https://doi.org/10.54361/ajmas.258335

Original article

Sustainable Green Hydrogen Generation from Biomass Waste: Technologies and Environmental Impact

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Abstract
This study assesses the potential of sustainable green hydrogen production from biomass waste as a renewable energy source for low-carbon economies. Among the technologies analyzed, gasification, pyrolysis, anaerobic digestion, and dark fermentation—gasification and anaerobic digestion emerge as the most viable, meeting 20–50% of regional hydrogen demand. Life cycle analysis highlights substantial benefits, including reduced greenhouse gas emissions, energy efficiency, and effective waste valorization. However, challenges persist in terms of technological efficiency and economic scalability. The study underscores the critical role of biomass-based hydrogen in sustainable energy systems. It identifies future priorities such as catalyst development for tar reduction and AI-driven supply chain optimization to overcome technical and policy barriers.
Keywords: Green Hydrogen, Biomass Waste, Circular Bioeconomy, Renewable Energy.

Introduction
Green hydrogen, produced via electrolysis powered by renewable energy, is emerging as a cornerstone of the global energy transition. It has the potential to decarbonize diverse sectors such as transportation, industry, and power generation, while enhancing grid stability, supporting Power-to-X frameworks, and converting surplus renewable electricity into clean energy carriers [1,2], Although thermochemical methods currently dominate hydrogen production, water electrolysis using low-carbon energy sources is gaining traction for its ability to significantly reduce greenhouse gas emissions [3]. Economic forecasts suggest that green hydrogen may achieve cost parity with fossil fuels by 2030, solidifying its role as a key driver in decarbonizing energy-intensive industries by 2050 [4]. However, challenges such as high production costs, infrastructure limitations, and regulatory hurdles necessitate technological innovation, infrastructure development, and policy interventions.
Biomass waste presents a sustainable and versatile feedstock for hydrogen production, addressing both energy and waste management challenges [5]. Hydrogen extraction from biomass can be achieved through various conversion technologies, including thermochemical methods such as gasification and pyrolysis, and biological approaches like anaerobic digestion and dark fermentation [6]. While conventional techniques like gasification are efficient for large-scale production, they face challenges such as high energy requirements and potential pollutant emissions. Emerging methods, such as photoelectrocatalytic conversion, offer cleaner alternatives and hold promise for the future [7].
Integrating biomass-derived hydrogen into a circular bioeconomy not only enhances sustainability but also optimizes waste utilization. Recent studies have explored diverse biomass feedstocks, including agricultural residues, algae, and industrial wastewater, for biohydrogen production through biotechnological and thermochemical processes [8]. These advancements contribute to renewable hydrogen development as a clean energy carrier, aiding in climate change mitigation and environmental impact reduction.
Hydrogen production from biomass features a variety of technological approaches, each with distinct efficiency, scalability, and environmental impact profiles [9,10]. Thermochemical methods like gasification and steam reforming are well-established for centralized, large-scale production, while biological techniques offer decentralized solutions but require further refinement [11]. Technologies such as steam biomethane reforming and biomass gasification are already market-ready [10], but significant challenges remain in scaling production, reducing costs, and improving environmental performance [12]. Comprehensive techno-economic and life cycle assessments are critical for identifying the most viable and sustainable pathways for widespread adoption. Continued research and development are essential to enhance the market viability of biomass-to-hydrogen technologies, ensuring their integration into the broader energy sector.
This paper aims to provide a comprehensive review of the current technologies available for producing green hydrogen from biomass waste, encompassing biological, thermochemical, and hybrid processes. Additionally, it assesses the environmental impacts through life cycle analysis to highlight the sustainability potential and challenges. By addressing these aspects, the study seeks to inform future research directions and policy development for advancing biomass-based green hydrogen as a key component of the global clean energy transition.

