

Progress and innovation in key technologies for converting biomass to hydrogen

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ABSTRACT

The growing demand for clean energy has spotlighted biomass as a promising resource for sustainable hydrogen production, providing a carbon-neutral alternative to traditional fossil fuels. This review examines the latest advancements in converting biomass to hydrogen, focusing on thermochemical methods like gasification and pyrolysis, catalyst development, and biotechnological approaches such as dark fermentation and biophotolysis. While these methods offer substantial environmental benefits, including waste reduction and renewable energy generation, challenges persist in optimizing feedstock diversity, enhancing catalyst stability, and achieving cost-effective scalability. Innovations in plasma-assisted reforming, advanced nanocatalysts, and integrated reactor designs show promise in overcoming these barriers. By fostering collaboration across academia, industry, and government, these advancements can pave the way for a viable, sustainable hydrogen economy and contribute significantly to reducing global carbon emissions.

1. Introduction

In the last decade, the global energy system has undergone significant and transformative changes. The gradual shift away from traditional fossil fuels, such as coal, gas, and oil, is an inevitable trend driven by their negative impacts on climate, water resources, land, and human health [1–3]. The search for clean energy solutions has become a top priority. Hydrogen, in particular, has attracted significant attention as a promising fuel source, and numerous studies have been dedicated to exploring its storage potential [4,5]. The rapid increase in population

and industrial activity has led to heightened fossil fuel consumption, highlighting an urgent need for sustainable and environmentally friendly energy alternatives [6].

Biomass is increasingly establishing itself as a key renewable resource for sustainable hydrogen production, thanks to its widely available sources and the growing efficiency of conversion technologies [2]. Utilizing biomass to generate hydrogen not only provides a sustainable alternative to fossil fuels but also offers significant environmental advantages [7]. The primary benefit of this type of fuel is its carbon neutrality, as the carbon dioxide emitted during hydrogen

Abbreviations: APR, Aqueous phase reforming; CO₂, Carbon dioxide; H₂, Molecular hydrogen; IRA, Inflation reduction act; NAD⁺, Nicotinamide adenine dinucleotide; EU, European union; Ni, Nickel; Rh, Rhodium; Al₂O₃, Aluminum oxide; Mg, Magnesium; Zr, Zirconium; Ce, Cerium; La, Lanthanum; CO, Carbon monoxide.

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production is offset by its absorption during biomass growth, resulting in a closed carbon cycle [8,9]. Additionally, agricultural and organic waste can be used as renewable biomass sources, ensuring a sustainable and stable raw material supply for the production process [10,11]. Furthermore, converting organic waste into hydrogen reduces landfill volumes and allows valuable energy recovery, contributing to the development of a circular economy. Moreover, producing hydrogen from biomass reduces dependency on non-renewable fossil fuels, enhancing energy security and diversifying energy sources (Fig. 1) [12, 13].

The conversion of biomass to hydrogen presents several challenges, primarily due to the diversity of source materials involved. This variation complicates the optimization of the process and hinders the ability to achieve consistent, stable hydrogen yields. Biomass materials, such as cellulose, hemicellulose, lignin, and other organic compounds, differ significantly in their chemical composition. These differences require tailored approaches for each biomass type to ensure effective conversion. As such, adjustments in process parameters – such as temperature, pressure, and catalyst selection – are often necessary. Failing to account for these factors can lead to decreased process efficiency and unstable hydrogen output [14,15].

For instance, Das and Veziroglu (2001) pointed out that the hydrogen production potential of different biological materials varies significantly due to compositional differences, which necessitates distinct approaches for each specific biomass type [16]. Similarly, Cherubini et al. (2011) emphasized that the efficiency of gasification and pyrolysis is influenced by variations in lignin and cellulose content, particularly in wood waste and agricultural residues [17]. In another study, Lin and Lay (2012) investigated the fermentation of food and agricultural waste, concluding that different biomass types require unique preparation and fermentation conditions to achieve stable hydrogen yields [18].

Research has also explored specific biomass sources. Meramo-Hurtado et al. (2020) conducted a study on biomass gasification for hydrogen production from cassava and rice waste in Colombia, using Aspen Plus for simulation. Their work demonstrated a production rate of 3944.51 kg/h of hydrogen with 97% purity and an inherent safety index score of 35 [19]. In a different approach, Hultberg and Karlsson (2009) developed an integrated system combining biomass gasification and water electrolysis for hydrogen production. Their analysis indicated a production cost of 39 SEK/kg H₂ at an annual output of 15,000 tons, though this cost was still higher than hydrogen produced through

natural gas steam reforming, which remains the more cost-effective option [20]. Further studies have assessed the potential for biomass and waste to support a green hydrogen economy. Karayel et al. (2023) estimated the potential for green hydrogen production from biomass and waste, with a total potential of 1.66 megatons/year, identifying Konya, Adana, and Ankara as the top producers. This potential was supported by systems such as gasification and incineration [21]. Additionally, Iribarren et al. (2014) examined biomass gasification and found that the exergetic efficiency of the process could reach 48%, highlighting the importance of factors such as poplar cultivation, biomass pre-treatment, and syngas cleaning for improving both energy and environmental performance [22].

Current research is focused on developing thermally stable catalysts that can withstand high temperatures and aggressive environments, which is especially important in the pyrolysis and gasification of various types of biomasses. This is necessary to ensure a stable hydrogen output regardless of the type of starting material [19,20]. There is also ongoing work on creating cost-effective catalysts that retain their activity and durability on an industrial scale, which is critical for successfully scaling hydrogen production technologies to make this process economically viable and sustainable in practice [21,22]. Despite advancements in biomass-to-hydrogen conversion, technical and economic challenges remain. Future studies should focus on developing robust and efficient catalysts, improving bio-photolysis and dark fermentation methods, and combining thermochemical and biological processes [23,24].

Several review articles have been published on various aspects of biomass-to-hydrogen conversion, including thermochemical and biological methods, as well as catalyst development to enhance process efficiency. However, most of these works either concentrate on individual technologies or do not sufficiently address the integration of different approaches and their sustainability assessments. This study evaluates both thermochemical and biological methods of biomass conversion, with an emphasis on the need for integration to improve hydrogen yields. This review article also defines the role of advanced catalysts resistant to harsh conditions and emphasizes the importance of comprehensive life cycle assessments for analyzing the environmental and economic aspects of these technologies. Additionally, the article explores the prospects of genetic engineering to enhance the efficiency of bio-photolysis and dark fermentation.

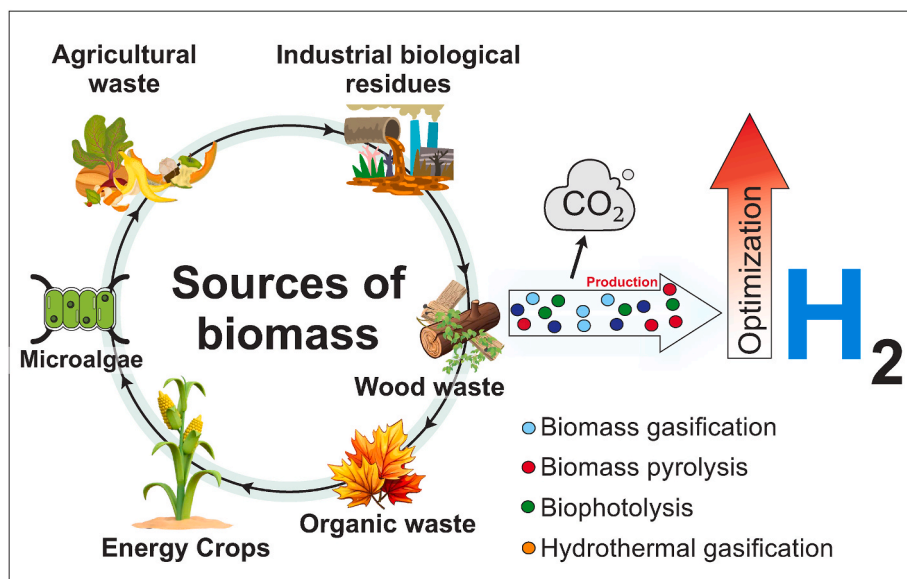


Fig. 1. Biomass sources and their conversion to hydrogen [12,13].

2. Technological advances in biomass to hydrogen conversion

2.1. Biomass gasification: innovations and improvements

Biomass gasification, a thermochemical process that converts organic materials into syngas, is becoming one of the most promising methods for renewable energy production [25]. This method allows for the efficient use of agricultural and forestry residues, organic waste, and other biomass types to produce environmentally friendly fuel, reducing dependence on fossil energy sources and decreasing the carbon footprint [26]. Amid the global energy transition and increased focus on sustainable development, biomass gasification technologies play a key role in shaping the energy systems of the future. The efficiency of biomass gasification is influenced by multiple factors, including system design, type of fuel used, materials involved in the gasification process, and the operational parameters applied during gasification. Researchers have explored these factors in detail to improve the efficiency of biomass gasification [27,28].

