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Advancing Renewable Energy: Hydrogen Production From Biomass For A Sustainable Future

Zeena P. Hamza[1*], Amrutha S. Rajan[1], Aneetha M. R.[1], Rejimon P.K[1], Suja N. R.[1], Venugopal B.[1]

[1]Postgraduate and Research Department of Chemistry, Maharaja's College, Ernakulam, Kerala, India, 682011
*Emails: zeenaphamza@maharajas.ac.in, zeenaphamza@gmail.com
***Corresponding Author**: Zeena P. Hamza
*Postgraduate and Research Department of Chemistry, Maharaja's College, Ernakulam, Kerala, India, 682011

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ABSTRACT

The increasing global demand for clean and sustainable energy sources has sparked interest in biomass-to-hydrogen conversion as a viable alternative to traditional fossil fuels. The quest for sustainable energy sources has led to extensive exploration of biomass-to-hydrogen conversion methods. This paper provides a comprehensive overview of various techniques employed in this conversion process, including thermochemical, biological, and electrochemical methods. Thermochemical conversion, particularly biomass gasification, emerges as a promising approach for hydrogen production, with different gasification techniques offering unique advantages and challenges. Biological processes such as dark fermentation and microbial electrolysis offer environmentally friendly alternatives but face challenges in scaling up production. Electrochemical methods, including electrolysis and steam reforming, provide efficient means of hydrogen generation but require further technological advancements for cost-effectiveness. Moreover, challenges such as feedstock availability, production costs, market demand, policy support, and environmental considerations are discussed. Addressing these challenges through technological innovation, policy incentives, and interdisciplinary collaboration will be crucial for realizing the full potential of biomass-to-hydrogen conversion as a sustainable energy solution.

Key words: sustainable energy sources, biomass gasification, thermochemical methods, elecrochemical methods, biological methods, microbial electrolysis, biomass gasification

Introduction

The energy crisis is currently the biggest barrier preventing human civilization from progressing (Ahmed S. F. et al., 2021). There have been concerns expressed about the way solid waste is finally treated, how quickly energy is produced and consumed, and how greenhouse gas (GHG) emissions are increasing (Mahlia et al., 2020). Furthermore, the fast-exhausting fossil fuel resources pose a severe danger to global energy security and are also a major cause of surface air temperature rise, ocean acidification, and climate change. It is apparent that organizations such as governments, universities, and research centers are becoming more and more involved in putting conservation measures into practice these days. Many companies and chemical processing facilities have recently shown interest in using sustainable development concepts (Ahmed S. F. et al., 2021). A sustainable and environmentally friendly future is possible when fossil fuels are replaced by renewable energy sources.

Biofuels are considered a smart substitute for fossil fuels in the search for ecologically friendly and sustainable energy solutions (Naira et al. 2020). A viable substitute is hydrogen, which has a high mass energy density (122 kJ/kg) and a safe combustion product (water). Hydrogen has proven to be a viable fuel platform as long as it can operate as a high-energy, clean, and environmentally friendly fuel that can be used to produce electricity in fuel cells. Development of technology and procedures that could make the manufacturing of this fuel more sustainable is required because the high production costs of H_2 negatively impact its commercial distribution. The two primary uses of hydrogen produced annually from fossil fuels are the synthesis of ammonia and the refining of oil (Navarro 2007). The development of new technologies to meet growing demand while reducing capital costs, production costs, and greenhouse gas emissions is necessary for the hydrogen economy to become a reality(Xu et al., 2013).

Rekindled interest in utilizing biomass resources has been sparked by the urgent global concerns of climate change, depleting fossil fuel stocks, and the need for cleaner alternatives. The most abundant renewable resource is biomass, which is also far more evenly distributed globally than fossil fuels (Rollin et al. 2015). Biomass, derived from organic materials such as agricultural residues, forestry waste, and organic municipal waste, offers a renewable and abundant feedstock for hydrogen production. Various conversion methods, including thermochemical, biological, and electrochemical processes, have been developed to harness the energy potential of biomass and generate hydrogen efficiently.

Renewably sourced feedstock and adaptable energy sources are combined in the production of biomass and hydrogen. Only water is released as a byproduct when using hydrogen, a high-energy-density fuel, to power various devices and activities, including fuel cells, transportation, and industrial operations. Utilizing the current infrastructure for distribution and utilization is one benefit of the symbiotic interaction between biomass and these energy carriers, which also has the potential to lower carbon emissions. The objective of this research is to provide insight into the changing biomass-to-hydrogen environment by analyzing the most recent methods, obstacles, and sustainability consequences.

Various conversion methods, including thermochemical, biological, and electrochemical processes, have been developed to harness the energy potential of biomass and generate hydrogen efficiently. Thermochemical conversion techniques, such as biomass gasification, involve the high-temperature decomposition of biomass in the presence of oxygen or steam. Gasification processes offer flexibility in feedstock selection and produce a syngas rich in hydrogen, carbon monoxide, and other combustible gases. However, challenges such as tar formation, reactor design optimization, and syngas purification need to be addressed for widespread adoption (P. Basu 2010, Tezer et al., 2022).