Methods
The research framework of this study employs a systematic review approach to analyze the technologies, processes, and environmental impacts associated with green hydrogen production from biomass waste. The

Received*: 23-05-2025 -* ***Accepted****: 20-07-2025 -* ***Published****: 26-07-2025*

framework includes a comprehensive literature review, comparative technology analysis, and environmental impact assessments. Relevant literature was identified using databases such as Scopus, Web of Science, and PubMed, focusing on publications from 2010 to 2025. Search terms such as "biomass waste + hydrogen production" and related keywords were used to ensure comprehensive coverage.

Inclusion criteria
Studies specifically focused on hydrogen production from biomass waste through thermochemical, biological, or hybrid methods; Publications from January 2010 to May 2025, ensuring the inclusion of recent advancements and trends. Including Articles written in English to maintain linguistic uniformity. And the Source Type: Peer-reviewed journal articles, conference proceedings, and technical reports from reputable institutions. Content Scope: Studies including practical implementations, technological evaluations, or environmental assessments of biomass-to-hydrogen pathways.

Exclusion Criteria
Studies focused solely on fossil fuel-based hydrogen production or theoretical models without experimental data. Duplicates, preprints, or non-peer-reviewed sources. Articles lacking quantitative data or detailed descriptions of methodologies. Publications predating 2010, unless considered highly cited foundational works.

Data analysis
Data extracted from selected studies were synthesized using both qualitative and quantitative methods. Key variables, including production efficiency, cost metrics, and emissions, were tabulated and visualized using graphs and comparative tables. Emerging trends were identified to provide insights into the future development of biomass-to-hydrogen technologies. Efforts were made to minimize bias, acknowledging the potential overrepresentation of certain regions or technologies.

Scope and Limitations
This review focuses exclusively on green hydrogen production technologies utilizing biomass waste. Exclusions include fossil fuel-derived hydrogen production and purely theoretical studies without practical application data. Limitations include potential variability in reported efficiency metrics across studies, regional differences in biomass availability, and publication bias. Acknowledging these challenges, the study highlights the need for diverse regional studies to ensure a more balanced global perspective.

Results and discussion
Biomass Waste
Types, Characteristics, and Availability: Biomass waste sources include a wide variety of organic materials that originate from agriculture, forestry, industrial activities, and municipal solid waste (MSW). These sources can generally be classified into the following categories:
Agricultural Residues The agricultural sector and agro-processing industries produce significant amounts of biomass waste, which includes crop by-products like rice straw, wheat straw, corn stover, and sugarcane bagasse [13]. These residues are abundant in cellulose and hemicellulose, making them ideal feedstocks for hydrogen production. In farming economies, agricultural residues are a readily accessible resource with considerable energy potential. Forestry Waste Forestry waste, which consists of sawdust, bark, and branches resulting from logging and timber processing, is another important biomass source. Although forestry waste typically has a high lignin content that can complicate biological conversion processes, it is still a vital input for thermochemical methods like gasification and pyrolysis [14]. Industrial Biomass Waste Industries, such as pulp and paper mills, generate energy-rich biomass waste during wood preparation, manufacturing processes, and wastewater treatment [15].
Industrial biomass waste is increasingly acknowledged for its sustainability advantages, such as local availability, lower environmental impacts, and the opportunity to create jobs in the bioenergy sector [16]. Municipal Solid Waste (MSW) The organic component of MSW, which includes food scraps and paper products, represents a valuable biomass source for hydrogen generation. MSW not only helps tackle the growing issues of urban waste management but also serves as a renewable energy resource. The trend of urbanization is increasing the availability of MSW, especially in densely populated urban areas. Classification and Potential Biomass can be divided into virgin biomass (e.g., terrestrial and aquatic plants) and waste biomass, each having unique compositions and energy potentials.
To effectively utilize biomass as a sustainable energy solution, it is crucial to assess its sources of generation, quantities, and geographic distribution. A variety of conversion methods—including mechanical, thermal, and biochemical techniques—allow for the transformation of biomass into biofuels and hydrogen. However, optimizing these processes necessitates addressing challenges such as feedstock variability and regional availability.