Recent studies by Qin and Li (2023) review advances in low-temperature plasma technology for converting biomass into hydrogen fuel [29]. This technology generates highly active particles at moderate temperatures, making reactions more efficient and increasing hydrogen yield. The study emphasizes that plasma reactors, such as dielectric barrier discharge reactors, can effectively convert biomass into a hydrogen-rich gas mixture (syngas). Another emerging area of interest is the combination of plasma with catalysts [30]. This approach merges the advantages of both technologies, potentially reducing reaction energy and increasing the efficiency and selectivity of hydrogen production. Studies indicate that these hybrid systems can address issues like tar formation and catalyst degradation, which are drawbacks of traditional methods [31].

Advances in plasma gasification represent a significant step forward in biomass-to-hydrogen conversion, offering a more efficient, cost-effective, and environmentally friendly approach to renewable hydrogen production [32]. A recent review by Zhang (2022) highlighted progress made in biomass-to-hydrogen conversion using catalytic reforming. This method involves the initial breakdown of biomass into bio-oil through pyrolysis, followed by catalytic reforming of bio-oil into hydrogen gas [33]. Researchers Yan et al. (2010) and Iriondo et al. (2008) contributed significantly to the development of nickel catalysts with cerium (CeO_2) and zirconium (ZrO_2) additives, which notably improved their efficiency and longevity [34,35]. These early works laid the foundation for more recent studies that continue to refine such catalysts. Recent advancements in this area show that doping catalysts with additional elements, such as praseodymium (Pr), lanthanum (La), and neodymium (Nd), enhances catalytic activity and stability [36,37].

In addition to catalyst development, significant attention has been given to researching new reactor designs to increase hydrogen yield [38]. These efforts aim to create more efficient reactor systems that minimize heat loss, optimize contact between catalyst and reactants, and improve control over reaction conditions. Such innovations are critical for boosting the productivity and sustainability of processes, achieving higher levels of hydrogen production efficiency on an industrial scale. Research by Wu et al. (2008) and Kechagiopoulos et al. (2007), focused on new reactor designs, such as two-stage fixed-bed reactors and fluidized-bed reactors, has laid the groundwork for further advancements in hydrogen yield and catalyst durability [39,40]. Modern approaches, such as membrane and microreactors, continue to build on these ideas, providing even higher efficiency through improved temperature control, minimized carbon buildup, and integration with new sorbent and membrane technologies for simultaneous carbon capture and hydrogen production [40,41].

Electro-catalytic reforming and CO_2 -adsorption reforming methods, extensively studied by Martavaltzi and Lemonidou in 2008 [42], have seen renewed interest in recent years. Current research continues to optimize these processes, integrating them with other technologies,

thereby increasing hydrogen production and improving energy efficiency, particularly within more environmentally sustainable approaches [43]. Bifunctional catalysts, such as $\text{Ru}/\text{Ca}_3\text{Al}_2\text{O}_6\text{--CaO}$, which combine steam methane reforming with CO_2 adsorption, demonstrate substantial potential for high-purity hydrogen production. This catalyst type exhibits high resistance to degradation and can undergo multiple regeneration cycles, enhancing cost-effectiveness and extending its service life [44].

A recent study by Mellalou et al. (2024) investigated a new method called flash photo-pyrolysis for rapid assessment of various biomass types for syngas production. This technique allows for detailed analysis of produced gases, providing valuable insights into the chemical properties of biomass and its potential to generate hydrogen-rich syngas. The study also emphasizes the importance of efficient gas processing to improve syngas quality for various applications [45]. Recently, Baral and Šebo (2024) explored the feasibility of combining renewable energy sources with systems that convert biomass into hydrogen fuel. The study demonstrated the potential of hybrid systems that integrate solar panels with energy storage and land-based wind turbines. Additionally, integrating solar thermal energy with an organic Rankine cycle for heat recovery increased efficiency and reduced costs [46].

Recent breakthroughs in biomass gasification for hydrogen production make this technology a more attractive option for clean energy. These advances improve process efficiency, environmental impact, and economic viability (Fig. 2).

In hydrothermal biomass gasification, the use of catalysts improves process efficiency and the quality of resulting products [47,48]. This approach enables the production of hydrogen-rich fuel gases at lower temperatures, reducing the overall energy required. However, challenges with catalysts remain, such as degradation, agglomeration, and damage caused by sulfur. Scientists need to develop more durable, efficient, and reusable catalysts to make this method of fuel production more practical and environmentally safe. An important focus is also on creating technologies that increase catalyst resistance to high temperatures and contamination, as well as implementing regeneration methods for repeated use.

Real-world examples of successful implementation of biomass-to-hydrogen conversion technologies confirm its substantial potential as a clean energy source. In Austria, a hydrogen production plant using biomass has been operating for over two decades, employing innovative gasification technologies to convert organic materials into hydrogen-containing fuel gas [49,50]. This project demonstrates that biomass gasification can not only meet the growing demand for hydrogen but also offer an environmentally sustainable alternative to traditional hydrogen production methods. The European Union has supported several innovative projects, such as BIONICO, which focuses on hydrogen production from biogas. The project aims to develop a pilot plant that converts biomass directly into hydrogen using an innovative biomass-to-hydrogen technology. This process combines a chemical looping system with biobased feedstock to achieve high efficiency and minimal CO_2 emissions. By using biomass as a renewable source, the pilot project seeks to demonstrate the feasibility of a more sustainable hydrogen production process compared to traditional methods. The technology is designed for scalability and offers a potential pathway to greener energy systems [51].

Chinese scientists have made significant progress in developing new methods for converting plant materials into hydrogen fuel using advanced reactor technologies [52–55]. This approach enables the processing of a wide range of biomass types and efficiently generates hydrogen-rich fuel gas, creating new possibilities for large-scale production of clean hydrogen. Improvements in technological processes have significantly boosted their efficiency, underscoring the promise of this technology for meeting the growing global demand for renewable energy. The project demonstrates how advanced technologies can transform biomass into clean energy, helping China achieve its renewable energy goals and contributing to global efforts toward a sustainable

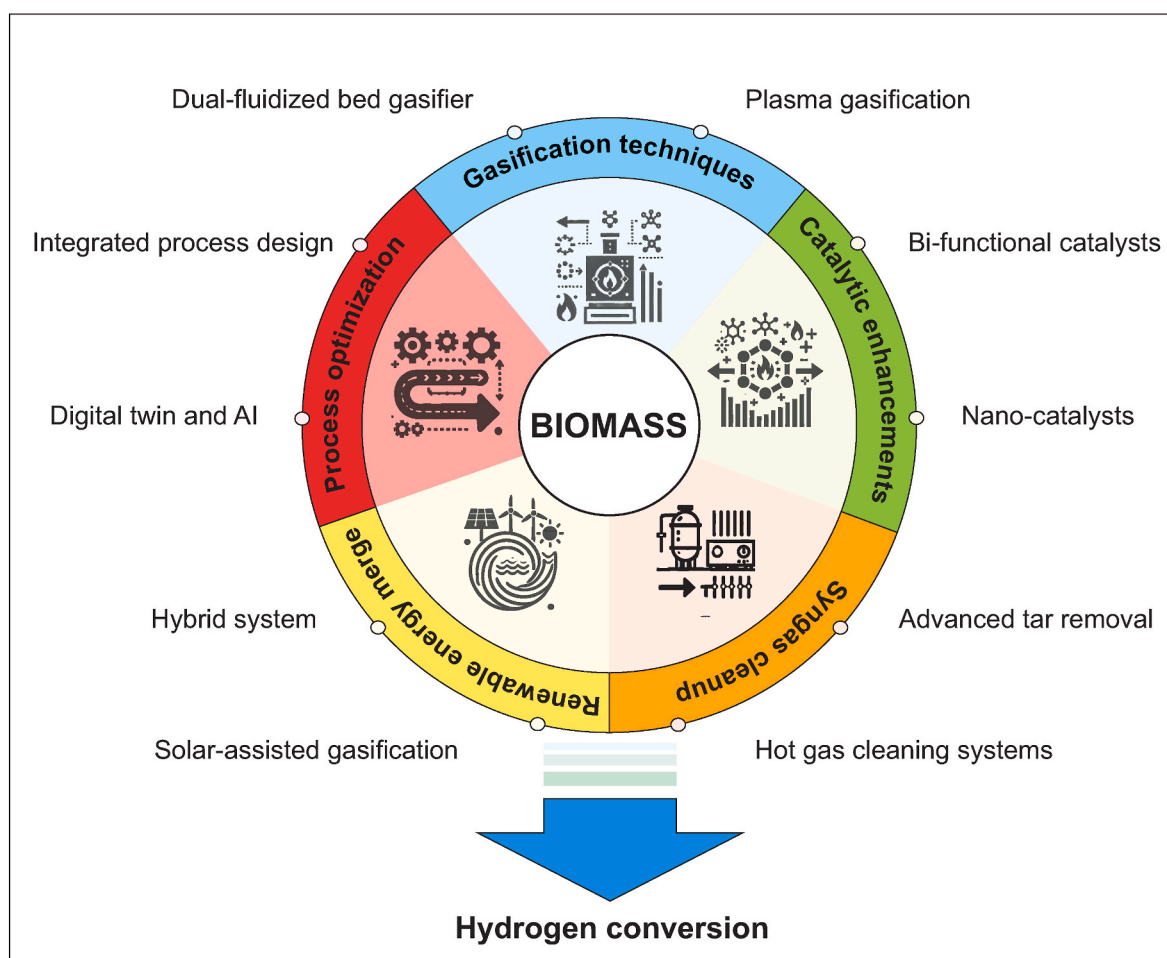


Fig. 2. Innovative ways of biomass gasification for hydrogen production [43–46].

future. The “biomass hydrogen production via fermentation” project is a sustainable technology that uses agricultural residues to produce hydrogen with minimal CO₂ emissions. Extensive research has been conducted in Brazil on this technology, making it a key part of the country’s renewable energy development (Table 1) [56,57].