Thermochemical methods

Thermochemical conversion is an advanced method for generating hydrogen from biomass (Lepage et al. 2021). The three primary thermochemical mechanisms are gasification, pyrolysis, and aqueous phase reforming (Huber et al. 2006). Gasification is a thermochemical process that produces hydrogen by operating at high temperatures and low pressures. Carbonaceous solids like biochar, ash, and tars are gasified to produce syngas, a gaseous byproduct that is combustible in nature and mostly consists of CO, CO_2, H_2, and CH_4(Mohanty et al. 2024).

Numerous factors, including the kind of biomass and reactor design, need to be optimized in order to control the composition of gases. The process can be classified as steam gasification, oxygen gasification, or air gasification based on the oxidizing agent used (Xu et al. 2018). Syngas has also been shown to contain trace amounts of organic and inorganic pollutants. The organic components include tar, a viscous liquid made of condensable organic compounds, and light hydrocarbons (LHC), such as CH_4. The inorganic molecules include H_2S, HCl, NH_3, and alkali metals. Gasification can be classified into three categories based on the setup of the process: direct blown, indirect gasification (Hannula & Kurkela 2010), fluidized bed gasification, steam/oxygen or air, dual fluidized bed (DFB) steam blown gasification (Thunman et al. 20), and entrained gasification flow [Weiland et al. 2013]. Using steam as the gasification medium is preferred when the targeted end product is hydrogen because it shifts the equilibrium to a higher share of hydrogen in the final gas [Nipattummakul et al. 2010].

The separation of the gasification process from the combustion required to sustain the process's heat is the fundamental idea of Dual fluidized bed (DFB) steam blown gasification. Materials are moved between the two processes in two separate reactors via a circulating bed material stream. If the gas is meant for fuel synthesis, this method allows the biomass to be burned with air instead of pure oxygen, which is typically the case with other technologies. Therefore, there is no need for an energy-intensive air separation unit (ASU). Compared to its predecessors, DFB gasification typically occurs at a lower temperature (700°C to 900°C), producing a gas with higher hydrocarbon contents but also tars that require downstream processing. Several studies on the production of hydrogen and hybrid systems based on DFB gasification have been carried out (Tock and Maréchal 2012).

Direct blown gasification of biomass can be done using air; however the resulting product gas is diluted and not appropriate for synthesis because nitrogen makes up the majority of air's composition. As a result, the gasification medium in direct blown gasification is often steam and pure oxygen. The benefits of this procedure include a considerably simpler design process than the DFB gasification process and the potential to pressurise the gasification reactor, which may eliminate the need for compression later on and allow for the use of a smaller, possibly more economical gasification reactor (Kraussler et al.2016; Fail et al. 2014). The disadvantage is that maintaining the oxygen process requires an air-separation unit (ASU), which is expensive and energy-intensive (Salkuyeh et al. 2018; Kraussler et al. 2017; Yao et al. 2017).

In contrast to the first two gasification processes, entrained flow gasification uses a distinct design and operation for the gasification reactor. As the name suggests, the feedstock is entrained with the gasification medium as it is introduced into the reactor's top. Because of this, processing the feedstock—which needs to be pulverised into a fine powder before being sprayed into the reactor—becomes quite difficult. Entrained flow gasification produces a clean gas with reduced tar and hydrocarbon content and high conversion rates due to its higher temperature (about 1300°C) than the previously mentioned techniques (Qin et al. 2012). Consequently, the process design can be made more intense and straightforward. The drawbacks of the technique include high feedstock preparation costs and expenses associated with the ASU. Low hydrogen content is one of the disadvantages of larger-scale biomass gasification (Lepage et al. 2021). This results in a variety of pollutants, such as tar and char, and is caused by the low hydrogen concentration (3-11 wt%) and compositional heterogeneity in the raw biomass (Adamovics et al. 2018). According to Ji et al. (2009), the process additionally has to incorporate carbon dioxide collection techniques, water-gas shift (WGS) processes to increase hydrogen concentration, and further separation steps for syngas purification to improve hydrogen generation.

Biological methods

Biological processes, including direct and indirect photolysis, photofermentation, dark fermentation, and microbial electrolysis, utilize microorganisms to convert biomass into hydrogen through anaerobic digestion or electrochemical reactions. These methods offer environmental benefits and can utilize diverse biomass sources but face challenges in scalability and efficiency (Farrell et al. 2006).

Direct photolysis is the process by which green algae and other photosynthesizing microbes convert sunlight into chemical energy that can be used later. Cyanobacteria can participate in indirect photolysis and use a two-phase process of photosynthesis to create and synthesise H_2. In nitrogen-deficient conditions, it uses light energy and reduced organic acids and catalyse the photo-fermentation of hydrogen in purple non-sulfur bacteria (Zagrodnik and Laniecki 2015).