***Received**: 23-05-2025 - **Accepted**: 20-07-2025 - **Published**: 26-07-2025*

Table 1: Biomass Waste Types and Their Hydrogen Production Potential

Biomass Type	Key Components	Preferred Conversion Method	Estimated Hydrogen Yield
Agricultural Residues	Cellulose, Hemicellulose	Gasification, Fermentation	50 million tons/year (global) [25]
Forestry Waste	Lignin, Cellulose	Pyrolysis, Gasification	20% of global forestry waste [26]
Industrial Waste	High organic content	Anaerobic Digestion	Varies significantly by industry
MSW	Food scraps, Paper	Gasification, Fermentation	138,000 tons/year (Mexico)

Chemical Composition Relevant to Hydrogen Production

The chemical composition of biomass waste plays a vital role in determining its appropriateness and efficiency for hydrogen production. Significant components that influence conversion processes include Cellulose and Hemicellulose. These polysaccharides constitute the primary carbohydrate component of biomass and can be broken down into fermentable sugars either enzymatically or chemically, which are crucial for biological hydrogen production techniques such as dark fermentation. They can also be converted into synthesis gas (syngas) via gasification or pyrolysis, acting as intermediates for hydrogen production [17]. Lignin: This intricate aromatic polymer is resistant to biological decomposition and possesses a high calorific value. It is effectively utilized as fuel in thermochemical conversion processes, particularly gasification, thereby enhancing the overall hydrogen yield.

The moisture level greatly influences process choice and efficiency. Elevated moisture content can hinder thermal processes by increasing the energy needed for drying, but it benefits biological methods like anaerobic digestion by creating a favorable aqueous environment for microbial activity. This makes anaerobic digestion particularly advantageous in areas with high-moisture organic waste, such as developing nations [18].

The inorganic residue known as ash affects reactor performance and system efficiency. Significant ash content can lead to fouling, slagging, and corrosion in thermochemical reactors, often requiring pretreatment or mixing with low-ash biomass to ensure stable operation. Moreover, the hydrogen yield from biomass is closely linked to carbohydrate content, whereas proteins and lipids have a minimal impact on hydrogen generation [19]. Hydrothermal gasification of biomass waste shows potential for improved hydrogen production, with catalysts enhancing yields and minimizing unwanted char buildup [20]. In air-steam gasification, the content of volatile matter critically influences gas distribution and conversion efficiency; a higher volatile content boosts gas conversion rates. Hence, a thorough understanding of the chemical composition of biomass waste is crucial for optimizing hydrogen production methods and evaluating their potential effectiveness across different conversion technologies.

Current Generation and Management Practices

Waste management practices for biomass show notable differences between developed and developing countries. Developed nations typically utilize sustainable and effective approaches such as composting, anaerobic digestion, and waste-to-energy incineration. These methods help reduce environmental pollution while also recovering energy and recycling nutrients from organic waste, thus supporting the goals of a circular economy [21,22]. In contrast, developing countries often resort to less efficient and environmentally damaging techniques like open burning and landfilling. These practices significantly contribute to air pollution, greenhouse gas emissions, and health hazards [23]. With organic materials making up a substantial portion of waste—often between 50% and 87%, mainly from food scraps—biological treatment technologies such as anaerobic digestion are particularly advantageous in these areas. Anaerobic digestion not only produces biogas but also minimizes waste volume and its environmental impact, providing a practical solution that considers waste characteristics and infrastructure challenges in these regions [24].

Incorporating biomass waste into hydrogen production processes offers a promising strategy with dual benefits. Techniques like anaerobic digestion, dark fermentation, and photo fermentation can convert various biowastes into biohydrogen and other renewable energy forms. This strategy addresses the urgent need for sustainable waste management while also generating clean energy, furthering environmental and economic sustainability objectives. By utilizing biomass waste for hydrogen production, these methods support global initiatives aimed at decarbonization and the development of a circular bioeconomy.

