies of 48.67% and exergoeconomic factors of 80.65%, with significant improvements in exergoenvironmental performance compared to biomass-only systems.

Liu et al. [20] showed that introducing solar energy to biomass gasification-fuel cell systems enhanced the unit biomass producing capacity and utilization rate by 36.3% and 63.8%, respectively, in comparison to reference systems without solar incorporation. Moharamian et al. [41] found that increasing photovoltaic/thermal solar collector area in biomass combined cycles decreased $CO_2$ discharge rates despite modest reductions in cycle efficiency. This trade-off demonstrates the environmental benefits of solar integration, particularly in contexts where carbon emissions reduction is prioritized over maximum thermodynamic efficiency.

#### *6.2.3 Challenges in Solar-Biomass Deployment*

Despite promising performance characteristics, large-scale deployment of solar-biomass hybrid systems faces significant challenges related to resource availability, logistics, and economics. Iloeje et al. [48] assessed the deployment of solar-driven hydrogen from biomass at scale in the United States, revealing that geospatial misalignment between biomass resources and solar intensity introduces substantial supply chain logistics costs and carbon emissions. The study found that while economies of scale apply at the processing facility level, a reverse effect occurs at the broader systems level driven by logistics constraints [48]. However, strategic system-level changes including optimized facility siting, improved transportation infrastructure, and integrated supply chain management can reduce logistics costs and enable sustainable, low-cost hydrogen production.

Aminov et al. [39] emphasized that addressing process efficiency and cost reduction in receivers and solar concentrators is crucial for improving the solar-biomass systems competitiveness. The high capital costs of concentrated solar power systems and photovoltaic arrays represent significant economic barriers, though declining solar technology costs are improving economic viability [39,41].

### *6.3 Feedstock Considerations and Waste Valorization*

#### *6.3.1 Biomass Feedstock Types and Characteristics*

The composition and characteristics of biomass feedstocks significantly influence conversion efficiency, hydrogen yields, and process economics. Wolff Leal et al. [29] emphasized that the composition of lignocellulosic biomass, including moisture content, ash content, and elemental composition, directly affects gasification efficiency and syngas quality. Agricultural residues, forestry wastes, energy crops, and dedicated biomass plantations represent primary feedstock categories for hydrogen production [31]. Zhang et al. [31] conducted a comparative review of thermochemical hydrogen production technologies from agricultural waste, highlighting the potential for high-value utilization of crop residues. Agricultural wastes offer advantages of abundance, low cost, and minimal competition with food production, though seasonal availability and distributed nature present logistical challenges. The study noted that pyrolysis and reforming of agricultural wastes can achieve high hydrogen yields, particularly when steam reforming is employed to promote water-gas shift reactions. Fig. 8 shows the flow chart for the production of hydrogen from biomass.

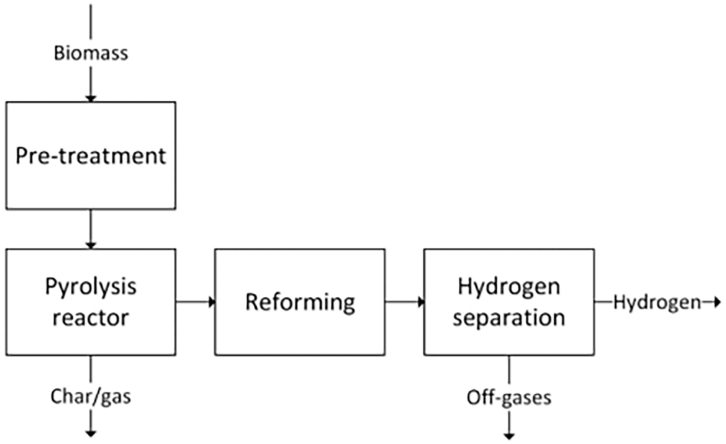



**Figure 8:** Generic flowchart for hydrogen production from biomass-based pyrolysis (ETIP, 2021) [49] [Reprinted with permission from Johan M. Ahlström–2020].

Aminov et al. [39] demonstrated hydrogen production from cotton stalk biomass. This application illustrates the potential for utilizing agricultural residues that might otherwise be burned or left to decompose, converting waste streams into valuable energy products while reducing environmental impacts.

#### *6.3.2 Organic Waste and Bio Waste Conversion*

Organic waste materials including food waste, municipal solid waste, wastewater sludge, and industrial organic residues represent particularly attractive feedstocks for hydrogen production due to their waste management benefits and potential for circular economy integration [32,34]. Garg et al. [32] reviewed waste-to-hydrogen processes including anaerobic digestion, gasification, and pyrolysis for converting organic waste into hydrogen-rich syngas or hydrogen gas. These processes generate clean energy while helping manage waste by reducing methane emissions from decomposition.

#### *6.3.3 Sustainability and Circular Economy Aspects*

Biomass-based hydrogen production aligns with circular economy principles by converting waste materials and residues into valuable energy carriers while minimizing environmental impacts [28,32,34].

Bengharbia and Younus [28] emphasized that sustainable green hydrogen generation from biomass waste offers substantial benefits including energy efficiency, reduced greenhouse gas emissions and effective waste valorization.

The integration of biomass-to-hydrogen systems with existing waste management infrastructure creates opportunities for enhanced resource efficiency and reduced environmental burdens. Garg et al. [32] noted that waste-to-hydrogen processes powered by renewable sources such as wind, solar, or biomass further reduce greenhouse gas emissions and promote a worldwide shift from traditional to sustainable energy sources. The potential for carbon-neutral or carbon-negative hydrogen production when biomass feedstocks are derived from renewable resources or wastes represents a key sustainability advantage [17].