Dark fermentation is a biological process that involves the anaerobic breakdown of organic materials by bacteria to produce hydrogen (Łukajtis et al. 2018). This method is favored over photo-fermentation due to its lower energy consumption. Nonetheless, a number of studies have been conducted on the dark fermentation of lignocellulosic biomass to create hydrogen, employing a range of earlier treatment techniques to get rid of the problems brought on by the lignin component of the biomass. Biological, chemical, mechanical, or combinations of those three pretreatment procedures include size reduction, acid treatment, and enzyme therapy (Manish and Banerjee 2008; Ren et al. 2016; Chong et al. 2009). Significant amounts of H_2 can be produced in conventional bioreactors utilising anaerobic bacteria that can only use cellulose as a carbon source when combined with cellulosic feedstocks (Islam et al. 2006, ; Levin et al. 2006; Magnusson et al. 2009; Ramachandran et al. 2008).

Microbial electrolysis is a biological process where microorganisms facilitate the electrolysis of water to produce hydrogen gas. This method shows potential for biomass-to-hydrogen conversion. Anaerobic digestion is another biological method that holds promise for biomass-to-hydrogen production, as it involves the breakdown of organic matter by microorganisms in an oxygen-free environment to generate biogas containing hydrogen.This process not only produces hydrogen but also yields valuable byproducts such as methane, making anaerobic digestion a versatile and efficient method for biomass-to-hydrogen production.Moreover, anaerobic digestion can be integrated with wastewater treatment plants to harness the organic waste streams for sustainable hydrogen production, showcasing its potential for decentralized energy generation.

Electrochemical methods

Electrochemical methods, such as electrolysis and steam reforming, utilize electricity or heat to split water or oxygenated hydrocarbons into hydrogen and oxygen. These processes offer high efficiency and purity of hydrogen but require energy-intensive operations and cost-effective catalysts.

Recent advancements in electrolysis technology have focused on improving efficiency and reducing costs through the development of high-performance catalysts and novel electrolyte materials. Generally speaking, 60-65% of the electrical energy input is converted into chemical energy stored in hydrogen gas via electrolysis devices, which have an efficiency of 60-65%. These advancements aim to make electrolysis a more competitive and sustainable method for hydrogen production.

A promising "biorefinery technology" for BDPM (biomass and its derived platform molecules) valorization is electrocatalysis, which allows for the gentle and environmentally friendly production of a variety of high-value chemicals and fuels. However, due to a lack of knowledge about the reaction processes, the progress of electrocatalytic upgrading of BDPMs is incredibly uneven (Fan et al., 2022).

When an electric current is passed via an alkaline or polymeric conducting electrolyte in water, water molecules split into H_2 and O_2, resulting in the production of H_2 by water electrolysis. The hydrogen obtained from the electrolysis of water is relatively high-quality because no carbon, sulphur, or nitrogenous compounds are produced. As a result, fuel cells require much less expensive hydrogen purification than solid metals. Even though electrolysis doesn't produce any emissions by itself, Levin and Chahine (2010) found that the process's power source directly affects the emissions over its lifetime.

Biological electrolysis is similar to water electrolysis except that biomass is used as the major fuel and the reaction takes place at the anode rather than at the cathode. One advantage is that biological electrolysis requires less energy than water electrolysis. The feedstock (water/biomass) is much more expensive, which is the main drawback. For the feedstock to yield organic acids or alcohols, it must ferment before handling. It becomes increasingly difficult to commercialise the technology as a result of the process being more costly and complex (Liu et al. 2016). The Microbial Electrolysis Cell (MEC) and the Proton Exchange Membrane Electrolysis Cell (PEMEC) are the two technologies that are currently being used for this purpose(Azwar et al. (2014).

The microbial electrolysis cell (MEC), uses an adjustable and sustainable procedure to create biohydrogen from wastewater (Mona et al. 2020). In the MEC architecture, an ion exchange membrane divides the cathode chamber from the anode chamber. The MEC's anode uses electrogenic bacteria, whilst the cathode is anaerobic. These cells work as factories of bio-electrochemistry, with the anode reducing organic acids and the cathode producing hydrogen. At the anode, electrogenic bacteria emit electrons, which combine with protons to create hydrogen in an anaerobic environment. There needs to be an external power source present in order to transfer the electrons to the opposing cathode. The microbial population, which can have many effects, may be impacted by competing microorganisms present in the wastewater. Hydrogen production may be decreased by competition between the acetogenic and electrogenic bacteria for the substrate. Similarly, methanogens require hydrogen and carbon dioxide in order to produce methane, indicating a limitation on the production of hydrogen. Inhibitors such as lumazine and 2-bromomethanesulfonate (BES) have been suggested as a way to overcome this constraint. The cathode needs to be selected carefully because it is the main location where hydrogen evolution occurs. The anode must be conductive and free of corrosion. Monitoring factors like pH, temperature, applied voltage, and substrate is crucial for achieving a greater yield. The anode's pH ought to be higher than the cathode's. Temperature variations affect the ways in which certain microbial species thrive. Applying a potential of at least 0.2 V is advised, and more hydrogen will evolve as the voltage is increased. Direct current sources, dye-sensitized solar cells, or MFCs are used to power the MECs. MECs have the ability to produce not just hydrogen but also biohythane, which is a combination of hydrogen and methane. Biohythane can be used as an alternative fuel to produce ethanol by means of microbial electron reduction. Furthermore, MECs have the capacity to recover ammonia and desalinate water. Sustainable and renewable sources of biohydrogen are being developed by MECs (Varanasi et al. 2019).