***Received**: 23-05-2025 - **Accepted**: 20-07-2025 - **Published**: 26-07-2025*

Potential Volumes for Hydrogen Production

The potential for hydrogen production from various biomass sources has been extensively researched, revealing considerable renewable energy capacity in agricultural residues, forestry waste, and municipal solid waste (MSW). Studies also underscore the capability of biomass waste to sustainably meet local and national hydrogen needs. Agricultural Residues: Abundant agricultural residues, such as rice straw, wheat straw, corn stover, and sugarcane bagasse, present highly promising feedstocks for hydrogen generation. Global projections indicate that rice straw alone could produce over 50 million tons of hydrogen per year, provided that efficient conversion technologies like gasification or dark fermentation are utilized [25]. These residues are particularly widespread in agrarian economies, where their use can greatly enhance energy security while alleviating waste management issues.

Forestry Waste: By-products from forestry, such as sawdust, bark, and branches, yield significant biomass potential. Approximately 20% of global forestry waste could be redirected sustainably towards hydrogen production without jeopardizing other industrial applications like bioenergy or pulp manufacturing [26]. Efficient use of these by-products not only facilitates renewable hydrogen generation but also promotes forest sustainability and mitigates reliance on fossil fuels.

Municipal Solid Waste (MSW): The rise in urbanization has increased the organic component of MSW, particularly food waste and paper. This growing feedstock is especially significant in densely populated urban areas where waste management poses considerable challenges. Research estimates that MSW in Mexico has the potential to generate 1.38×10^5 tons of hydrogen each year, enough to satisfy 20% of the fuel cell vehicle demand in Mexico City [28]. Similarly, landfills in California are expected to produce between 300 and 430 Gg of hydrogen annually by 2025, which could power 1.3 to 1.9 million fuel cell vehicles [27].

Green Hydrogen Pathways and Global Perspectives: Despite the current dominance of fossil fuels in hydrogen production—natural gas steam reforming constitutes 50% of global output—renewable methods are gaining popularity. Promising technologies encompass electrolysis, thermal and thermochemical water splitting, fermentation, and catalytic decomposition of methanol. In the U.S., domestic resources are projected to fulfill an additional 10 million metric tonnes of hydrogen demand by 2040 without causing considerable pressure on existing resources [28]. Integrating biomass waste into hydrogen production systems presents a significant opportunity for addressing both energy and waste management issues. This approach aligns with sustainability objectives and supports the circular economy by transforming waste into valuable energy carriers. With ongoing advancements in conversion technologies, biomass represents a feasible pathway to scalable green hydrogen generation.

Implications and Challenges

The use of biomass as a feedstock for hydrogen production holds significant promise due to its renewable nature and widespread availability. However, several challenges must be addressed to realize its full potential. These include:

Feedstock Variability

Biomass waste composition and availability vary significantly based on region, season, and source, posing challenges for biofuel production and biorefinery operations. This variability arises from factors such as biomass type, growth conditions, and harvesting practices. Key attributes impacted include ash content, carbohydrate composition, lignin content, moisture levels, and particle morphology [29].

Ash Content: Ash levels can differ significantly, with woody biomass containing up to ten times less ash compared to herbaceous feedstocks [29]. Lignin Content: Lignin concentrations can vary by up to 50%, which impacts biological conversion processes like fermentation [30]. Moisture Content: High moisture levels in certain feedstocks hinder thermal processes such as pyrolysis and direct combustion [31]. This variability directly affects the efficiency and yield of conversion processes, including fermentation, hydrothermal liquefaction, and pyrolysis [31]. For example, inconsistencies in feedstock characteristics can significantly reduce efficiency and output in biofuel production. Addressing these challenges is crucial for the emerging biorefinery industry, as feedstock variability impacts the entire value chain, from preprocessing to conversion [32]. Future research should focus on developing strategies to mitigate these effects, thereby enhancing the reliability and efficiency of fuel and chemical production.