Biomass gasification offers a promising approach to converting organic materials into hydrogen. Innovations in this field, such as low-temperature plasma technologies and hybrid plasma-catalytic systems, have significantly increased both the efficiency and hydrogen yield [58, 59]. Additionally, advancements in catalytic reforming, including the development of improved catalysts and reactor designs, have further enhanced performance [60,61]. Successful implementations in countries like Austria, the United States, and China highlight the practical viability of these technologies. Despite these advancements, challenges remain, particularly concerning the durability and efficiency of catalysts.

The application of nanotechnology has become the next step in enhancing biomass gasification processes. New nanomaterials are used as catalysts to improve reactivity and increase hydrogen yield [62]. Nanocatalysts, such as nanostructured nickel and iron particles, not only accelerate reactions but also effectively remove tar compounds, significantly improving the quality of the produced gas. These innovations also address a key issue – the longevity of catalysts – by increasing their resistance to deactivation and providing more stable operation for gasification systems [63,64].

Recent advancements in optimizing biomass gasification process parameters have focused on improving hydrogen production efficiency while reducing tar formation [65]. One approach involves using

nanocatalysts, such as Ni-Co/Si-P and Ni-based catalysts, which enhance steam reforming of tar, significantly boosting hydrogen output. These catalysts demonstrate improved stability and reactivity at high temperatures, making the gasification process more efficient [66,67]. Moreover, advanced methods such as chemical looping gasification have shown an improved gas composition. By optimizing process parameters such as temperature and steam-to-biomass ratio, these methods effectively reduce tar content, resulting in cleaner syngas with a higher hydrogen concentration [68,69].

Additionally, innovations like catalytic filter candles for hot gas cleaning have shown high efficiency in reducing tar content, further improving gas quality and process stability [70,71].

2.2. Breakthroughs in biomass pyrolysis technologies for enhanced hydrogen production

Pyrolysis is a thermal decomposition process for organic materials in the absence of oxygen, resulting in gaseous, liquid, and solid products, including hydrogen, bio-oil, and biochar. Key process parameters, such as maximum treatment temperature, heating rate, particle size, and inert gas flow rate, significantly impact the yield and composition of these products [72]. Achieving uniformity in these parameters poses a challenge, which can negatively affect hydrogen yield and quality [73]. Innovations in pyrolysis reveal that higher temperatures and longer residence times generally lead to increased hydrogen yield [74,75].

For example, Lott et al. (2022) demonstrated that gas-phase methane pyrolysis for hydrogen production and carbon capture is feasible using an electrically heated high-temperature reactor operating in the

Table 1
Recent advances in biomass-to-hydrogen projects.

Project	Energy efficiency	Environmental benefit	Commercial potential	Scalability	Description	Meaning	Ref.
Güssing biomass gasification plant (Austria)	The plant in Güssing achieves a conversion efficiency of approximately 61 MW of hydrogen from 100 MW of biomass (wood chips) with a moisture content of 20%.	The environmental benefit lies in reducing CO ₂ emissions compared to traditional methods.	Moderate, suitable for regional markets.	The plant has already demonstrated its scalability through the use of a dual fluidized bed system, making it well-suited for increased hydrogen production.	The hydrogen production project in Austria utilizes advanced gasification technologies and catalysts to enhance hydrogen yield and reduce carbon emissions.	It demonstrates practical and environmentally beneficial hydrogen production.	[49,50]
BIONICO project (biogas to hydrogen pilot plant)	The project increases energy efficiency by optimizing hydrogen production from biogas. The reactor, with an efficiency of up to 72%, reduces costs and minimizes environmental impact.	The project has reduced CO ₂ emissions by up to 10% compared to traditional hydrogen production methods by using renewable biogas in steam reforming.	The project offers high commercial potential, providing a cost-effective method for producing high-purity hydrogen from biogas. This approach reduces costs and meets the growing demand for clean energy, making it attractive for industrial and energy markets.	The process is easily scalable through integration into existing biogas facilities. Its efficiency and adaptability make it well-suited for large-scale industrial applications, meeting the growing demand for hydrogen across various sectors.	The project aims to produce high-purity hydrogen from biogas through steam reforming. It focuses on improving energy efficiency, reducing production costs, and minimizing environmental impact, making hydrogen a more viable and sustainable energy source.	The project is an important step toward clean energy by optimizing hydrogen production. It demonstrates the potential of renewable sources to replace fossil fuels, reducing carbon emissions and supporting a sustainable energy future.	[51]
Advanced biomass-to-hydrogen conversion in China	High hydrogen yield achieved through advanced reactor technology and process optimization.	The process significantly reduces CO ₂ emissions by using renewable plant materials instead of fossil fuels, lowering the carbon footprint compared to traditional methods like methane steam reforming.	The technology has high commercial potential, especially in regions rich in biomass resources. Its scalability and efficiency make it attractive for large-scale energy projects and decentralized systems.	The method is highly scalable due to its ability to process a wide range of biomass materials. It can be adapted for both large industrial operations and smaller regional facilities.	The project is developing efficient reactor technology for converting biomass into hydrogen fuel, enabling emissions reduction and supporting large-scale production of environmentally friendly hydrogen.		[52–55]
Hydrogen production from biomass by fermentation	The process shows potential for high hydrogen yields depending on the type of biomass and fermentation conditions.	Using renewable biomass instead of fossil fuels significantly reduces CO ₂ emissions in hydrogen production, eliminating the carbon footprint associated with traditional methods.	The high commercial potential is supported by substrate versatility, including waste materials, enabling applications in industries such as food processing and wastewater treatment.	Scalability can be enhanced with further research and optimization. Co-fermentation of multiple biomass sources and improved fermentation efficiency are promising strategies for scaling up.	The project focuses on using biological fermentation to convert biomass, including agricultural and industrial waste, into hydrogen fuel, creating renewable energy with low carbon emissions.	This project represents a sustainable hydrogen production method, reducing dependence on fossil fuels and promoting cleaner energy by utilizing waste materials.	[56,57]

1200–1600 °C range. Their study indicated that extended residence time reduces by-products and increases hydrogen yield, with 1400 °C being optimal for nearly complete methane conversion and high hydrogen output [76]. Additionally, electric heating reduces unwanted by-products and greenhouse gas emissions, providing a more environmentally friendly hydrogen production process. Catalyst development for pyrolysis focuses on improving catalytic activity, durability, and selectivity, enhancing hydrogen yield and reducing by-products [77, 78]. Xu et al. (2023) studied the catalytic effects of various materials on boosting hydrogen production in biomass pyrolysis. They found that metal catalysts like nickel and iron significantly lower the required reaction temperature and increase hydrogen yield by promoting biomass component breakdown [79]. Catalysts such as Ni-zeolite showed substantial improvements in hydrogen yield by increasing pyrolysis vapor production [80,81]. These catalysts promote more efficient decomposition of organic compounds, improving access to active sites and enhancing reactivity, allowing greater hydrogen selectivity and reducing by-products. In studies by Li et al. (2024), such catalysts achieved hydrogen yields of up to 117.9 mL/g biomass at a pyrolysis temperature of 700 °C, underscoring their effectiveness for hydrogen production [82].

Several recent studies have identified optimization methods to increase hydrogen yield in biomass pyrolysis. A hybrid pyrolysis process integrated with plasma reforming, which combines plasma-assisted reforming and cellulose pyrolysis, significantly enhances hydrogen production. These methods offer promising paths for achieving greater hydrogen production efficiency from biomass [83,84]. Similarly, research by Ongis et al. (2023) indicated that using membrane reactors for small-scale hydrogen production can significantly improve efficiency. Their studies emphasize optimizing parameters like reactor temperature, pressure, and steam-to-carbon ratio. For example, operating a reactor at 500 °C and 12 bar, with a permeate-side pressure of 0.1 bar, increased hydrogen production by 33% and improved hydrogen recovery by 40%. Additionally, rhodium-based catalysts significantly enhanced reaction rates and hydrogen yield. These findings underscore the potential of membrane reactor technology to improve hydrogen production efficiency from biomass pyrolysis [85].

Microwave and rotary reactors offer substantial advantages in biomass pyrolysis, enhancing hydrogen yield through unique heating mechanisms. Microwave pyrolysis enables even heating by directly transferring electromagnetic energy to the biomass, resulting in faster and more efficient heating than traditional methods, reducing energy consumption and increasing reaction rate. Microwave heating creates "hot spots," lowering the activation energy needed for decomposition, thus significantly increasing hydrogen yield. Furthermore, using catalysts like metal oxides (e.g., CaO, Fe₂O₃) in microwave systems enhances hydrogen yield and bio-oil quality [86]. Microwave reactors also demonstrate low energy consumption, making them more sustainable and suitable for industrial scaling [87,88].