However, sustainability considerations must account for potential impacts on food security, land use, water resources, and biodiversity [50]. Obiora highlighted challenges including environmental impact and food supply concerns associated with biomass hydrogen production. Sustainable deployment requires careful feedstock selection prioritizing wastes, residues, and non-food biomass sources, along with comprehensive life cycle assessments to ensure net environmental benefits.

### *6.4 Challenges and Future Perspectives*

#### *6.4.1 Technical Challenges and Research Priorities*

Despite significant progress in biomass-to-hydrogen technologies, multiple technical challenges require continued research and development. Garg et al. [32] identified ongoing research priorities including scalability, enhancing efficiency, and waste-to-hydrogen technologies cost-effectiveness. Wolff Leal et al. [29] emphasized challenges in optimizing gasification processes, developing more efficient catalysts, and integrating gasification with other renewable energy production systems. Catalyst development represents a critical research priority across multiple conversion pathways. Bengharbia and Younus [28] highlighted catalyst development for tar reduction in gasification as a key future priority, as tar formation remains a significant challenge affecting syngas quality and downstream processing requirements.

Process optimization for biological pathways requires addressing low efficiencies and hydrogen productivity [27,37]. Kumar and Fiori [37] reviewed thermochemical and biological routes for green hydrogen production, noting that biological methods generally exhibit lower performance than thermochemical processes. Enhancing microbial strains, optimizing operating conditions, and developing hybrid biological-thermochemical systems represent important research directions.

#### *6.4.2 Economic and Policy Considerations*

Economic viability and supportive policy frameworks are essential for widespread deployment of biomass-based hydrogen production. Giakoumakis et al. Production of Hydrogen from Biomass and other Sustainable Sources: Applications, Storage, and Policy Recommendations provided policy recommendations for accelerating the hydrogen adoption as a reliable and clean energy carrier, emphasizing the need for integrated strategies combining technological development, economic incentives, and regulatory support. Rising carbon costs and carbon pricing mechanisms are expected to improve the competitiveness of biomass-based green hydrogen relative to fossil fuel-based production [17]. Yagmur Goren et al. [17] noted that carbon pricing may reduce the reasonable price of fossil-based hydrogen and promote cost-competitiveness of biomass-based alternatives. Policy instruments including carbon taxes, emissions trading systems, renewable energy credits, and production subsidies can accelerate market development and technology deployment.

Infrastructure development for hydrogen production, storage, transportation, and utilization requires substantial investment and coordinated planning [18,51]. Akpasi et al. [18] stressed the importance of

international collaboration and government policies in addressing infrastructure needs and enabling hydrogen economy development. Integration with existing energy systems, development of hydrogen refueling networks, and establishment of safety standards and regulations represent critical policy priorities.

#### *6.4.3 Future Technological Directions*

Emerging technologies and system integration approaches offer promising pathways for advancing biomass-based hydrogen production. Obiora et al. [50] highlighted the potential of machine learning and artificial intelligence for improving hydrogen production through supply chain management, predictive maintenance, and process optimization. AI-driven approaches can optimize complex multi-parameter systems, predict performance under varying conditions, and identify opportunities for efficiency improvements.

Advanced gasification technologies including solar thermal gasification, microwave-assisted gasification, and plasma gasification represent next-generation approaches with potential for enhanced performance [29]. These technologies remain largely at research stages but offer prospects for improved efficiency, reduced emissions, and enhanced product quality. Continued development and scale-up demonstrations are needed to assess commercial viability.

Integration of biomass-to-hydrogen systems with carbon capture, utilization, and storage technologies enables carbon-negative hydrogen production [36]. Ghannadi and Dincer [36] demonstrated iron-based chemical looping with carbon capture achieving hydrogen production rates of 10.5 kg/s with simultaneous $CO_2$ capture of 1120 kg/s. Such systems can produce hydrogen while removing $CO_2$ from the atmosphere when biomass feedstocks are derived from renewable sources, contributing to climate change mitigation.

#### *6.4.4 Global Potential and Deployment Scenarios*

The global potential for biomass-based hydrogen production is substantial, though realization depends on sustainable feedstock availability, technological advancement, and supportive policies. Tavares Borges et al. [30] estimated global potential for hydrogen production from solid biomass at 45.03 EJ in an optimal trends scenario for 2050, with significant regional variations. Brazil's potential was estimated at 6.5 EJ, reflecting the country's abundant biomass resources and agricultural sector.

Bengharbia and Younus [28] suggested that gasification and anaerobic digestion technologies could meet 20%–50% of regional hydrogen demand, indicating substantial potential for biomass-based hydrogen to contribute to energy systems. However, achieving this potential requires addressing challenges in technological efficiency, economic scalability, feedstock logistics, and policy support. Al-Janabi et al. [52] conducted bibliometric analysis revealing increasing research attention to hydrogen production from sustainable resources through thermochemical and biological pathways. The growing body of research and development activities, coupled with increasing policy support and investment, suggests accelerating progress toward commercial deployment of biomass-based hydrogen technologies. Continued innovation, demonstration projects, and knowledge sharing will be essential for realizing the full potential of biomass as a sustainable hydrogen source.

### *6.5 Critical Analysis of Solar–Biomass Hybrid Systems*

Solar-assisted biomass systems improve energy efficiency by integrating concentrated solar thermal energy into gasification or reforming processes [24]. Despite promising simulation and experimental results, these systems continue to face economic, material, and system-integration challenges, with several emerging configurations remaining at TRLs 4–6 [42]. High initial investment and storage requirements currently limit commercial viability [23]. Variability in regional solar irradiance and biomass logistics further

complicates standardized techno-economic assessments. Future development should focus on modular designs, advanced thermal energy storage, and comprehensive life cycle assessments under realistic operating conditions to bridge the gap toward industrial-scale demonstration.