Logistics and Collection Costs

The dispersed nature of biomass waste sources poses significant challenges for transportation and collection, especially in rural and remote areas. This logistics directly impacts the economic feasibility of bioenergy projects. Transportation costs follow an S-curve relationship, with rapid escalation beyond 90 km. Optimizing the distribution of collection points is crucial to controlling costs. For example, suggested thresholds include 22 km for first-level and 63 km for second-level collection locations [33]. Simulation and linear programming models can further optimize biomass flow and equipment selection, reduce logistic costs while adhering to operational constraints [34]. The mobility of conversion facilities also plays a role in cost efficiency. Modular systems that relocate every 1–2 years have demonstrated potential viability under

Received*: 23-05-2025 -* ***Accepted****: 20-07-2025 -* ***Published****: 26-07-2025*

specific conditions. Additionally, factors such as economies of scale, biomass availability, and energy costs significantly influence supply chain expenses [35]. Overall, optimizing logistics is essential for the economic success of bioenergy projects, as logistics costs often exceed the delivered value of the biomass resource [36].

Technologies for Green Hydrogen Generation from Biomass Waste
Biomass and organic waste present promising opportunities for green hydrogen production through various technologies. These technologies can be broadly categorized into biological, thermochemical, and emerging hybrid methods, each with specific advantages and challenges.

Biological Methods
Biological processes leverage microorganisms to produce hydrogen under mild conditions: Anaerobic Digestion and Dark Fermentation: Microbial breakdown of organic matter produces hydrogen but suffers from lower yields and longer processing times [37]. Microbial Electrolysis Cells (MECs): These use electrical stimulation to enhance hydrogen production, representing an emerging but still developing technology.

Thermochemical Methods
Thermochemical processes convert biomass at high temperatures to release hydrogen: Gasification (including steam gasification): This method effectively converts both moist and dry biomass, including biomass briquettes, into hydrogen-rich syngas. Advances in gasifier design, gas cleanup, and hydrogen separation have improved efficiency and reduced costs [38,39]. Pyrolysis: Thermal decomposition in the absence of oxygen produces bio-oil and syngas, which can be further processed to extract hydrogen. Catalytic Gasification: Utilizes catalysts to reduce tar formation and increase hydrogen yield, offering enhanced performance over traditional gasification [40].

Emerging and Hybrid Technologies
Catalytic Reforming: Enhances hydrogen production by facilitating more efficient biomass conversion reactions. Plasma Gasification: Uses plasma to break down biomass at extremely high temperatures, resulting in cleaner syngas and hydrogen, but currently with high energy input requirements.