The Proton Exchange Membrane Electrolysis Cell (PEMEC) is seen to be a viable technique for producing pure hydrogen; it provides the opportunity for biomass degradation without the high pressures and temperatures required for biomass thermal conversion (Kumar and Himabindu, 2019; Xie et al. 2022). A proton exchange membrane (PEM) in a PEMEC helps protons (H^+) get to the cathode quickly. High-purity hydrogen is produced as a consequence of this procedure (H_2). This method's primary benefit is that it does away with the requirement for a second separation step to purify the hydrogen (Ayers, 2021). Lewis acid ($FeCl_3$) can be used to create hydrogen from biomass feedstock, such as glucose, starch, lignin, and cellulose at room temperature, according to research by Umer et al. using a 100 mL h-type proton exchange membrane electrolysis cell. This process has a greater production rate than water electrolysis while using less electricity (Umer et al., 2024).

Biohydrogen is also produced in a double compartmentalised electrochemical photobioreactor (EPBR). The anode generates protons at low voltage, and the cathode generates hydrogen. In this reaction, both systems remove oxygen from the cathode chamber and make hydrogen. The Spirulina strain is known as "biohydrogen" because of its capacity to manufacture hydrogen in both the light and dark phases. It was found that by employing EPBR in the anode, the cathode was utilised for electrochemical hydrogen generation. The voltage applied has an impact on how quickly hydrogen is created in both chambers. Furthermore, because it produces hydrogen with the least amount of voltage possible, it is thought to be better than previous attempts on MECs (Hasnaoui et al. 2020).

Advances in reforming technologies, such as Steam methane reforming (SMR) and Auto-thermal reforming (ATR), have been geared towards enhancing process efficiency, increasing hydrogen yield, and minimizing carbon emissions. Integration of carbon capture and utilization (CCU) techniques is also being explored to mitigate environmental impacts.

Hydrogen can also be produced via steam reformation or water reformation of oxygenated hydrocarbons such as fructose, glycerol, methanol, and ethanol, utilising a variety of temperatures and catalysts.Breaking C-C bonds, C-H bonds, and/or O-H bonds is necessary for the catalytic method for the production of hydrogen and carbon dioxide from oxygenated hydrocarbons in aqueous phase in order to generate adsorbed species on the catalyst surface. Oxygenated hydrocarbons can form in the aqueous phase and produce hydrogen gas when a platinum-based catalyst is present (Amoretti et al. 2002). In order to avoid the production of steam and guarantee that the reaction sequence takes place in the aqueous medium, the conversion happens at pressures between 27 and 54 bar and at a moderate temperature of around 223-264 ^{0}C. In the presence of Ir, Co, and Ni catalysts supported on ceria, hydrogen can be generated by Steam reforming oxygenated hydrocarbons. At temperatures about 500 K (227^{0}C), (Huber et al. 2003) reforming of oxygenated hydrocarbons (ethanol, glycerol) derived from biomass is employed in aqueous phase over tin- or alumina supported Ni catalysts. Ir, Co, and Ni catalysts supported by cerium oxide (CeO_2, ceria) were employed by Zhang et al. (Zhang et al. 2007). At low temperatures (<220^{0}C) and pressures, alkaline enhanced reformation (AER) can be used to transform aqueous hydrogenated organic molecules to gaseous H_2 at an alkaline pH, which makes conditions that are thermodynamically more approving than traditional steam reforming (Reichman et al. 2007). As a result, the reforming process occurs at much lower temperatures, and the carbon produced by the reforming reaction precipitates rather than the CO and CO_2 gases that are typically produced as a solid salt (Na_2CO_3) byproduct of steam reforming. This simplifies the AER reactor and offers the opportunity to produce renewable H_2 without simultaneously producing greenhouse gases.

Carbon monoxide (CO) and hydrogen (H_2) are produced when steam reacts with methane (CH_4) at temperatures as high as 800^{0}C in steam methane reforming (SMR) processes. To create more hydrogen and carbon dioxide, the carbon monoxide (CO) and vaporised water react again. Traditionally, SMR has used natural gas to make hydrogen, however steam reforming methane from landfills is becoming more and more common (Muradov and Smith 2008).