Rotary reactors improve the uniformity of biomass heating due to the continuous rotation of the raw material, which prevents hot spots and particle agglomeration. This design promotes better heat distribution and more complete decomposition of organic matter. Combining rotation with microwave heating further improves efficiency by providing uniform electromagnetic wave exposure to the biomass, increasing hydrogen yield [89,90]. Recent studies on rotary reactors in biomass pyrolysis have shown they play an essential role in improving performance by ensuring uniform heating and optimizing the decomposition process. One example is the use of rotary reactors in slow pyrolysis, where uniform biomass mixing enhances heat transfer and promotes more complete feedstock decomposition, leading to increased yields of hydrogen and bio-oil [91]. In rotating cone reactors, thermal uniformity improvements allow more efficient use of high temperatures for pyrolyzing various biomass types, such as wood waste and agricultural residues [92].

A recent review by Wang et al. (2024) on plasma-assisted catalysis

for hydrogen production highlights rotary reactors as a key technology in biomass-to-hydrogen production due to their ability to provide even heat distribution and improve reaction kinetics. The study emphasizes that integrating non-equilibrium plasma systems with catalytic processes significantly increases hydrogen yield by facilitating interactions with high-energy electrons that accelerate the decomposition of feedstock, such as methane or biomass [93]. This approach enables substantial greenhouse gas emissions reductions and enhances hydrogen production efficiency, especially when using renewable energy sources.

A study by Becker and Agar (2022) examined a rotating film reactor for hydrogen production from methane using pyrolysis. The study emphasized that a rotating layer of liquid metal (e.g., tin) inside the reactor protects the walls from carbon deposits and facilitates solid carbon removal, preventing reactor blockages. The work also investigated operating parameters, such as liquid flow rate, rotation speed, and reactor diameter, and their impact on methane conversion and hydrogen yield. Results indicate that optimizing these parameters greatly increases hydrogen production efficiency while reducing energy losses.

These innovations – including high-temperature reactors, catalytic advancements, and plasma support – contribute to increased efficiency and hydrogen yield from biomass. Further research and development in these areas are essential for optimizing biomass pyrolysis as a promising method for producing clean hydrogen fuel.

2.3. Key technological developments for improving biomass reforming for hydrogen production

Biomass reforming, especially catalytic steam reforming, is a promising approach for hydrogen production, as it effectively converts complex compounds derived from biomass into hydrogen-rich syngas [94]. Recent advances in biomass reforming for hydrogen production, similar to the other two processes, include the development of new high-efficiency catalysts and reactor design improvements, allowing optimized reaction conditions and reduced energy costs. These innovations contribute to more sustainable and efficient hydrogen production from biomass [95].

Recent studies have made substantial progress in developing biomass reforming catalysts, particularly in the context of catalytic steam reforming. Feng et al. (2023) emphasized the use of supported metal catalysts in ethanol steam reforming, addressing challenges like catalyst deactivation due to sintering and carbon deposition. They noted that while noble metals like Rh and Ru exhibit high catalytic activity, their high costs have led researchers to explore more economical alternatives such as non-noble metals like Ni, Co, and Cu [96]. Advances in porous nanomaterials have significantly improved the efficiency and feasibility of biomass reforming processes. These nanomaterials, specifically those designed with tailored porosity and large surface areas, have shown great potential for enhancing catalytic activity in hydrogen production from biomass. The incorporation of various functional groups and metal ions into these nanomaterials has further improved their catalytic properties, making them essential for efficient biomass reforming [97].

Significant progress has also been achieved in developing iron-based catalysts for biomass reforming, especially in the CO₂ hydrogenation process. These catalysts are notable for their accessibility, high product yield, and excellent performance in reactions such as the reverse water-gas shift and Fischer-Tropsch synthesis. The use of density functional theory and microkinetic modeling in theoretical studies has provided deeper insights into mechanisms involving metallic iron, iron oxides, and iron carbides, as well as the effects of alkali and transition metals on these processes [98]. Santiago and colleagues explored the catalytic conversion of CO₂ into valuable chemicals, such as methanol and dimethyl ether, using Cu, Zn, and Al-based catalysts. Their research provided valuable insights into reaction mechanisms and highlighted the critical role of adsorption capacity in catalytic performance. The study demonstrated that the integration of advanced catalytic materials and reaction condition optimization can significantly enhance the

efficiency and selectivity of biomass reforming processes [99].

Research by Guan et al. showed that catalysts like RuNi/TiO₂ and Ni₂Pt@ZIF-8 greatly increase catalytic activity, lowering activation energy and optimizing particle size [100]. The integration of metal-organic frameworks (MOFs) into catalyst design represents a breakthrough. MOFs provide a stable environment for reactions, and their pyrolysis results in catalysts with large surface areas and porosity. Adding metal or non-metal elements into MOFs during pyrolysis can further enhance catalytic activity and stability, as demonstrated by Zhang et al. (2019) [101]. The incorporation of 3D electrode structures on conductive substrates could significantly improve hydrogen production efficiency via water electrolysis. This approach increases active site availability, enhances conductivity, and facilitates material transport [102,103]. These achievements in process design and operation underscore ongoing efforts to optimize biomass reforming technologies for enhanced hydrogen production. Implementing these innovative approaches can yield substantial improvements in catalyst efficiency, stability, and overall process performance.

Integrating reforming with other biomass conversion methods has been explored to enhance the efficiency and sustainability of hydrogen production. Maron et al. (2022) demonstrated that combining steam reforming with catalytic partial oxidation (CPO) using an Rh–Ce_{0.5}Zr_{0.5}O₂ catalyst can significantly improve hydrogen production efficiency. Their study highlighted the advantages of using pure oxygen generated during electrolysis for CPO, which enhances heat exchange due to the exothermic nature of CPO. By synthesizing Ce_{0.5}Zr_{0.5}O₂ via a microemulsion method and impregnating it with Rh, the researchers achieved high reducibility and methane conversion, outperforming other catalysts under various conditions. This approach not only leverages existing reforming infrastructure but also enables the efficient use of green hydrogen, reducing the process's overall carbon footprint [104].

Lakhtaria et al. (2022) investigated the integration of aqueous phase reforming (APR) with a high-temperature proton exchange membrane fuel cell. Their study highlights the benefits of APR's lower operating temperatures, which enhance catalyst stability and energy efficiency. Using platinum-based catalysts and non-noble nickel-based catalysts, APR effectively generates hydrogen and supports the water-gas shift reaction. These findings illustrate the potential of combining reforming with other biomass conversion methods, showcasing advancements in catalyst development and process design that move the field forward [105].

2.4. Current trends in biotechnology for hydrogen generation

Biotechnological methods for hydrogen production, such as biophotolysis and dark fermentation, continue to show considerable potential in the context of sustainable energy development. Biophotolysis involves the use of photosynthetic microorganisms, such as green algae and cyanobacteria, which utilize light energy to split water molecules into oxygen and hydrogen. This clean method has low energy requirements but is limited by low energy conversion efficiency and inhibition of hydrogenase enzyme activity by oxygen [106,107]. In contrast, dark fermentation is a light-independent process where microorganisms decompose carbohydrate-rich substrates to produce molecular hydrogen and other by-products. This process is mainly carried out by facultative or obligate anaerobic bacteria, including species from the genera *Clostridium*, *Enterobacter*, and *Bacillus*. The main advantage of dark fermentation is its independence from light, making it less sensitive to environmental conditions compared to photobiological methods [108,109].

Despite the differences between biophotolysis and dark fermentation, both methods have shown notable advancements in hydrogen production, particularly in terms of genetic modification of microorganisms [110], optimization of cultivation conditions [111,112], improvements in bioreactor design [113,114], metabolic engineering, and

the use of mixed cultures [115]. Genetic modification of microbial strains includes the introduction of genes encoding key enzymes for hydrogen metabolism, increasing resistance to oxidative stress, and optimizing substrate uptake. Modifying strains, such as *Clostridium* and *Rhodobacter*, can enhance hydrogen yields by increasing hydrogenase activity and reducing competing metabolic pathways [116]. Strategies for redirecting metabolic pathways to favor hydrogen production include modifying pathways that compete for electrons with hydrogenases, one of the key strategies to increase hydrogen production under various environmental conditions.

For example, Kumaraswamy et al. (2013) achieved a significant increase in hydrogen yield up to 400 μmol H₂/mg dry biomass by deleting genes in cyanobacteria that encode enzymes involved in the early stages of glycolysis, such as hexokinase and phosphofructokinase, and re-routing organic acid assimilation pathways. This improvement is significant compared to the baseline yield of about 100–150 μmol H₂/mg for unmodified strains [117]. Structural modifications in the light-harvesting complexes of photosynthetic microorganisms remain a key research area for enhancing light utilization efficiency and hydrogen yield. Ongoing research seeks to optimize the photosynthetic apparatus and develop strategies to improve light absorption and energy transfer within light-harvesting complexes, overcoming current limitations and maximizing biophotolysis efficiency [118]. Current studies involve molecular and engineering approaches to modify photosynthetic microorganisms, improving their light capture abilities and adaptability to various lighting conditions. Reducing the size of light-harvesting complexes and lowering chlorophyll content minimizes photorespiration and directs electron flow toward hydrogenases, thus enhancing hydrogen production [119]. Ahmed et al. (2021) reported substantial progress in increasing hydrogen production in microalgae through modifications to light-harvesting complexes and reduced chlorophyll content [120].