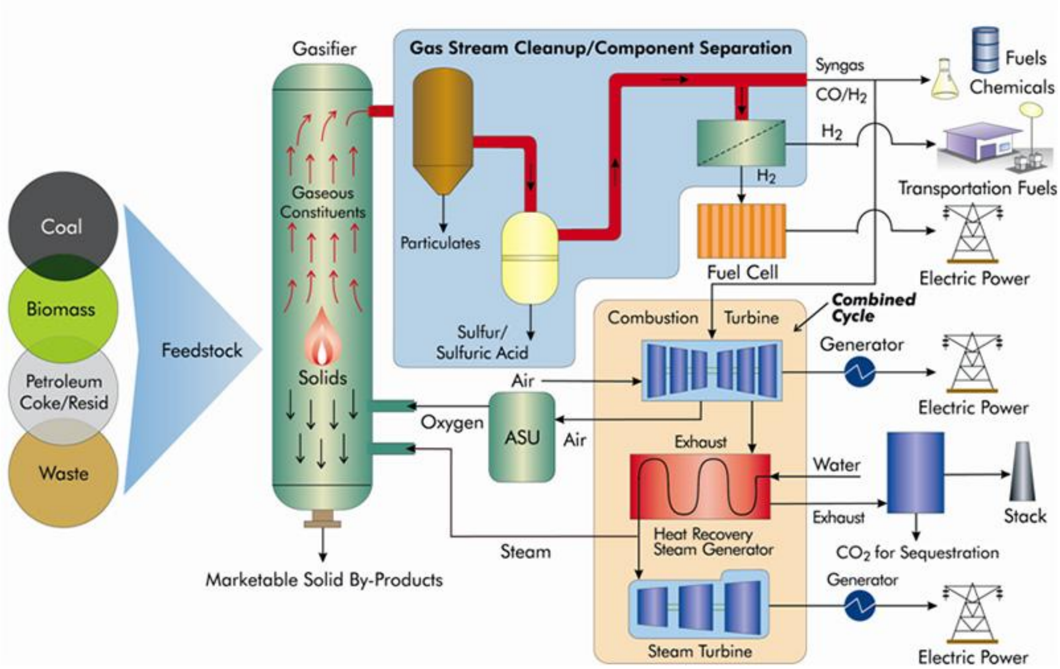

Figure 1. Flowchart for gasification

Conversion Technologies: Advantages and Challenges
Efficient biomass-to-hydrogen conversion depends on advanced technologies with distinct profiles:

Thermochemical Methods
Gasification and steam reforming are mature technologies with high hydrogen output and flexibility for processing different biomass types. However, they face challenges such as tar formation, reactor fouling, and significant energy consumption [41,42].

Biological Methods
Anaerobic digestion and dark fermentation operate under milder conditions and lower energy inputs but

***Received**: 23-05-2025 - **Accepted**: 20-07-2025 - **Published**: 26-07-2025*

have longer process times and typically lower hydrogen yields [43]. Research focuses on improving feedstock pretreatment and microbial efficiency.

Electrochemical Methods

These emerging technologies, including microbial electrolysis cells, hold promise for sustainable hydrogen production but require further development for scalability.

Table 2: Comparison of Hydrogen Production Technologies

Technology	Advantages	Challenges	Hydrogen Yield	Scalability	TRL (Technology Readiness Level)
Gasification	High efficiency, scalable	Tar formation, high energy input	~10–15 kg H_2/ton	High	8–9
Pyrolysis	Produces biochar as a byproduct	Requires feedstock drying	~8–12 kg H_2/ton	Moderate	6–7
Anaerobic Digestion	Low-temperature process	Slow, low hydrogen yield	~1–3 kg H_2/ton	High	7
Dark Fermentation	Utilizes wet biomass	Needs pretreatment	~2–4 kg H_2/ton	Moderate	5–6

Economic Viability

The economic feasibility of biomass-to-hydrogen production depends on its ability to compete with conventional methods such as steam methane reforming (SMR) and electrolysis. Financial incentives, subsidies, or carbon pricing mechanisms may be required to ensure cost-competitiveness.

1. *Cost Competitiveness*

Economic assessments indicate that biomass gasification can produce hydrogen at costs ranging from $3.71 to $4.27 per kilogram, comparable to solar-powered electrolysis [40]. However, these costs remain higher than those of large-scale SMR, which currently dominates the hydrogen market [44].

1. *2. Technological Variability*

Thermochemical Processes: Technologies like gasification are mature and suitable for large-scale hydrogen production. Steam gasification is versatile, processing both wet and dry biomass effectively [45].
Biological Methods: These are more appropriate for decentralized applications but require further optimization to achieve cost-competitiveness [46].

2. *3. Environmental Benefits*

Biomass-to-hydrogen pathways offer significant environmental advantages. Combining biomass conversion with in-situ electricity generation and carbon capture can result in negative emissions, further enhancing the appeal of these technologies.

3. *4. Financial Incentives and Policy Support*

To level the playing field with conventional hydrogen production methods, financial measures such as subsidies, carbon pricing, or renewable energy credits are essential. These can offset higher initial costs and drive broader adoption of biomass-to-hydrogen technologies.