## 7 Solar Thermochemical Hydrogen

Since solar energy is abundant, renewable, and favorable to both photochemical and electrolytic water splitting, it is one of the most practical and sustainable methods of creating hydrogen. Solar energy produces hydrogen with no greenhouse gas emissions. Furthermore, distributed energy generation which is essential for off-grid locations with significant solar energy potential is made possible by solar hydrogen synthesis, improving sustainability and energy availability. In order to create high temperatures by splitting water into hydrogen and oxygen, solar thermal hydrogen production requires concentrated sun energy. By reflecting sunlight onto a receiver, the reflector generates heat for thermochemical processes or high-temperature electrolysis. Without the need of fossil fuels, this environmentally friendly method offers a sustainable way to produce hydrogen. There are three main ways that solar energy may be transformed into hydrogen: thermochemical, photochemical, and biological processes. Solar Thermo Chemical Hydrogen (STCH) production is a promising method for generating hydrogen using solar energy through thermochemical cycles. This process involves using concentrated solar energy to drive chemical reactions that split water into hydrogen and oxygen at lower temperatures than direct thermal dissociation. The STCH process is considered a sustainable and efficient approach to hydrogen production, with potential applications in various sectors, including transportation and energy storage. The following sections provide a detailed overview of the key aspects of STCH processes.

STCH processes utilize thermochemical cycles, which involve a series of chemical reactions to split water into hydrogen and oxygen. These cycles can be direct, involving only chemical steps, or hybrid, combining chemical and electrochemical steps [53]. Notable cycles include the zinc oxide cycle and the hybrid sulfur cycle, which are valued for their simplicity and efficiency [53]. Concentrated solar energy is used to provide the thermal energy required for the chemical reactions in STCH processes. This approach allows for the conversion of solar energy into storable chemical energy, making it a viable option for large-scale hydrogen production [54]. STCH processes aim to produce $CO_2$-neutral hydrogen, contributing to the reduction of greenhouse gas emissions and reliance on fossil fuels [53]. The integration of solar energy in hydrogen production can lead to significant environmental benefits, including reduced carbon emissions and mitigation of global warming [55]. Advances in materials and system design are crucial for improving the efficiency and feasibility of STCH processes. Research efforts focus on optimizing thermal energy storage systems and enhancing the performance of thermochemical cycles [55,56]. While STCH processes hold significant promise for sustainable hydrogen production, challenges remain in terms of cost and scalability. Recent techno-economic and life cycle assessment studies indicate that solar thermochemical hydrogen has strong potential for future carbon-neutral energy systems, particularly in regions with high solar irradiance. Continued advancements in solar concentrator technology, reactor engineering, materials science, and process integration are expected to accelerate the commercialization of sustainable solar thermochemical hydrogen production and contribute significantly to the global hydrogen economy. Continued research and technological advancements are essential to overcome these barriers and fully realize the potential of solar thermochemical hydrogen production. The solar-assisted methods for producing $H_2$ from (a) water and fossil fuels and (b) carbonaceous gases or solid feedstock are depicted in Fig. 9.

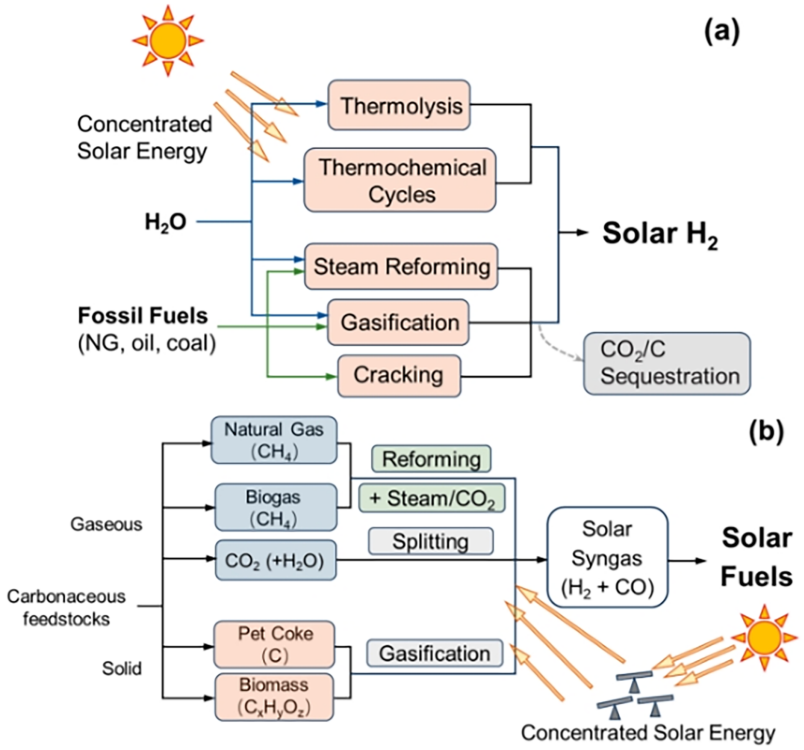



**Figure 9:** Solar-aided routes to produce $H_2$, with (**a**) from water and fossil fuels; and (**b**) carbonaceous gases or solid feedstock [57] [Reprinted with permission from Deng et al.–2024].