Recent developments in biological hydrogen production technology focus on improving the functionality of hydrogenases and nitrogenases. A key achievement is protein engineering of hydrogenases to enhance oxygen resistance, an essential solution for biophotolysis, where oxygen presence can inhibit hydrogen production. Increased oxygen tolerance in these hydrogenases enables continuous hydrogen generation even under aerobic conditions [121]. In a recent study by Jiang et al. (2023), a new biocatalyst was developed by encapsulating [NiFe]-hydrogenases within a protein shell of carboxysomes. This encapsulation significantly increased hydrogen production, as well as enhanced oxygen tolerance and thermal stability compared to non-encapsulated [NiFe]-hydrogenases. This biocatalyst holds promise for sustainable hydrogen production applications [122].

Significant research efforts are also focused on modifying Fe–Fe hydrogenases to increase their activity and resistance to oxygen inhibition – a primary limitation in photobiological hydrogen production. Through mutation and genetic engineering, strains have been created with hydrogenases resistant to oxygen inhibition, resulting in hydrogen production rates up to 30 times higher than in original strains [123–125]. Advances in enhancing oxygen tolerance of [FeFe]-hydrogenases have been achieved through the development of new biocatalysts demonstrating improved resilience against oxygen damage. Research to increase the catalytic activity and durability of [FeFe]-hydrogenases includes creating mutant and chimeric versions of these enzymes, showcasing the potential for improved efficiency in biotechnological processes. For example, 113 chimeric versions of algal hydrogenase genes were developed by recombining segments from three parental hydrogenases (CrHydA1, CrHydA2 from *Chlamydomonas reinhardtii* and HydA1 from *Scenedesmus obliquus*), achieving hydrogen production up to three times higher than the wild-type enzyme. These approaches demonstrate how directed evolution and genetic modifications can enhance the key properties of hydrogenases for use in environments requiring high resilience and catalytic activity [126].

Another approach under investigation is the use of strictly anaerobic

extremophiles, such as methanogenic archaea, as a viable solution to address these challenges [127]. These developments provide a comprehensive understanding of the current state and future potential of hydrogen production using microalgae- and cyanobacteria-based biophotolysis. Sundaram et al. (2023) provide valuable insights into optimizing dark fermentation processes using various bacterial strains, highlighting the importance of selecting resilient microbial consortia that can effectively produce hydrogen under anaerobic conditions. Recent studies have focused on enhancing the metabolic pathways of these bacteria to increase hydrogen yield and reduce inhibitory by-products [128].

Dark fermentation represents a biological hydrogen production method with the advantages of continuous operation without light energy requirements and the ability to utilize a wide range of substrates, including renewable biomass and organic waste. Hydrogen production rates in dark fermentation exceed those of biophotolysis and photo-fermentation processes. Recent research has aimed to improve hydrogen production efficiency by enhancing microbial strains. Despite these achievements, the current production rates and yields remain economically unfeasible for large-scale application. Enhancing bioprocesses through strategies such as selecting more efficient microbial strains and further metabolic engineering is necessary. Cao et al. (2022) emphasized the need for a comprehensive understanding of metabolic pathways and rational design of hydrogen-producing strains to overcome existing challenges [129]. Hallenbeck et al. (2009) emphasized the critical role of strain improvement in making dark fermentation competitive with traditional hydrogen production methods, outlining various strategies for identifying efficient hydrogen-producing strains and applying metabolic engineering to increase hydrogen yields [129]. The low solar energy conversion efficiency in biophotolysis requires large areas for photobioreactors [130]. Qu et al. (2022) described the potential of using organic wastewater for hydrogen production through dark anaerobic fermentation, highlighting this method's numerous advantages, including low energy consumption and the dual benefits of wastewater treatment and hydrogen production [131].

Biotechnological processes hold significant promise for sustainable hydrogen production; however, they generally exhibit lower energy efficiency and hydrogen yield compared to other methods. For instance, according to studies by Zhang et al. (2017), overall energy conversion efficiency in biotechnological processes using photo- and dark-fermentation wastewater was 22.28% [132]. Hydrogen production through dark fermentation is a promising method for sustainable bio-hydrogen generation from biomass and organic waste. Studies show hydrogen yields ranging between 10 and 30%, depending on factors such as temperature, pH, substrate concentration, and reactor type. Optimal results are often achieved at mesophilic temperatures (35–40 °C) and neutral pH (6–7). This process is attractive due to its simplicity and low energy costs, particularly in comparison to photo-fermentation, and can be integrated with anaerobic digestion to enhance efficiency [133].

Processes such as gasification, pyrolysis, and sorption-enhanced steam reforming (SESR) have high potential compared to biotechnological processes, as they improve hydrogen yield and reduce energy costs. For example, in the study by Poluzzi et al. (2022), the fuel efficiency of direct gasification (DG) systems was 79.62%, while that of indirect gasification (IG) systems was slightly lower at 77.89%. Hydrogen yield in direct gasification systems reached 45.93%, whereas in indirect systems it was 56.46% [134]. According to a study by Hanif et al. (2016), the energy efficiency of the pyrolysis process varies depending on operating conditions. Specifically, for various biomass types, overall energy efficiency in pyrolysis can reach 75.5% at around 589 °C, indicating maximum energy recovery from pyrolysis products such as biochar, bio-oil, and syngas [135]. In a 2023 study by Gao et al., a new method for converting pyrolysis vapors into hydrogen using chemical looping technology was proposed. At temperatures above 850 °C and using Fe–Al–Ni composite oxides, hydrogen purity of over

98% was achieved from biomass, promising for sustainable hydrogen production [136]. For SESR, energy efficiency can reach 79% with heat recovery, and hydrogen yield on a dry basis can reach 90% [137] (Fig. 3).

Biotechnological processes remain the least efficient in terms of energy efficiency and hydrogen yield; however, they hold substantial potential in the context of sustainable development. These processes rely on renewable resources and offer environmentally friendly solutions for hydrogen production. In the long term, with technological advancements such as genetic modification of microorganisms and optimization of cultivation conditions, biotechnological methods may improve their efficiency and become competitive with thermochemical processes.

3. Technical barriers and limiting factors in biomass-to-hydrogen conversion processes

Biomass-based hydrogen production encounters multiple technical and economic barriers across gasification, pyrolysis, reforming, and biotechnological processes. In gasification, catalysts often degrade or become contaminated by sulfur and other impurities, leading to reduced performance and the need for more robust, long-lasting catalytic materials. Tar formation lowers syngas quality and necessitates additional treatment methods, such as hot filtration or catalytic tar reforming, which increase both capital and operational costs. High-temperature requirements drive up energy consumption and complicate process control, while challenges in reactor design – including thermal losses and limited scalability – further constrain overall efficiency. Advanced approaches, such as plasma gasification or the use of nanocatalysts, remain in development and face issues with durability, stability, and affordability.

Pyrolysis also suffers from irregular process parameters – temperature, heating rate, and particle size – that diminish hydrogen yields. Maintaining the high temperatures needed is energy-intensive, and catalysts can degrade or become poisoned by char and other by-products. Innovative reactor designs, including microwave and rotary pyrolysis, may offer advantages but struggle with uniform heat distribution and scaling. More complex systems like membrane and plasma reactors can further enhance yields but entail significant financial and engineering challenges. Similar to gasification, pyrolysis requires careful optimization of temperature, residence time, and reactor conditions to improve efficiency and minimize tar formation.

Reforming of biomass experiences major obstacles related to catalyst deactivation from carbon fouling, sintering, and agglomeration. Noble-metal catalysts, though highly active, are prohibitively expensive, driving research into more accessible options based on nickel, cobalt, or copper. These alternatives, however, often require additional tuning to achieve sufficient stability and longevity under harsh operating conditions. High energy demands, particularly when coupled with methods such as catalytic partial oxidation or the water-gas shift reaction, add to process complexity and cost. Efforts to develop novel porous materials and metal-organic frameworks show promise but are hampered by difficulties in scaling up production and ensuring long-term performance under industrial conditions.