Policy and Regulatory Support

Supportive policy frameworks are essential for promoting biomass-based hydrogen production and its adoption as a key component of sustainable energy systems. Policies should focus on funding research, supporting pilot projects, providing tax incentives, and incorporating hydrogen into national energy strategies.
Importance of Strategic Policy Frameworks**:** Strategic initiatives are required to optimize hydrogen production from renewable sources and develop efficient storage solutions [47]. Policies must address the unique challenges faced by renewable hydrogen, including cost, capacity, and technical barriers. Insights from Key Studies Oluwadayomi et al., 2024: Emphasize the need for enhanced cross-border coordination, capacity-based incentives, and infrastructure development to overcome existing challenges. Policy frameworks should prioritize renewable hydrogen for integration into sustainable energy systems.
Bleischwitz & Bader, 2008: Notes that while EU energy policies have significant potential, they are underutilized. The current framework does not obstruct hydrogen development but lacks the robust push factors necessary for rapid advancement. Graczyk et al., 2025: Highlights recent EU efforts to create cohesive regulatory and market frameworks. Initiatives such as the European Hydrogen Bank aim to support renewable hydrogen adoption in hard-to-abate sectors through market-based mechanisms, direct mandates, and targeted funding.
Recommendations for Policy Development: To accelerate the adoption of biomass-based hydrogen, policy recommendations include: Enhanced cross-border coordination for shared infrastructure development.

Received*: 23-05-2025 -* ***Accepted****: 20-07-2025 -* ***Published****: 26-07-2025*

Implementation of capacity-based incentives to address economic and technical barriers. Increased funding for pilot projects and technology innovation. Development of a cohesive regulatory framework to support hydrogen integration into hard-to-abate sectors [48]. Carbon pricing thresholds to achieve cost parity with SMR: For example, a carbon price of approximately $100 per ton CO_2 could bridge the estimated cost gap of about $2.77 per kg of hydrogen produced by biomass-based methods compared to Steam Methane Reforming (SMR) [63, 64].

Current Challenges and Outlook

Despite ongoing efforts, challenges such as high costs, technical limitations, and infrastructure gaps persist. Addressing these issues through supportive policies will be critical for scaling up hydrogen production and achieving broader energy transition goals [49].

Environmental Considerations

Biomass is a renewable resource with significant potential for sustainable energy production. However, its large-scale production and utilization can have substantial environmental impacts if not managed responsibly.

1. Biodiversity and Ecosystem Health: While biomass crops can enhance biodiversity at the field scale, extensive commercial production may negatively affect areas of high conservation value. Unsustainable harvesting can lead to biodiversity loss, ecosystem degradation, and soil and water resource depletion [50].
2. Land and Resource Use Biomass production often competes with other land uses, potentially leading to: Arable Land Competition: Reduced availability for food crops and increased pressure on natural habitats [51]. Soil Disturbance: Loss of soil fertility due to nutrient depletion and erosion. Water Quality Impairment: Increased sedimentation and nutrient runoff are impacting aquatic ecosystems [52,53].
3. Strategies for Sustainability: Sustainable sourcing practices are essential to mitigate these risks. Key strategies include: Implementing sustainable forest management practices and certification schemes. Using effective planning tools to integrate biodiversity considerations into landscape-scale biomass production. Prioritizing the production of biomass on marginal lands or using agricultural residues to avoid competition with food crops.

Environmental Impact Assessment

Environmental impacts of waste-to-energy (WTE) technologies are critical to assess, especially in the context of biomass and organic waste utilization. Life Cycle Assessment (LCA) provides a comprehensive framework for evaluating these impacts across the entire lifecycle of WTE technologies.

Overview of Life Cycle Assessment (LCA) Methodology

LCA is a robust tool for identifying major environmental burdens, determining energy return on investment (EROI), and comparing the environmental impacts of various products and technologies [54]. It evaluates resource use, emissions, and waste generation throughout the lifecycle, from feedstock harvesting to final energy production [55].