## 8 Hydrogen Transportation and Storage

Utilizing existing and suitable salt caverns, aquifers, and depleted gas reserves is one viable way to store compressed gaseous hydrogen. Underground Hydrogen Storage (UHS) was created specifically for the medium- and long-term storage of large amounts of excess hydrogen produced by seasonal renewable energy sources or imported. When assessing a possible UHS site, geological characteristics are undoubtedly the primary considerations for researchers and engineers. For pure hydrogen storage, the salt cavern is typically the best option. It is because of its viscoelastic evaporitic rocks, which serve as excellent gas sealing, in addition to the tightness of its deposits, the favorable mechanical qualities of salt, and its resistance to chemical reactions. Additionally, the microbial consumption of stored hydrogen is suppressed by the saltwater environment. Sadly, the salt caves are not widely dispersed and have quite tiny volumes. The geological structure and properties of depleted gas reserves are well-identified throughout exploration and exploitation, making them bigger in volume and offering significant benefits. However, remaining natural gas might lower the quality of hydrogen that has been stored. The aquifer, which has a very high volume and is easily located, will be an alternative for hydrogen storage if the host rock has acceptable reservoir properties and an impermeable barrier to prevent migration of the stored hydrogen.

Carl von Linde and William Hampson independently developed a cyclic technique in 1895 to liquefy air fit for industrial usage. For instance, a single hydrogen liquefaction facility in Leuna, Germany, has been in operation since 2007 and has a production capacity of 5.5 metric tons per day (mTPD). In 2021, the second liquefier in Leuna with the same capacity was supposed to go online. The 4.4 mTPD facility in Ingolstadt, which had been in operation since 1992, was shut down. Linde provides and runs all of these plants, which are based on the Claude system with liquid nitrogen pre-cooling. Modern hydrogen

liquefaction facilities are contrasted with the original Claude system. Fig. 10 shows an illustration of several methods for producing hydrogen.




**Figure 10:** Illustration of various routes for $H_2$ production (Patel et al., 2024) [Reprinted with permission from Patel et al.–2024].

## 9 Biological Biomass Conversion

Biological hydrogen production encompasses diverse microbial processes that convert organic substrates into hydrogen through enzymatic reactions under controlled environmental conditions. These bioprocesses offer advantages including ambient temperature operation, utilization of diverse feedstocks, and potential for waste valorization [27,51].

### *9.1 Dark Fermentation*

Dark fermentation represents the most extensively studied biological hydrogen production pathway, utilizing anaerobic microorganisms to metabolize carbohydrate-rich substrates in the absence of light [58,59]. The process involves facultative and obligate anaerobes, predominantly from genera

*Clostridium*, *Enterobacter*, and *Thermoanaerobium*, which degrade organic matter through glycolytic pathways producing hydrogen, carbon dioxide, and volatile fatty acids [27,60].

The stoichiometry of dark fermentation varies with metabolic pathways, with the acetate pathway yielding theoretical maximum of 4 mol $H_2$/mol glucose, while the butyrate pathway produces 2 mol $H_2$/mol glucose [60,61]. Recent studies report practical hydrogen yields ranging from 1.5–3.5 mol $H_2$/mol glucose, significantly below theoretical maxima due to competing metabolic pathways and thermodynamic constraints [62]. Process optimization focuses on critical operational parameters including pH (optimal range 5.5–6.5), hydraulic retention time, temperature, and organic loading rate [60,63,64]. Feedstock pretreatment strategies including acid hydrolysis (0.2% w/w HCl), alkaline treatment (0.2% w/w NaOH), thermal processing, and enzymatic saccharification enhance substrate accessibility and hydrogen yields from lignocellulosic biomass [60,65].

Recent advances in reactor design include Anaerobic Sequencing Batch Reactors (ASBR), Continuous Stirred-Tank Reactors (CSTR), and packed-bed reactors, with reported volumetric hydrogen production rates reaching 2–15 L $H_2$/L/day depending on substrate and operational conditions [66].

### *9.2 Photofermentation*

Photofermentation employs primarily Purple Non-Sulfur Bacteria (PNSB), photosynthetic bacteria, including *Rhodobacter capsulates* and *Rhodobacter sphaeroides*, to convert organic acids into hydrogen using light energy under anaerobic conditions [60]. The process follows the stoichiometry: $CH_3COOH + 2H_2O + \text{light} \rightarrow 4H_2 + 2CO_2$, with theoretical yields of 4 mol $H_2$/mol acetate [60].

However, photofermentation faces significant challenges including low light conversion efficiency (1%–5%), requirement for large illuminated surface areas, and sensitivity to oxygen inhibition [60,67]. Recent research focuses on photobioreactor design optimization, including tubular, flat-panel, and column reactors with enhanced light distribution and mass transfer characteristics.

### *9.3 Integrated Dark-Photo Fermentation Systems*

Integration of dark and photofermentation in sequential two-stage systems represents a promising strategy for maximizing hydrogen yields and substrate conversion efficiency [65,68]. In this configuration, dark fermentation converts carbohydrates to hydrogen and organic acids, while subsequent photofermentation utilizes the organic acid-rich effluent for additional hydrogen production [68].

Theoretical combined yields can reach 12 mol $H_2$/mol glucose, significantly exceeding single-stage processes [60,68]. Lee [68] demonstrated that dark-photo fermentation systems in Asian circular economies achieved 30%–50% higher hydrogen yields compared to standalone dark fermentation, with improved substrate utilization and reduced waste generation.

Implementation challenges include pH management between stages, selection of compatible microbial consortia, and optimization of inter-stage processing [65]. Single-stage integration approaches, where dark and photofermentative microorganisms coexist, show promise for cost reduction but require careful control of light exposure and oxygen levels [65].

### *9.4 Biophotolysis and Microbial Electrolysis*

Biophotolysis utilizes photosynthetic microorganisms including cyanobacteria and green algae to split water directly into hydrogen and oxygen using light energy [60]. Direct biophotolysis involves water splitting by photosystem II followed by hydrogen production via hydrogenase enzymes, while indirect biophotolysis separates hydrogen and oxygen evolution temporally through intermediate carbon fixation [60].