Biotechnological methods, including biophotolysis and dark fermentation, are hindered by relatively low hydrogen yields and energy efficiencies when compared to thermochemical pathways. Biophotolysis depends on solar energy, but low conversion rates, oxygen inhibition of hydrogenase enzymes, and the need for extensive photobioreactor areas limit its practicality. Dark fermentation avoids reliance on light yet suffers from modest hydrogen output and inhibitory by-products, reducing its viability for large-scale applications. Enhancing metabolic pathways through genetic engineering, improving microbial strains, and optimizing bioreactor configurations are all areas that require further exploration. Despite ongoing research, the low productivity, high sensitivity to operating conditions, and lack of cost-effectiveness in scaling continue to impede the broader industrial uptake of

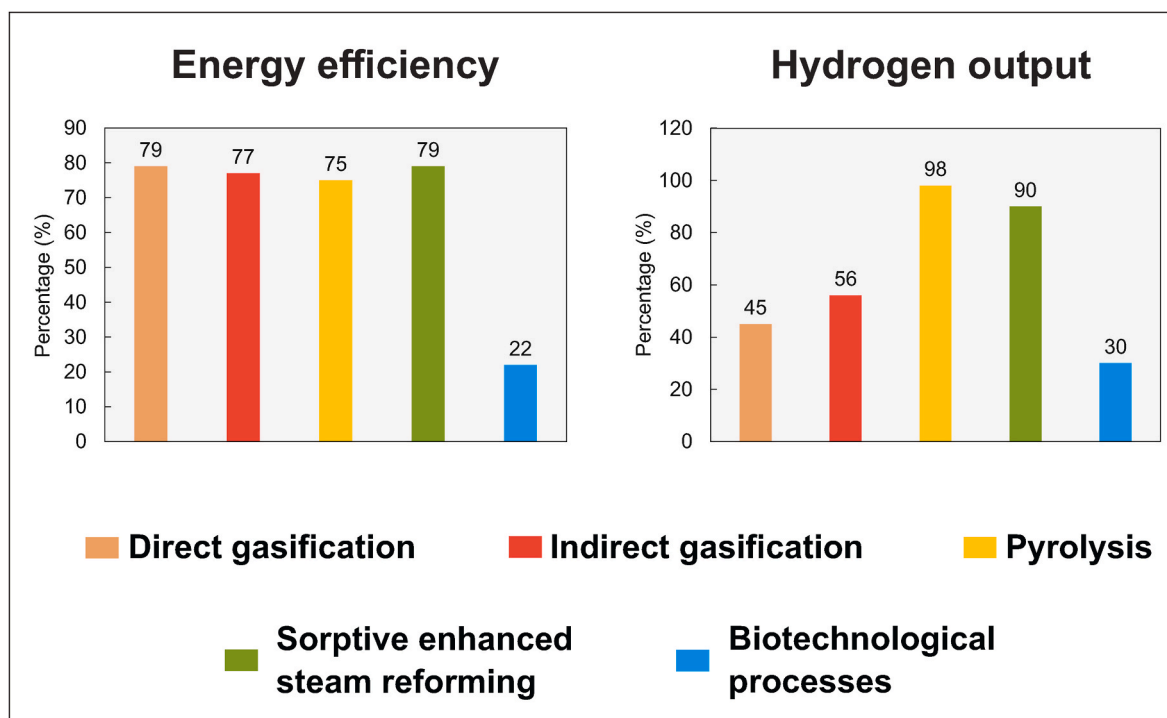


Fig. 3. Comparison of energy efficiency and hydrogen yield for different biomass conversion methods [134–137].

biotechnological routes for hydrogen generation.

The development and implementation of biomass-to-hydrogen conversion technologies face numerous technical barriers that significantly impact their efficiency and reliability. Despite substantial advancements, these barriers must be overcome to make biomass-to-hydrogen conversion a viable and competitive option in renewable energy [138]. Producing biohydrogen from microalgae is a promising pathway within the broader scope of biomass-to-hydrogen conversion. Microalgae, known for their high photosynthetic efficiency and ability to produce hydrogen under specific conditions, offer a renewable and potentially sustainable source of biohydrogen. However, realizing the full potential of this technology requires addressing several critical challenges and barriers, including economic factors, technological bottlenecks, process efficiency issues, oxygen sensitivity, and optimal light intensity requirements. Overcoming these issues is essential to advance biohydrogen production from microalgae as a practical and competitive renewable energy solution [139,140].

Ahmed et al. (2021) emphasize that biohydrogen production from microalgae faces serious challenges related to process engineering, low productivity, oxygen sensitivity, and high operational costs [121]. Although there are various metabolic pathways, these challenges impede commercialization. For instance, direct biophotolysis demonstrates over 80% solar conversion efficiency, yet its performance is highly dependent on oxygen levels and sunlight availability [141]. Economic viability remains a significant challenge for biohydrogen production from microalgae. High costs associated with cultivating microalgae, maintaining optimal growth conditions, and biomass harvesting and processing present major obstacles. Additionally, the current low hydrogen yield per unit biomass requires further research and development to make the process economically competitive with other hydrogen production methods. Implementing cost-effective scaling strategies and developing integrated biorefinery concepts, where microalgal biomass yields multiple valuable products, could improve this technology's economic prospects [142,143].

Various technological bottlenecks, including techno-economic and environmental feasibility of conventional methods, represent significant challenges for biomass-to-hydrogen conversion. Dependence on fossil

fuels for certain processes and the difficulties associated with hydrogen transport and storage further complicate hydrogen commercialization. Addressing these issues is crucial to enhance the sustainability and economic viability of hydrogen production [144]. The efficiency of different hydrogen production methods varies widely. For example, electrochemical processes can achieve biohydrogen production efficiencies exceeding 90% but often require significant energy inputs and face scalability and stability challenges [145,146]. Dark fermentation provides higher hydrogen production rates and volumes but faces issues with low hydrogen concentration and requires a purification stage to remove impurities [147,148]. However, dark fermentation also faces challenges such as the accumulation of inhibitory substances that can negatively impact hydrogen yield, as well as a low overall hydrogen yield per unit biomass. Addressing these inhibitory factors is essential for successful process scaling and commercial application [149].

For example, Romão et al. (2019) explored hydrogen production through dark fermentation using whey permeate and a microbial consortium. In their study, a semi-continuous process was employed in a 700 mL reactor, focusing on optimizing medium replacement parameters and replacement frequency to maintain stable hydrogen production. The results showed that removing the medium every 24 h during the early stages of fermentation, followed by switching to 12-h intervals, helped suppress lactic acid bacteria, which release substances that inhibit the growth of hydrogen-producing microorganisms. This strategy effectively suppressed lactic acid bacteria that produce bacteriocidal substances hindering hydrogen-producing microbes. However, further research is needed to enhance the economic viability of dark fermentation. In particular, this includes developing more resilient microbial strains capable of efficiently producing hydrogen and optimizing bioreactor design [150].

Thus, while dark fermentation holds considerable potential, the process remains limited due to several factors, including low hydrogen concentration and the need for additional purification stages. Implementing more efficient microbial consortia and improved management of inhibitory substances could substantially impact the commercial feasibility of this technology. Further process optimization and development of biorefineries where biomass simultaneously yields multiple

products will help improve the profitability and sustainability of biomass-based hydrogen production.

One of the primary challenges in biohydrogen production, especially in direct biophotolysis, is hydrogen production inhibition due to oxygen accumulation. Additionally, high light intensity requirements and low photochemical efficiency in some processes hinder their practical application. For example, photofermentation, while advantageous in light utilization, demonstrates lower solar conversion efficiency compared to biophotolysis and electrochemical processes [151]. Biomass-to-hydrogen conversion technologies face numerous technical barriers that impact their efficiency and reliability. These barriers include feedstock variability, process optimization, catalyst development, energy integration, technological maturity, and economic viability. Table 2 outlines these technical barriers, specific challenges they present, and proposed solutions to address them.

For example, Navas-Angueta et al. (2020) highlight the need to develop reliable pretreatment and preparation methods to standardize biomass feedstock quality. They note that maintaining consistent feedstock quality is key to achieving stable and efficient hydrogen production processes [152]. Optimizing various stages of biomass-to-hydrogen conversion, including gasification, pyrolysis, and reforming, is crucial to improve overall process efficiency. Kim et al. (2017) suggest that

integrating carbon capture and storage technologies into biomass conversion processes can significantly enhance their sustainability and efficiency. They recommend that process optimization should aim to maximize hydrogen yield while minimizing carbon emissions [153].

The development of efficient and durable catalysts remains a major challenge in both thermochemical and biochemical conversion processes. García-Olivares et al. (2018) emphasize the need for advancements in catalyst materials to increase reaction rates and selectivity in biomass reforming and gasification processes. They advocate for focusing research on catalysts capable of resisting deactivation due to impurities commonly found in biomass feedstock [154].

Effective integration of energy inputs and outputs in biomass-to-hydrogen conversion systems is critical to improving overall process efficiency. Brand et al. (2020) explore the potential benefits of combining renewable energy sources, such as wind and solar, with biomass conversion technologies. They argue that such integration can provide more stable and sustainable energy supply for hydrogen production, reduce dependence on fossil fuels, and enhance system reliability [155].

Many biomass-to-hydrogen conversion technologies are still in the early stages of development and have not been tested at commercial scale. Krause et al. (2020) underscore the importance of pilot and demonstration projects to verify the performance and scalability of these technologies. They note that successful large-scale deployment will require overcoming technical and economic challenges through targeted research and development efforts [156].

The economic viability of biomass-to-hydrogen conversion technologies depends on factors such as capital costs, operational expenses, and market competitiveness. Aklilu et al. (2020) discuss the economic aspects of implementing biomass-based hydrogen production. They indicate that policy support, including subsidies and incentives, is critical to making these technologies economically viable. Furthermore, they advocate for continued research to reduce production costs through technological improvements and economies of scale [157] (Table 2).