The Conversion of Biomass to Hydrogen: Challenges and Considerations

However, each of the H_2 manufacture technologies is coupled with a set of technological challenges, including feedstock kinds, conversion efficiency, and the requirement for production systems to be securely interconnected with storage and purifying technologies (Levin et al. 2010). Biomass gasification can employ renewable feedstocks derived from forestry and/or agricultural residues (Guoxin and Hao 2009); however, these processes also yield a range of gaseous and occasionally liquid phase co-products (Milliken 2008). The primary barrier to producing hydrogen by steam reformation of oxygenated hydrocarbons is the requirement for low-cost catalysts with extremely high conversion efficiencies. This also holds true for reforming in alkaline media, although there is an additional difficulty in that catalyst fouling results from the carbon that is sequestered as a precipitate of sodium carbonate during the reforming processes. Supercritical water partial oxidation is a method for producing clean hydrogen, but it requires a lot of energy to raise a mixture's temperature and pressure over its thermodynamic critical point. Fermentation-based biological hydrogen production has a lot of potential, particularly for systems that use cellulosic feedstocks and/or waste streams from food processing that are high in sugar. To be competitive in the market, biological hydrogen systems must, however, be able to create H_2 at rates high enough for practical application. Two examples of research and development aimed at boosting H_2 yields and synthesis speeds include genetic modification of hydrogen synthesising bacteria and bioreactor designs optimised for rapid removal of CO_2 and H_2 to maintain low hydrogen partial pressures. But whether they use biological or thermocatalytic processes, renewable hydrogen systems all have to deal with the same issue. Both biological fermentation systems and thermocatalytic processes, such as the reformation of organic compounds in aqueous medium, produce gas mixtures of hydrogen and carbon dioxide. For example, equal amounts of CO_2 and H_2 are produced at low density and pressure by anaerobic bacteria that ferment sugars, starches, or cellulose; also, a significant amount of water vapour is present in the gas stream. For this reason, all renewable hydrogen generation systems require the contemporaneous development and integration of hydrogen storage and purification technologies.

The tremendous optimism that automobiles with hydrogen fuel cells will someday replace those with petrol and diesel engines is currently illusory for a number of reasons, including the slower development of the infrastructure needed for hydrogen storage, transportation, and recharging. It follows that the car industry is most likely to be the last to adopt hydrogen technology. It is now more likely that the development of hydrogen fuel cells will come from specialised applications, that the number of techniques required to support various fuel cell applications will expand gradually as hydrogen storage techniques evolve, and that the development of hydrogen fuel cells will come from specialised applications. Implementing CCU technologies in biomass-to-hydrogen conversion processes can significantly reduce greenhouse gas emissions. Future plans include developing more efficient carbon capture methods and exploring the utilization of captured CO_2 in various industrial applications.

Although generating hydrogen from biomass is a potential approach to sustainable energy, there are certain financial issues that need to be resolved. The availability, cost, and market demand of feedstock are some of the economic factors that affect the production of hydrogen from biomass.

- The availability of biomass feedstocks varies by region and is influenced by elements including soil quality, climate, and agricultural methods. It is essential to provide a steady supply of biomass without diminishing natural resources. Crop rotation and ethical forestry are two examples of sustainable practices that must be implemented. Transporting biomass to the production site can have a big effect on total costs. One important economic aspect is proximity to sources of biomass.

- Gasification and pyrolysis are two examples of effective conversion technologies that are crucial for maximising hydrogen generation and reducing waste. In this field, research and development can lower production costs. Economies of scale are frequently realised by large-scale production facilities, lowering the cost per unit of hydrogen produced. Costs are influenced by catalysts, processing needs, and the type of biomass used. Certain types of biomass might need additional processing, which would raise overall costs.
- Market dynamics are impacted by the need for hydrogen, particularly in industries and sectors like transportation. Government regulations and incentives encouraging the use of hydrogen can increase demand. The cost of hydrogen generated from biomass must be competitive with that of hydrogen obtained from alternative sources, such as electrolysis or natural gas. Gaining traction in the market requires economic viability. Production can be matched with actual demand by keeping an eye on market trends, such as the increasing popularity of hydrogen fuel cell vehicles.
- Grants, tax breaks, and subsidies can make the production of hydrogen from biomass economically feasible. Investor confidence depends on long-term policy commitments and political stability. Carbon pricing mechanisms have the potential to increase the competitiveness of biomass-based hydrogen in relation to fossil fuels, given the growing emphasis on decreasing carbon emissions.
- Research and innovation spending should not stop in order to spur advances in biomass conversion technologies that would lower the process's cost. Investing in the newest technologies to train a competent workforce guarantees effective operations, which lowers operating expenses.
- It is crucial to evaluate the entire environmental impact, including carbon emissions. Though it is thought to be greener, the whole production lifetime needs to be addressed.

Tackling the financial aspects of producing hydrogen from biomass calls for a comprehensive strategy. It entails maximizing technological advancements, guaranteeing a steady and sustainable supply of biomass, coordinating production with market demands, utilizing legislative backing, and stimulating innovation. In order to overcome these financial obstacles and establish biomass-based hydrogen as a competitive and feasible energy source, cooperation between governments, businesses, and academic institutions is essential.

Conclusion

The synthesis of hydrogen from biomass has great potential for the development of sustainable and renewable energy sources. A practical solution to the global challenges of climate change and the need to transition away from fossil fuels is the production of hydrogen from biomass. These procedures use biological materials—from algae to agricultural waste—to produce renewable energy sources.

Advances in hydrogen production are being driven by biological and thermochemical processes, hybrid systems, and enhanced catalysis. In order to make the conversion of biomass to hydrogen not only more environmentally friendly but also commercially feasible, researchers are concentrating on increasing efficiency, investigating the use of waste biomass, and incorporating renewable energy sources. While comprehensive techno-economic evaluations and life cycle assessments are ensuring the profitability and sustainability of these approaches, electrochemical methods and sustainable feedstocks are broadening the possibilities.