Despite theoretical appeal, biophotolysis faces severe limitations including low light conversion efficiency (<1%), oxygen sensitivity of hydrogenase enzymes, and requirement for large cultivation areas [60,67]. Current research focuses on genetic engineering approaches to enhance hydrogenase oxygen tolerance and improve photosynthetic efficiency [67].

Microbial Electrolysis Cells (MEC) represent an alternative bioelectrochemical approach, applying small external voltages (0.2–0.8 V) to drive hydrogen evolution from organic substrates through exoelectrogenic bacteria [60]. MECs achieve higher hydrogen recovery rates (>90%) compared to fermentation but require electrical input and face challenges in scaling and electrode fouling [60,64].

## 10 Environmental Resource Use

### *10.1 Life Cycle Assessment and Carbon Footprint*

LCA studies consistently demonstrate favorable environmental profiles for biomass-derived hydrogen compared to fossil fuel-based production routes [6,28,69]. Bengharbia that gasification and anaerobic digestion of biomass waste achieve 60%–80% reductions in greenhouse gas emissions compared to steam methane reforming, for conventional processes. Jin et al. [70] conducted comprehensive LCA of dark-photo fermentation from wheat straw, revealing net negative carbon emissions when accounting for avoided waste disposal and fossil fuel displacement. The study identified energy consumption during feedstock pretreatment and hydrogen purification as primary environmental hotspots, contributing 40%–50% of total life cycle impacts [70]. Solar-driven hydrogen production via photocatalytic and photoelectrochemical systems exhibits even lower carbon footprints, with reported values below 1 kg $CO_2$-eq/kg $H_2$ when utilizing renewable electricity for auxiliary systems [63]. However, embodied emissions from catalyst and reactor manufacturing require consideration in comprehensive LCA frameworks [6].

### *10.2 Waste Valorization and Circular Economy*

Biomass-based hydrogen production enables effective valorization of diverse waste streams including food waste, agricultural residues, industrial effluents and municipal solid waste [28,34,51]. This waste-to-energy approach addresses dual challenges of waste management and renewable energy generation, aligning with circular economy principles [68]. Bengharbia and Younus [28] estimated that biomass waste-derived hydrogen could meet 20%–50% of regional hydrogen demand while diverting significant waste volumes from landfills and reducing methane emissions from organic waste decomposition. The integration of hydrogen production with existing waste management infrastructure offers economic and environmental synergies [69]. Hosseinzadeh et al. [69] demonstrated that bio-waste hydrogen systems generate valuable co-products including biochar, organic fertilizers, and recovered nutrients, enhancing overall process economics and resource efficiency. The nutrient-rich digestate from anaerobic digestion processes can substitute synthetic fertilizers, reducing agricultural environmental impacts [51].

### *10.3 Water and Land Resource Considerations*

Water consumption represents a critical consideration for hydrogen production systems, with electrolysis and biological processes including feedstock moisture and process water [6,64]. However, many biological systems can utilize wastewater streams, reducing freshwater demand and providing wastewater treatment benefits [51,60].

Land use requirements vary substantially across technologies. Thermochemical processes (gasification, pyrolysis) require relatively compact facilities, while biological systems, particularly photofermentation and biophotolysis, demand larger areas due to light collection requirements [60,63]. Buffi et al. [6] emphasized

that sustainable biomass sourcing must avoid competition with food production and prevent deforestation or land-use change, necessitating careful feedstock selection and supply chain management.

The sustainability of biomass resources depends critically on regeneration rates, harvesting practices, and ecosystem impacts [6,64]. Utilization of forestry waste, agricultural residues, and dedicated energy crops on marginal lands offers pathways to minimize land-use conflicts while maintaining biodiversity and soil health [28,34].

## 11 Key Challenges in Hydrogen Energy Systems

### *11.1 Technical and Efficiency Barriers*

Despite significant research progress, green hydrogen technologies face persistent technical challenges limiting commercial deployment [67,71]. Biological hydrogen production suffers from low conversion efficiencies, with practical yields typically 30%–50% of theoretical maxima due to competing metabolic pathways, product inhibition, and thermodynamic constraints [60,62,72]. Osman et al. [60] identified oxygen sensitivity of hydrogenase enzymes, hydrogen partial pressure inhibition, and accumulation of volatile fatty acids as critical bottlenecks in fermentative systems. Substrate inhibition at high organic loading rates and requirement for strict anaerobic conditions complicate reactor operation and scale-up [66,72].

Thermochemical processes face challenges including tar formation during gasification (requiring complex gas cleaning systems), catalyst deactivation, and energy-intensive feedstock drying for high-moisture biomass [28,61]. Lepage et al. [61] that tar removal and syngas purification account for 30%–40% of capital costs in biomass gasification systems. Solar-driven photocatalytic systems exhibit low solar-to-hydrogen conversion efficiencies (typically <5%), limited by charge carrier recombination, narrow light absorption ranges, and photocorrosion of semiconductor materials [63]. Song et al. [63] emphasized that achieving commercially viable efficiencies (>10%) requires breakthroughs in catalyst design, light harvesting, and charge separation mechanisms.

### *11.2 Economic and Scalability Challenges*

Economic competitiveness remains the primary barrier to widespread adoption of green hydrogen technologies [27,69]. Hosseinzadeh et al. [69] identified capital costs (40%–50% of levelized cost), feedstock costs (20%–30%), and purification expenses (15%–25%) as dominant economic factors. Scaling biological systems from laboratory to industrial scale presents significant challenges related to reactor design, process control, and maintaining optimal microbial activity [67,73]. Zhang et al. [73] demonstrated that pilot-scale fermentation systems (>1000 L) require sophisticated monitoring and control systems to maintain stable hydrogen production. Infrastructure requirements for biomass collection, storage, transportation, and preprocessing add substantial costs and logistical complexity [28,64]. Seasonal variations in biomass availability necessitate storage facilities and supply chain management systems, increasing overall system costs [6,61]. Ghasemi et al. [74] emphasized that thermochemical processes demonstrate higher technology readiness levels compared to biological and electrochemical systems, indicating that gasification and pyrolysis are closer to commercial deployment but still require cost reductions through technological improvements and economies of scale.