Biomass-to-hydrogen conversion technologies face numerous technical barriers that impact their efficiency and reliability, such as feedstock variability, process optimization, catalyst development, energy integration, technological maturity, and economic viability. Overcoming these challenges requires reliable pretreatment methods, integration of carbon capture and storage technologies, advancements in catalyst materials, renewable energy integration, pilot project implementation, and economic incentives. Addressing these issues is essential to enhance the performance and scalability of these technologies, ultimately enabling their widespread adoption and contribution to a sustainable energy future.

4. Current status and growth prospects

In recent years, many countries and companies have increased investments in hydrogen production, advancements in its technological processes, and its broad application, as global energy demand continues to rise with population growth and urbanization. Hydrogen energy, especially when combined with renewable energy sources, can reduce carbon dioxide emissions and support the development of sustainable energy systems. During this period of global energy transition, hydrogen energy has the potential to accelerate the shift toward a carbon-free future by replacing traditional fossil fuels.

Leading countries worldwide have implemented large-scale programs aimed at developing the hydrogen economy. For example, in 2022, the United States passed the Inflation Reduction Act (IRA), which offers tax incentives to support hydrogen production and carbon capture technologies. Under this law, the amount of tax credits available for hydrogen production depends on the level of carbon emissions throughout the product's life cycle. Additionally, the Bipartisan Infrastructure Law allocated \$9.5 billion toward hydrogen infrastructure development in the U.S. [158]. It is projected that hydrogen production

Table 2
Technical barriers and solutions in the field of biomass to hydrogen conversion.

Technical barrier	Problems	Solutions	Ref.
Feedstock variability	Biomass feedstock naturally varies in composition and quality, leading to inconsistent hydrogen yields and process inefficiencies.	Navas-Angueta et al. (2020) emphasize the importance of developing reliable pretreatment and preparation methods to standardize biomass feedstock.	[152]
Process optimization	Optimization of various stages in biomass-to-hydrogen conversion, such as gasification, pyrolysis, and reforming, is essential for enhancing overall process efficiency.	Kim et al. (2017) propose using carbon capture and storage (CCS) technologies to maximize hydrogen yield while minimizing carbon emissions.	[153]
Catalyst development	The development of efficient and durable catalysts is crucial for thermochemical and biochemical conversion processes.	García-Olivares et al. (2018) emphasize the need for improved catalytic materials to enhance reaction rates and selectivity in biomass reforming and gasification.	[154]
Energy integration	Efficient integration of energy inputs and outputs is essential in biomass-to-hydrogen conversion systems.	Brand et al. (2020) explore the potential of combining renewable energy sources, such as wind and solar, with biomass conversion technologies.	[155]
Technological maturity	Many biomass-to-hydrogen conversion technologies are in the early stages of development and lack proven commercial success.	Krause et al. (2020) emphasize the importance of pilot and demonstration projects to test performance and scalability.	[156]
Economic viability	High capital costs, operational expenses, and market competition impact economic viability.	Aklilu et al. (2020) propose policy support, including subsidies and incentives, as well as further research to reduce production costs through technological advancements and economies of scale.	[157]

in the U.S. could reach 10 million tons annually by 2030 and 50 million tons by 2050. The Hydrogen Energy Earthshot initiative aims to reduce hydrogen production costs to \$1 per kilogram, increasing hydrogen energy's accessibility and adoption [159,160].

South Korea has made significant strides toward a hydrogen economy, with comprehensive plans to develop hydrogen as a clean and efficient energy source. The country's "Hydrogen Economy Roadmap" focuses on vehicles, hydrogen fuel cell production, and infrastructure development. Major companies, such as Hyundai Motors Group, Doosan, and POSCO, are actively leading the way in hydrogen technology development [161,162]. By 2050, the global green hydrogen market is expected to reach \$300 billion, potentially creating 400,000 new jobs. Additionally, it is estimated that green hydrogen could replace approximately 10.4 billion barrels of oil with equivalent energy resources [163,164].

Many countries view green hydrogen as a future energy solution and are supporting related projects. For instance, Saudi Arabia, Australia, and India are undertaking large-scale projects in this field. One prominent example is the NEOM project in Saudi Arabia, valued at \$8.5 billion, which plans to produce 1.2 million tons of green hydrogen annually [165,166]. China also aims to increase hydrogen production as part of its goal to achieve carbon neutrality by 2060, with plans to raise hydrogen's share of total energy consumption to over 10%. The country is undertaking the world's largest green hydrogen production project, with investments exceeding \$180 billion [167].

In Europe, hydrogen production and infrastructure integration are expected to expand over the next decade, according to studies on hydrogen infrastructure development. Four main growth areas are identified: Spain and France, Ireland and the UK, Italy, and Southeast Europe. These areas are key for delivering hydrogen to consumption centers. While "blue" hydrogen is considered a short-term solution in the early stages of the energy transition, expanding green hydrogen production will be essential in the long term [168] (Table 3).

Key areas for scaling up hydrogen production include its use across various sectors of the economy, such as transportation, metallurgy, chemical, and cement industries. The goal is to significantly reduce global carbon dioxide emissions by 2050 through the use of hydrogen as a carbon-free fuel. Hydrogen use in industry is expanding, with particular focus on developing "green" hydrogen (produced through water electrolysis) and "blue" hydrogen (derived from methane with CO₂ capture). According to the International Energy Agency (IEA), by 2050 most hydrogen production will need to be carbon-free, contributing significantly to overall greenhouse gas emissions reduction [169].

In addition, innovations in hydrogen storage and transportation are

necessary, as current methods are challenged by inefficiencies and the explosive nature of materials in contact with hydrogen. Promising directions for hydrogen storage and transport include liquid chemical forms, such as ammonia, methanol, or methylcyclohexane.

Hydrogen fuel is increasingly used in heavy industries like metallurgy and engineering, which require its continuous and large-scale application. Infrastructure development plays a critical role in this context [170]. Moreover, light industries, such as food and medical sectors, also utilize clean hydrogen sources, requiring specific storage and production conditions. For example, in the food industry, hydrogen fuel is used in hydrogenating vegetable oils to produce pure fats, where hydrogen molecules interact with oils to convert them into saturated fats, a process commonly applied in products like margarine. Hydrogen is also used as a packaging gas to create a controlled atmosphere, which extends shelf life and slows microorganism growth [171].

In medicine, hydrogen therapy is gaining importance due to its antioxidant and anti-inflammatory properties. Inhaling hydrogen gas has proven effective in treating ischemic brain injuries and reducing lung inflammation [172]. Hydrogen-rich water helps prevent neurodegenerative diseases like Parkinson's and Alzheimer's by reducing harmful oxygen radicals in the body [173,174]. Hydrogen is also used in cancer treatment to mitigate the side effects of radiotherapy and chemotherapy by protecting tissues [175]. Inhaling hydrogen gas can improve immune cell function, leading to better treatment outcomes. Therefore, hydrogen is seen as a promising agent for treating neurodegenerative and inflammatory diseases [176,177].

Currently, most commercial hydrogen is produced from fossil fuels, such as coal gasification and natural gas reforming. Hydrogen can also be obtained from biomass using similar methods [178]. Although water electrolysis has long been used to produce hydrogen, the recent advancement of technologies and the availability of affordable renewable energy have rekindled interest in this process [179]. Future trends point toward producing "green" hydrogen via water electrolysis powered by clean, renewable energy sources. This method is environmentally friendly and aligns with carbon emission reduction goals [180]. This approach is expected to become more cost-effective than traditional industrial methods, as energy sources such as solar, wind, hydro, and wave power are utilized. Additionally, hydrogen production technology from biomass, algae, and through biotransformation processes is still under research and testing, becoming a key focus in national hydrogen strategies [181,182] (Fig. 4).

5. Challenges and perspectives

Biomass-to-hydrogen conversion holds promise for providing a cleaner and more sustainable energy supply, yet multiple barriers must be surmounted before it can be deployed at scale. One critical challenge lies in the inconsistent quality of biomass feedstocks. Variations in chemical composition, moisture content, and contaminant levels significantly affect process efficiency and catalyst performance. More sophisticated pretreatment strategies – encompassing physical, chemical, and biological methods – are needed to standardize raw materials for consistent conversion yields. Developing robust, selective, and contamination-tolerant catalysts will play a central role in enabling high throughput while limiting operational downtime and maintenance costs.

Another ongoing issue is tar formation in gasification and pyrolysis systems. Tars can foul equipment, degrade catalyst surfaces, and reduce the calorific value of syngas. Although strategies such as hot gas filtration, plasma-assisted reforming, or the use of advanced sorbents have demonstrated improved tar cracking, further refinements are necessary to lower capital expenditures and minimize catalyst deactivation. Similarly, pyrolysis and steam reforming processes often require high temperatures or pressures, posing energy-intensity and cost concerns. Coupling these routes with renewable energy inputs – particularly wind, solar, or waste heat recovery – could substantially reduce lifecycle

Table 3
World programs and initiatives for the development of hydrogen energy.