Notwithstanding, several obstacles persist, such as the necessity for additional investigation into catalyst development, enhancement of conversion procedures, and establishment of expansive, financially feasible manufacturing infrastructures. It is also essential to address environmental issues related to the production, harvesting, and processing of biomass. A cleaner future is being shaped by ongoing research and innovation in biomass-to-hydrogen technologies, despite these obstacles. These developments offer a window into a future where energy is plentiful and ecologically benign, while also helping to lower greenhouse gas emissions and paving the path for a more sustainable energy landscape. Realising the full potential of biomass-based hydrogen generation will require cooperation between scientists, engineers, and policymakers in order to make substantial progress towards a cleaner and more sustainable energy future.

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References

1. Adamovics, R. Platace, A. Kakitis, S. Ivanovs, Evaluation of combustion properties of biomass fuel. Engineering for Rural Development. (2019).
2. Ahmed, S. F., Rafa, N., Mofijur, M., Badruddin, I. A., Inayat, A., Ali, M. S., ... Yunus Khan,
3. T. M. (2021). Biohydrogen production from biomass sources: Metabolic pathways and economicanalysis. Frontiers in Energy Research, 9. doi:10.3389/fenrg.2021.753878
4. Amoretti, M., Amsler, C., Bonomi, G., Bouchta, A., Bowe, P., Carraro, C., ... van der Werf, P. (2002). Production and detection of cold antihydrogen atoms. Nature, 419(6906), 456-459. doi:10.1038/nature01096
5. Ayers, K. (2021). High efficiency PEM water electrolysis: enabled by advanced catalysts, membranes, and processes. Current Opinion in Chemical Engineering, 33(100719), 100719. doi:10.1016/j.coche.2021.100719
6. M.Y. Azwar, M.A. Hussain, A.K. Abdul-Wahab, Development of biohydrogen production by photobiological, fermentation and electrochemical processes: A review. Renew. Sust. Energ. Rev.31, 158-173 (2014). https://doi.org/10.1016/j.rser.2013.11.022
7. Basu, P. (2010). Biomass Gasification and Pyrolysis: Practical Design and Theory. Elsevier Inc., Amsterdam.
8. M.L. Chong, V. Sabaratnam, Y. Shirai, M.A. Hassan, Biohydrogen production from biomass and industrial wastes by dark fermentation. Int. J. Hydrog. Energy 34(8), 3277-3287 (2009). https:// doi.org/10.1016/j.ijhydene.2009.02.010
9. Fail, S., Diaz, N., Benedikt, F., Kraussler, M., Hinteregger, J., Bosch, K., ... Hofbauer, H. (2014). Wood gas processing to generate pure hydrogen suitable for PEM fuel cells. ACS Sustainable Chemistry & Engineering, 2(12), 2690-2698. doi:10.1021/sc500436m
10. Fan, Z., Zhang, W., Li, L., Wang, Y., Zou, Y., Wang, S., & Chen, Z. (2022). Recent developments in electrode materials for the selective upgrade of biomass-derived platform molecules into high-value-added chemicals and fuels. Green Chemistry: An International Journal and Green Chemistry Resource: GC, 24(20), 7818-7868. doi:10.1039/d2gc02956a
11. Farrell, A. E., Plevin, R. J., Turner, B. T., Jones, A. D., O'Hare, M., & Kammen, D.
12. (2006). Ethanol can contribute to energy and environmental goals. Science (New York, N.Y.), 311(5760), 506-508. doi:10.1126/science.1121416
13. H. Guoxin, H. Hao, Hydrogen rich fuel gas production by gasification of wet biomass using a CO2 sorbent. Biomass Bioenergy 33(5), 899-906 (2009).