### *11.3 Feedstock and Infrastructure Limitations*

Feedstock availability, quality, and sustainability represent critical constraints for biomass-based hydrogen systems [6,64,72]. Lignocellulosic biomass requires extensive pretreatment to overcome recalcitrance, adding costs and energy consumption [65,72]. Rani et al. [72] that pretreatment can account for 30%–50% of

total processing costs for lignocellulosic feedstocks. Feedstock heterogeneity complicates process optimization and control, as composition variations affect conversion efficiency and product distribution [60,66]. Seasonal availability and geographic distribution of biomass resources necessitate distributed production systems or extensive transportation networks [28,61].

Competition for biomass resources among energy, materials, and food applications raises sustainability concerns [6,64]. Buffi cautioned that large-scale biomass demand could drive deforestation, land-use change, and food security impacts without careful resource management and policy frameworks. Infrastructure gaps in hydrogen storage, distribution, and utilization limit market development and economic viability [71]. The lack of established hydrogen supply chains, refueling stations, and end-use applications creates chicken-and-egg challenges for technology deployment [69,74].

Policy and regulatory frameworks remain underdeveloped in many regions, with insufficient incentives, unclear standards, and limited support for green hydrogen compared to fossil fuel alternatives [28,71]. Bengharbia and Younus [28] emphasized that overcoming technical and policy barriers requires coordinated efforts across research, industry, and government sectors.

A comparative assessment of green hydrogen production and utilization pathways is presented in Table 2, delineating their technological maturity, operational parameters, and industrial viability. Currently, thermochemical routes most notably gasification and pyrolysis reforming represent the most mature pathways for large-scale industrial deployment, characterized by technology readiness levels (TRL) of 7–8 and high conversion efficiencies. In contrast, biological methods, such as dark fermentation, photofermentation, and microbial electrolysis, offer sustainable, decentralized alternatives but are currently hindered by lower TRLs stemming from persistent challenges in process stability, yield optimization, and scalability. Emerging frontiers, including solar thermochemical hydrogen production and supercritical water gasification, hold substantial promise for carbon-neutral generation; however, their commercial trajectory remains contingent upon further techno-economic optimization. Regarding utilization, Proton Exchange Membrane Fuel Cells (PEMFCs) and Solid Oxide Fuel Cells (SOFCs) are established as high-performance conversion systems, with SOFCs exhibiting notable fuel flexibility for biomass-derived syngas. The progression toward a viable green hydrogen economy necessitates a synergistic integration of mature thermochemical infrastructures with advancing biological and electrochemical technologies. Fig. 11 illustrates the comparative technology readiness levels (TRLs) of green hydrogen production technologies, highlighting the higher commercial maturity of thermochemical routes compared with emerging biological and hybrid systems.

**Table 2:** Comparative assessment of green hydrogen production and utilization technologies: Technical maturity, operational characteristics, and industrial scalability.

| S. No. | Technology | Primary References | Key Characteristics & Maturity (TRL) |
|---|---|---|---|
| 1. | **Gasification** | Tavares Borges et al. (2024); Wolff Leal et al. (2024); Bengharbia & Younus (2025) [28–30] | High maturity (TRL 7–8); converts solid biomass to syngas at 700°C–1000°C; suitable for large-scale industrial applications. |
| 2. | **Pyrolysis and Reforming** | Hassan et al. (2024); Wang et al. (2021); Zhang et al. (2024) [2,10,31] | Thermochemical route with high yields; TRL 7–8; centralized production; enhanced by steam reforming of pyrolysis products. |

(Continued)

**Table 2 (continued)**

| S. No. | Technology | Primary References | Key Characteristics & Maturity (TRL) |
|---|---|---|---|
| 3. | **Anaerobic Digestion** | Buffi et al. (2022) [6] | Competitive economic viability (~1.28 EUR/kg $H_2$); suitable for decentralized waste management. |
| 4. | **Photofermentation** | Osman et al. (2023); Lee (2021); Song et al. (2022) [60,63,68] | Biological conversion using light and PNSB bacteria; higher theoretical yields than dark fermentation but low light conversion efficiency (1%–5%). |
| 5. | **Dark Fermentation** | Hassan et al. (2024); Zhao et al. (2024) [2,66] | Lower temperature biological pathway; early-stage development (TRL 4–6); challenges with productivity and limited yields. |
| 6. | **Solar Thermochemical Hydrogen (STCH)** | Gorensek et al. (2018); Abanades (2011); Santamaria Padilla et al. (2024) [53–55] | Uses concentrated solar energy for water splitting; $CO_2$-neutral; potential for large-scale carbon-neutral energy systems. |
| 7. | **PEM Fuel Cells (PEMFC)** | Kiani et al. (2025); Kumar et al. (2025) [22,24] | High efficiency and rapid response (TRL 7–9); suitable for transportation; sensitive to syngas impurities. |
| 8. | **Solid Oxide Fuel Cells (SOFC)** | Kumar et al. (2025) [24] | Superior fuel flexibility; high-temperature operation allows direct use of biomass syngas; material degradation challenges. |