Country/ Region	Hydrogen energy development programs	Financing and Investments	Goals and forecasts
USA	Inflation reduction Act, Bipartisan infrastructure law	\$9.5 billion; tax credits for low- carbon technologies	2030 - 10 million tons; 2050 - 50 million tons of hydrogen
South Korea	Hydrogen economy Roadmap	Support of large companies (Hyundai, Doosan, POSCO)	Development of transport, infrastructure, green hydrogen
Saudi Arabia	NEOM green hydrogen project	\$8.5 billion	Production of 1.2 million tons of green hydrogen per year
China	Transition to a low- carbon economy by 2060	Over \$180 billion in investments	The share of hydrogen in energy consumption is above 10%
Europe	Development of hydrogen infrastructure	Various infrastructure projects	Increased production and expansion of infrastructure

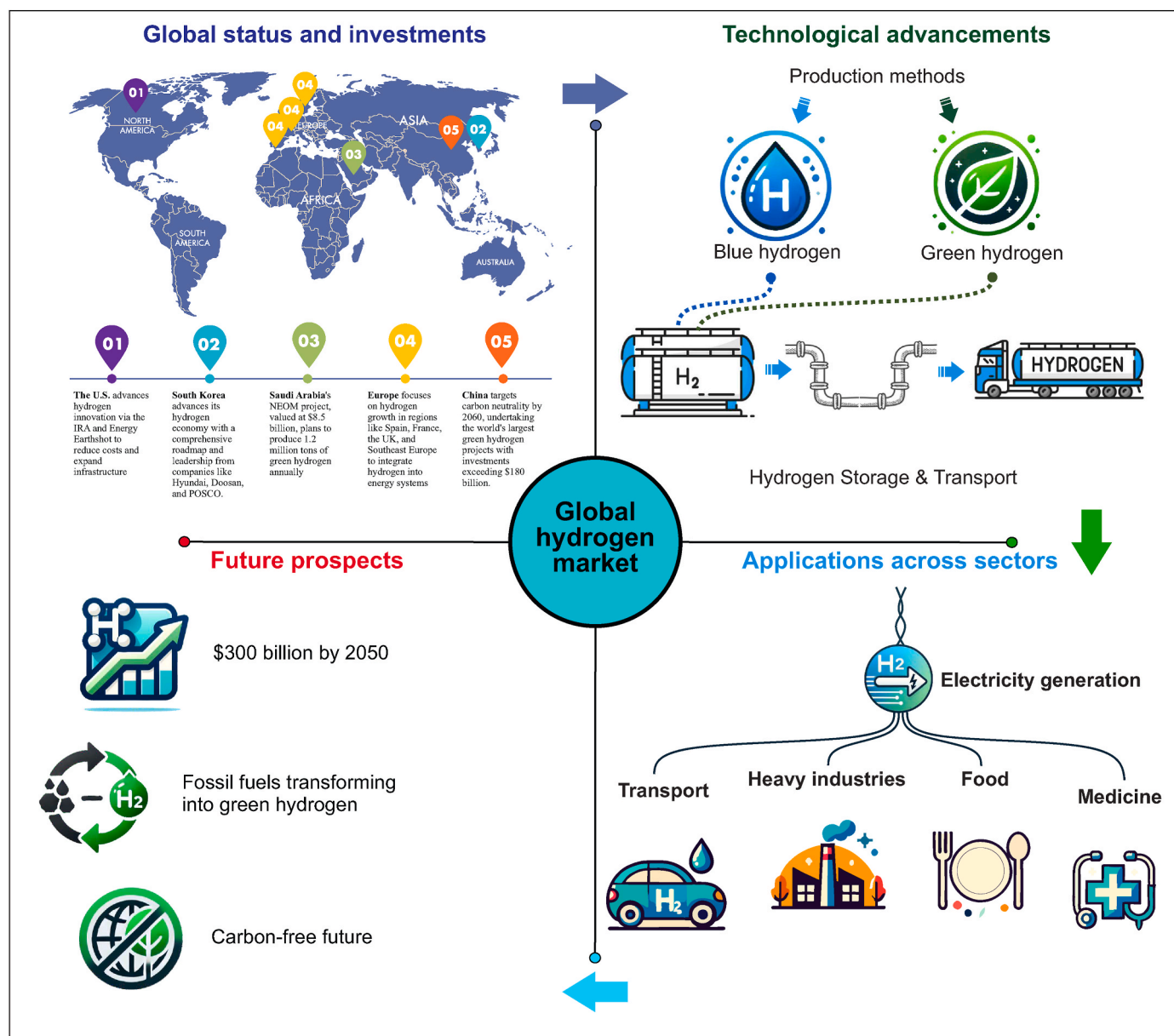


Fig. 4. Global Hydrogen Market: technological advancements and future prospects [181,182].

emissions and enhance techno-economic feasibility.

From a biotech perspective, despite the eco-friendly appeal of dark fermentation, photofermentation, and microalgae-based systems, low hydrogen yields, oxygen sensitivity, and inhibitor accumulation hinder commercial viability. Metabolic engineering, synthetic biology, and mixed-culture approaches offer pathways to overcome these bottlenecks. Targeted genetic modifications to improve hydrogenase activity and oxygen tolerance have demonstrated encouraging results, but scaling these methods to large reactors requires better strategies for maintaining stable microbial communities, optimizing nutrient supply, and managing inhibitory by-products.

While biomass-to-hydrogen conversion shows strong potential, several key challenges and research gaps must be addressed to enable large-scale implementation. One priority is the development of durable catalysts that can withstand poisoning and thermal degradation; nano-structured materials, metal-organic frameworks, and novel support architectures offer promising routes to enhance reaction rates and extend catalyst lifespans. In parallel, hybridizing thermochemical pathways with biological processes may boost overall hydrogen yields by using

syngas to feed engineered microbes. However, such integrated systems require thorough techno-economic assessments and life-cycle analyses to confirm their viability at scale. Innovations in reactor designs are equally essential: advanced configurations like plasma-assisted fluidized beds, membrane reactors, and rotary systems aim to optimize heat and mass transfer, minimize tar formation, and accommodate variable feedstocks. Continued progress in biotechnological breakthroughs, including the development of oxygen-tolerant hydrogenases and genetically modified microbial consortia, could significantly enhance yields in photobiological and fermentation-based approaches, provided stable productivity is demonstrated under industrial conditions. On the experimental side, high-throughput platforms, automated reactors, and advanced in situ characterization methods can rapidly screen novel materials and pinpoint deactivation mechanisms, accelerating the discovery of more robust process parameters. Modeling and simulation also play a pivotal role: multi-scale computational frameworks that couple fluid dynamics with reaction kinetics can offer critical insights for reactor optimization, while genome-scale metabolic models might identify bottlenecks in microbial pathways. Furthermore, artificial

intelligence and machine learning hold considerable promise for predicting optimal catalyst compositions, designing efficient reactors, and reducing trial-and-error experimentation. By systematically tackling these issues through interdisciplinary collaboration and innovative methodological approaches, the field can move closer to achieving cost-effective, high-yield biomass-to-hydrogen conversion on a commercial scale.

6. Conclusion

In conclusion, this review highlights the significant advancements and ongoing research in biomass-to-hydrogen conversion, which holds great promise for sustainable and renewable hydrogen production. These technologies play a crucial role in reducing dependence on fossil fuels and mitigating environmental impact. Various technological approaches – such as gasification, pyrolysis, reforming, and biological methods – have shown potential for efficient hydrogen production from biomass, each offering unique benefits and challenges that underscore the need for continuous innovation and optimization. Key developments in catalyst design, reactor configurations, and the integration of renewable energy sources have improved the efficiency and viability of biomass-to-hydrogen conversion processes. However, technical barriers, such as feedstock variability, process optimization, and catalyst durability, must be addressed to enhance the effectiveness and reliability of these technologies. Economic and environmental factors are also critical in evaluating the feasibility of these technologies. Comprehensive techno-economic analyses, policy support, and market incentives are essential to promote the adoption of biomass-to-hydrogen conversion technologies. Especially, biohydrogen production can be leveraged from existing biomass waste streams [183]. It serves two extent needs: rural energy resiliency and decarbonization of heavy industry, including the production of ammonia and other H-dependent nitrogenous product. Future research should focus on emerging technologies, process optimization, and increasing hydrogen yield. Collaborative efforts among academia, industry, and government will be vital to overcoming current challenges and advancing the field. Tackling these issues is key to building a sustainable hydrogen economy and contributing to a cleaner, greener energy landscape. By leveraging biomass as a renewable resource, biomass-to-hydrogen conversion technologies can make a substantial contribution to the global transition toward sustainable energy systems. Continued research and development, supported by favorable policy frameworks and market dynamics, will be essential to fully realize the potential of these technologies and achieve long-term energy sustainability.

CRedit authorship contribution statement

Gulzhanay K. Kamshybayeva: Visualization, Software, Data curation. **Asemgul K. Sadvakasova:** Validation, Formal analysis, Data curation. **Ayaz M. Belkozhaev:** Validation, Formal analysis, Data curation. **Bekzhan D. Kossalbayev:** Resources, Investigation. **Meruyert O. Bauenova:** Resources, Investigation. **Sergey K. Zharmukhamedov:** Validation, Software, Data curation. **Harvey J.M. Hou:** Writing – review & editing, Supervision. **Suleyman I. Allakhverdiev:** Writing – review & editing, Supervision.

Declaration of interests

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

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