https://doi.org/10.1016/j.biombioe.2009. 02.006

14. I. Hannula, E. Kurkela, A semi-empirical model for pressurised air-blown fluidized- bed gasification of biomass. Bioresour. Technol. 101(12), 4608-4615 (2010).
15. https://doi.org/10.1016/j.biortech. 2010.01.072
16. Hasnaoui, S., Pauss, A., Abdi, N., Grib, H., & Mameri, N. (2020). Enhancement of bio-hydrogen generation by spirulina via an electrochemical photo-bioreactor (EPBR). International Journal of Hydrogen Energy, 45(11), 6231-6242. doi:10.1016/j.ijhydene.2019.12.144
17. Huber, G. W., Shabaker, J. W., & Dumesic, J. A. (2003). Raney Ni-Sn catalyst for H2 production from biomass-derived hydrocarbons. ChemInform, 34(40). doi:10.1002/chin.200340015
18. Islam, R., Cicek, N., Sparling, R., & Levin, D. (2006). Effect of substrate loading on hydrogen production during anaerobic fermentation by Clostridium thermocellum 27405. Applied Microbiology and Biotechnology, 72(3), 576-583. doi:10.1007/s00253-006-0316-7
19. M. Kraussler, M. Binder, S. Fail, K. Bosch, M. Hackel, , H. Hofbauer, Performance of a water gas shift pilot plant processing product gas from an industrial scale biomass steam gasification plant. Biomass Bioenergy 89, 50-57 (2016). https://doi.org/10.1016/j.biombioe.2015.12.001
20. M. Kraussler, P. Schindler, H. Hofbauer, An experimental approach aiming the production of a gas mixture composed of hydrogen and methane from biomass as natural gas substitute in industrial applications. Biores. Technol. 237, 39-46 (2017).
21. https://doi.org/10.1016/j.biortech.2017.03. 040
22. Kumar, S. S., & Himabindu, V. (2019). Hydrogen production by PEM water electrolysis-A review. Mater. Sci. Energy Technol, 2, 442-454.
23. Lees, J. P., Poireau, V., Tisserand, V., Garra Tico, J., Grauges, E., Palano, A., … BABAR Collaboration. (2012). Search for lepton-number violating processes inB+→h−l+l+decays. Physical Review, 85(7). doi:10.1103/physrevd.85.071103
24. Lepage, T., Kammoun, M., Schmetz, Q., & Richel, A. (2021). Biomass-to-hydrogen: A review of main routes production, processes evaluation and techno-economical assessment. Biomass & Bioenergy, 144(105920), 105920. doi:10.1016/j.biombioe.2020.105920
25. Levin, D. B., Chahine, R., & Chahine, R. (2010). Richard Chahine, international journal of hydrogen energy 35. International Journal of Hydrogen Energy, 35, 4962-4969.
26. Levin, D., Islam, R., Cicek, N., & Sparling, R. (2006). Hydrogen production by Clostridium thermocellum 27405 from cellulosic biomass substrates. International Journal of Hydrogen Energy, 31(11), 1496-1503. doi:10.1016/j.ijhydene.2006.06.015
27. Li, H., (Charles) Xu, C., Yuan, Z., & Wei, Q. (2018). Synthesis of bio-based polyurethane foams with liquefied wheat straw: Process optimization. Biomass & Bioenergy, 111, 134-140. doi:10.1016/j.biombioe.2018.02.011
28. W. Liu, Y. Cui, X. Du, Z. Zhang, Z. Chao, Y. Deng, High efficiency hydrogen evolution from native biomass electrolysis. Energy Environ. Sci. 9(2), 467-472 (2016). https://doi.org/10.1039/ c5ee03019f
29. Łukajtis, R., Hołowacz, I., Kucharska, K., Glinka, M., Rybarczyk, P., Przyjazny, A., & Kamiński, M. (2018). Hydrogen production from biomass using dark fermentation. Renewable and Sustainable Energy Reviews, 91, 665-694. doi:10.1016/j.rser.2018.04.043
30. Magnusson, L., Cicek, N., Sparling, R., & Levin, D. B. (2009). Continuous hydrogen production during fermentation of a-cellulose by the thermophillic bacterium Clostridium thermocellum.

Biotechnol. Bioeng, 102, 759-766.

31. Mahlia, T. M. I., Syazmi, Z. A. H. S., Mofijur, M., Abas, A. E. P., Bilad, M. R., Ong,
32. H. C., & Silitonga, A. S. (2020). Patent landscape review on biodiesel production: Technology updates. Renewable and Sustainable Energy Reviews, 118(109526), 109526. doi:10.1016/j.rser.2019.109526
33. Manish, S., & Banerjee, R. (2008). Comparison of biohydrogen production processes. International Journal of Hydrogen Energy, 33(1), 279-286. doi:10.1016/j.ijhydene.2007.07.026
34. K.L. Milliken, C.P. North, The editor's page. J. Sediment. Res. 78(8), 499-499 (2008). https://doi. org/10.2110/jsr.2008.063
35. Mohanty, A. K., Vivekanandhan, S., Das, O., Romero Millán, L. M., Klinghoffer, N. B., Nzihou, A., & Misra, M. (2024). Biocarbon materials. Nature Reviews. Methods Primers, 4(1). doi:10.1038/s43586-024-00297-4
36. Mona, S., Kumar, S. S., Kumar, V., Parveen, K., Saini, N., Deepak, B., & Pugazhendhi, A. (2020). Green technology for sustainable biohydrogen production (waste to energy): A review. The Science of the Total Environment, 728(138481), 138481. doi:10.1016/j.scitotenv.2020.138481
37. N. Muradov, F. Smith, Thermocatalytic conversion of landfill gas and biogas to alternative transportation fuels. Energy Fuels: Am. Chem. Soc. J. 22(3), 2053-2060 (2008). https://doi. org/10.1021/ef8000532
38. Naira, V. R., Das, D., & Maiti, S. K. (2020). A novel bubble-driven internal mixer for improving productivities of algal biomass and biodiesel in a bubble-column photobioreactor under natural sunlight. Renewable Energy, 157, 605-615. doi:10.1016/j.renene.2020.05.079
39. Navarro, R. M., Pena, M. A., & Fierro, J. L. G. (2007). Hydrogen production reactions from carbon feedstocks: Fossil fuels and biomass. ChemInform, 38(50). doi:10.1002/chin.200750271
40. N. Nipattummakul, I.I. Ahmed, S. Kerdsuwan, A.K. Gupta, Hydrogen and syngas production from sewage sludge via steam gasification. International Journal of Hydrogen Energy. 35(21), 11738- 11745 (2010). https://doi.org/10.1016/j.ijhydene.2010.08.032.
41. Qin, K., Jensen, P. A., Lin, W., & Jensen, A. D. (2012). Biomass gasification behavior in an entrained flow reactor: Gas product distribution and soot formation. Energy & Fuels: An American Chemical Society Journal, 26(9), 5992-6002. doi:10.1021/ef300960x
42. Ramachandran, U., Wrana, N., Islam, R., Cicek, N., Sparling, N., & Levin, D. B. (2008). Hydrogen production by a novel cellulolytic bacterium, Clostridium termitidis strain CT1112, isolated from a termite. Int. J. Hydrog. Energy, 33, 7006-7012.
43. Reichman, B., Mays, W., Strebe, J., & Fetcenko, M. (2007). Fuel reformation using alkaline enhancement. In Proceedings International Hydrogen Energy Congress and Exhibition (pp. 13-15). Istanbul.
44. Ren, N.-Q., Zhao, L., Chen, C., Guo, W.-Q., & Cao, G.-L. (2016). A review on bioconversion of lignocellulosic biomass to H2: Key challenges and new insights. Bioresource Technology, 215, 92-99. doi:10.1016/j.biortech.2016.03.124
45. • • Rollin, J. A., Martin del Campo, J., Myung, S., Sun, F., You, C., Bakovic, A., … Zhang, Y.-H.
46. P. (2015). High-yield hydrogen production from biomass by in vitro metabolic engineering: Mixed sugars coutilization and kinetic modeling. Proceedings of the National Academy of Sciences of the United States of America, 112(16), 4964-4969. doi:10.1073/pnas.1417719112