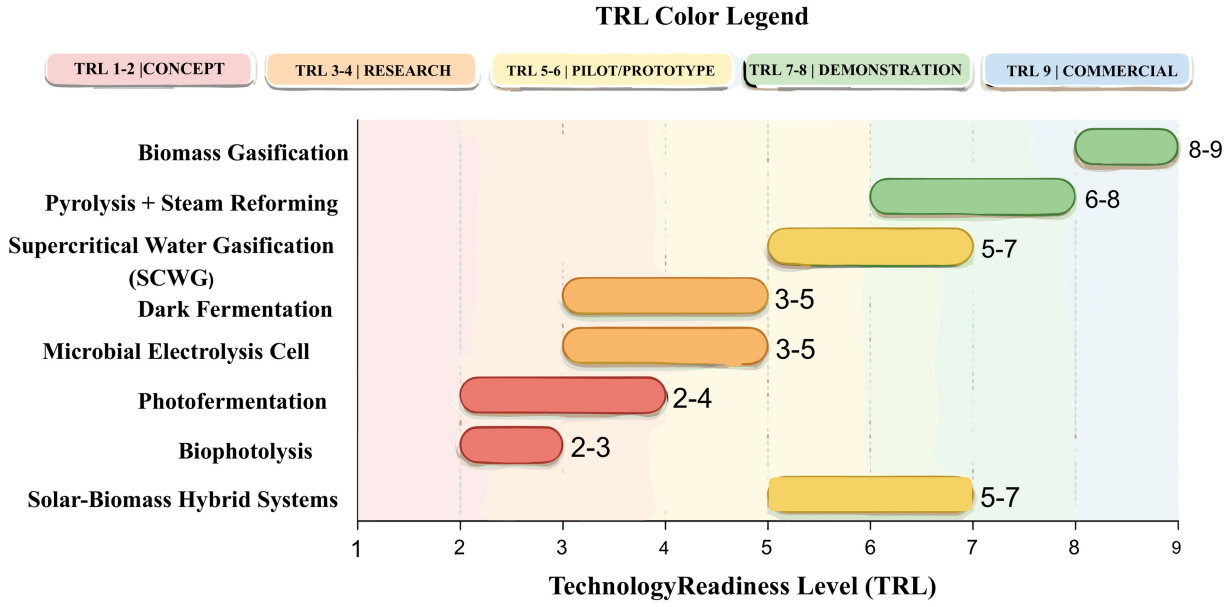



**Figure 11:** Comparative technology readiness level (TRL) of green hydrogen production technologies.

## 12 Positioning of the Present Review

Research published between 2023 and 2025 has significantly deepened the discourse on green hydrogen production. However, the current literature is predominantly fragmented, characterized by a focus on individual technology pathways (e.g., exclusively thermochemical or biological) or isolated methodologies (e.g., bibliometrics vs. TEA). This fragmented approach lacks a cross-comparative synthesis of diverse production routes under a standardized evaluative framework. The present review addresses this limitation by systematically integrating multiple hydrogen production pathways thermochemical, biological, and hybrid within a single, critical assessment. Unique to this study is the comprehensive benchmarking of hydrogen yield and energy efficiency alongside environmental impacts and commercialization potential. Furthermore, we provide a detailed analysis of research gaps and future development pathways, as summarized in Table 3, positioning this work as a strategic resource for industrial implementation and policy-driven decarbonization. The comparative synthesis in Table 3 distinguishes this work from the 2023–2025 literature by emphasizing a multi-pathway integration over traditional, single-technology reviews. While previous studies often focus exclusively on either thermochemical or biological routes, the present review provides a standardized evaluation of energy efficiency, carbon intensity, and commercialization potential across all major green hydrogen technologies, offering a strategic roadmap for researchers and policymakers.

**Table 3:** Comparison of recent review articles (2023–2025) and the positioning of the present review.

| Review Article | Main Focus | Limitation (for Comparison) |
|---|---|---|
| **Hassan et al. (2024)** [2] | Comprehensive overview of biomass hydrogen production technologies | Primarily summarizes production technologies with limited TRL, commercialization, and integrated biomass–solar analysis. |
| **Al-Janabi et al. (2024)** [52] | Biological and thermochemical hydrogen production with bibliometric analysis | Emphasizes publication trends but provides limited comparative techno-economic evaluation and commercialization assessment. |
| **Ghasemi et al. (2024)** [74] | Techno-economic and environmental assessment | Focuses mainly on TEA and environmental aspects; limited integration with solar hydrogen systems and TRL comparison. |
| **Abawalo et al. (2025)** [34] | Biowaste-based hydrogen production | Concentrates on biowaste conversion technologies without a comprehensive comparison of all biomass and solar-assisted routes. |
| **Kumar et al. (2025)** [24] | Biomass- and water-based hydrogen production | Reviews emerging production pathways but does not provide a comprehensive TRL mapping, commercialization roadmap, or integrated biomass–solar framework. |
| **Present Review (This Work)** | **Integrated biomass–solar green hydrogen systems** | Comprehensive comparison, critical evaluation, TRL assessment, commercialization analysis, sustainability assessment, and future research roadmap |

## 13 Overall Critical Summary

Biomass-derived hydrogen technologies exhibit divergent levels of maturity and efficiency. Thermochemical routes currently dominate industrial applicability, while biological processes offer sustainable, though less productive, alternatives [24]. Solar-assisted hybrid systems enhance renewable potential but require significant cost reductions and technological maturation (TRL 4–7) before widespread adoption [42]. Future efforts must prioritize standardized performance metrics, carbon capture integration, and digital monitoring to accelerate the transition to a sustainable hydrogen economy. The synergy between high-yield thermochemical methods and low-energy biological pathways represents the most viable trajectory for future energy landscapes. Fig. 12 compares biomass-based hydrogen production routes in terms of hydrogen yield, carbon emissions, and commercial readiness, demonstrating the trade-offs between production efficiency, environmental sustainability, and technology maturity.

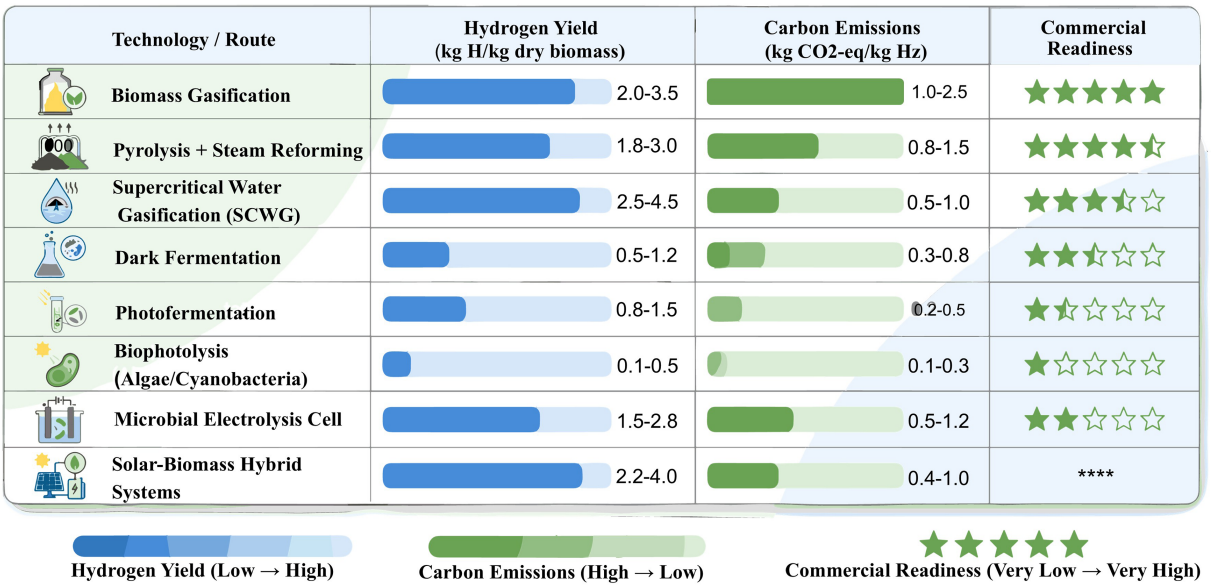



**Figure 12:** Comparison of hydrogen yield, carbon emissions, and commercial readiness of biomass-based hydrogen production routes.

### *Future Research Directions*

During the short term (1–5 years), efforts should focus on improving catalyst performance, process efficiency, feedstock utilization, and pilot-scale validation while reducing production costs through process optimization and comprehensive techno-economic analyses. In the medium term (5–10 years), research should emphasize scaling up biomass and solar hydrogen technologies, integrating carbon capture with biomass conversion, improving reactor designs, and establishing reliable hydrogen storage, transportation, and distribution infrastructure. Fig. 4 shows the Roadmap for green Hydrogen Production from Biomass and Solar Energy Systems and Table 4 shows the roadmap for green hydrogen production from biomass and solar energy systems.

**Table 4:** Roadmap for green hydrogen production from biomass and solar energy systems.

| Time Horizon | Biomass Hydrogen Priorities | Solar Hydrogen Priorities | Commercialization & Policy Priorities |
|---|---|---|---|
| Short-term (1–5 years) | Improve catalyst activity and durability; optimize gasification, pyrolysis, and fermentation; enhance feedstock pretreatment; improve hydrogen purification; conduct pilot-scale demonstrations | Develop high-efficiency photocatalysts and photo electrodes; improve PV-electrolysis integration; enhance solar-to-hydrogen efficiency; improve catalyst stability | Expand pilot plants; establish hydrogen quality standards; reduce production costs; strengthen government incentives and funding; perform techno-economic and life-cycle assessments |
| Medium-term (5–10 years) | Scale biomass conversion technologies; integrate carbon capture and utilization/storage (CCUS); improve process intensification and waste valorization; develop hybrid biomass–solar systems | Demonstrate large-scale PEC and photocatalytic systems; improve reactor design; develop durable, low-cost semiconductor materials; integrate renewable energy storage | Build hydrogen infrastructure; establish supply chains; reduce electrolyzer costs; expand industrial applications; implement supportive regulatory frameworks and carbon pricing |
| Long-term (>10 years) | Commercial deployment of integrated biorefineries producing hydrogen and value-added chemicals; AI-enabled process optimization; net-negative emission systems through BECCS | Commercial-scale solar hydrogen plants using advanced photocatalytic and thermochemical technologies; high-efficiency tandem systems; autonomous operation using artificial intelligence | Establish a global green hydrogen economy; widespread sector coupling (power, industry, transport); international hydrogen trade; fully integrated green hydrogen ecosystems supporting net-zero emissions |

## 14 Conclusion

Green hydrogen production from biomass and solar energy systems represents a vital pathway toward decarbonizing global energy systems and achieving climate targets. This review has demonstrated that biomass-derived hydrogen, through both mature thermochemical routes and emerging biological processes, offers dispatch-able, potentially carbon-negative hydrogen when integrated with carbon capture technologies. Solar-biomass hybrid systems exploit synergies between continuous biomass feedstocks and variable solar resources, enhancing system flexibility and reducing environmental impacts. However, realizing the full potential of these technologies requires addressing critical challenges: scaling up biological conversion processes, harmonizing techno-economic and life cycle assessment methodologies, reducing capital costs, ensuring sustainable feedstock sourcing, and developing supportive policy frameworks and infrastructure. Future research should prioritize integrated system designs, advanced conversion technologies with improved energy efficiency, and comprehensive sustainability assessments that account for water, land, and carbon trade-offs. With continued innovation and strategic deployment, biomass and solar-biomass hydrogen systems can play a central role in the future low-carbon energy landscape.

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