47. Salkuyeh, Y. K., Saville, B. A., & MacLean, H. L. (2018). Techno-economic analysis and life cycle assessment of hydrogen production from different biomass gasification processes. International Journal of Hydrogen Energy, 43(20), 9514-9528. doi:10.1016/j.ijhydene.2018.04.024
48. Thunman, H., Gustavsson, C., Larsson, A., Gunnarsson, I., & Tengberg, F. (2019). Economic assessment of advanced biofuel production via gasification using cost data from the GoBiGas plant. Energy Science & Engineering, 7(1), 217-229. doi:10.1002/ese3.271
49. Tock, L., & Maréchal, F. (2012). Co-production of hydrogen and electricity from lignocellulosic biomass: Process design and thermo-economic optimization. Energy (Oxford, England), 45(1), 339-349. doi:10.1016/j.energy.2012.01.056
50. Umer, M., Brandoni, C., Jaffar, M., Hewitt, N. J., Dunlop, P., Zhang, K., & Huang, Y. (2024). An experimental investigation of hydrogen production through biomass electrolysis. Processes (Basel, Switzerland), 12(1), 112. doi:10.3390/pr12010112
51. Varanasi, J. L., Veerubhotla, R., Pandit, S., & Das, D. (2019). Biohydrogen production using microbial electrolysis cell: Recent advances and future prospects. Microbial Electrochem. Technol, 843-869.
52. Weiland, F., Hedman, H., Marklund, M., Wiinikka, H., Öhrman, O., & Gebart, R. (2013). Pressurized oxygen blown entrained-flow gasification of wood powder. Energy & Fuels: An American Chemical Society Journal, 27(2), 932-941. doi:10.1021/ef301803s
53. Xie, Z.; Yu, S.; Ma, X.; Li, K.; Ding, L.; Wang, W.; Cullen, D.A.; Meyer, H.M., III; Yu, H.; Tong, J.; et al. (2022). MoS_2 nanosheet integrated electrodes with engineered 1T-2H phases and defects for efficient hydrogen production in practical PEM electrolysis. Appl. Catal. B Environ. , 313, 121458.
54. Xu, X., Thornton, P. E., & Post, W. M. (2013). A global analysis of soil microbial biomass carbon, nitrogen and phosphorus in terrestrial ecosystems: Global soil microbial biomass C, N and P. Global Ecology and Biogeography: A Journal of Macroecology, 22(6), 737-749. doi:10.1111/geb.12029
55. X. Yao, D. Song, T. Qin, C. Yang, Z. Yu, X. Li, ... H. Su, Interaction between G- quadruplex and zinc cationic porphyrin: The role of the axial water. Sci. Rep. 7(1), 10951 (2017). https://doi.org/ 10.1038/s41598-017-11413-8
56. • • R. Zagrodnik, M. Laniecki, The role of pH control on biohydrogen production by single stage hybrid dark- and photo-fermentation. Bioresour. Technol. 194, 187-195 (2015). https://doi.org/ 10.1016/j.biortech.2015.07.028
57. Zhang, S., Gao, N., Quan, C., Wang, F., & Wu, C. (2020). Autothermal CaO looping biomass gasification to increase process energy efficiency and reduce ash sintering. Fuel (London, England), 277(118199), 118199. doi:10.1016/j.fuel.2020.118199