Greenhouse Gas Emissions and Energy Balance

WTE technologies generally reduce greenhouse gas (GHG) emissions compared to conventional waste management methods, such as landfilling or incineration [56]. Anaerobic digestion and pyrolysis-gasification systems are particularly effective, showing lower climate change impacts and better energy balances. However, the choice of methodology and quality of input data can significantly influence LCA outcomes, requiring careful interpretation of results [57].

Feedstock Harvesting and Logistics

The environmental impacts of feedstock harvesting and logistics, including transportation and preprocessing, are significant. Sustainable sourcing and efficient logistics planning are crucial to minimizing emissions and energy losses. Proper planning can also mitigate biodiversity loss and habitat disruption.

Waste-to-Energy Benefits and Trade-Offs

WTE technologies, when implemented with sustainable practices, offer dual benefits:

Energy Generation: Transforming waste into renewable energy reduces dependency on fossil fuels.

Waste Management: Diverts waste from landfills, reducing methane emissions and land use.

Despite these benefits, potential trade-offs include emissions from feedstock transportation and the generation of secondary pollutants, which must be carefully managed [57].

Comparative Environmental Impacts of WTE Technologies

A comparison of common WTE technologies reveals significant differences in their environmental footprints:

***Received**: 23-05-2025 - **Accepted**: 20-07-2025 - **Published**: 26-07-2025*

Landfills and Incineration: High GHG emissions and substantial contributions to climate change [54]. Anaerobic Digestion and Pyrolysis-Gasification: Lower impacts on respiratory inorganics and acidification, making them more environmentally favorable.

Table 3: Comparative table summarizing the environmental impacts of common Waste-to-Energy (WTE) technologies, focusing on CO_2-equivalent emissions and energy return on investment (ROI), based on reputable sources

WTE Technology	CO_2-equivalent Emissions (kg CO_2eq/MWh)	Energy Return on Investment (Energy ROI)	Other Environmental Impacts	References
Landfills	500 - 1200 (high due to methane emissions)	Low (<1)	High methane emissions, groundwater contamination risk	IPCC, 2019 [58] EPA, 2021 [59]
Incineration	~350 - 600	Moderate (1.5 - 2.5)	High NOx, particulate matter emissions	UNEP, 2019 [60] IEA, 2020 [61]
Anaerobic Digestion (AD)	~50 - 150	High (3 - 5)	Low acidification, reduced respiratory inorganics	European Commission, 2016 [62]
Pyrolysis-Gasification	~100 - 200	High (3 - 6)	Low acidification, low particulate emissions	

Summary of Recent Pilot and Commercial Projects

Green hydrogen production projects using renewable energy sources, such as water electrolysis, are gaining momentum worldwide:

Pilot Projects: Numerous initiatives focus on alkaline and proton exchange membrane (PEM) electrolyzers powered by solar and wind energy, demonstrating scalability and system efficiency improvements. For example, Project Alpha achieved 12 kg H_2/ton production at $3.80/kg cost in a controlled pilot setup [63].

Commercial Deployment: Large-scale implementations, such as the hydrogen production facility in Fukushima, Japan, integrate renewable energy with electrolysis technologies to produce hydrogen for industrial and transport sectors. This facility is projected to generate 900 tons of hydrogen annually, with an energy efficiency of over 70% [64].

Innovations in Process Optimization and Hydrogen Yield Improvements

Recent advancements in technology and design have enhanced the efficiency and economic viability of green hydrogen production:

Electrolyzer Design: Innovations in materials and engineering have improved the efficiency and durability of electrolyzers, significantly reducing energy requirements [65].

Photocatalyst Development: Lab-scale research on solar water splitting focuses on stable and efficient photocatalysts, with efforts to scale these technologies for commercial application. The Beta Photocatalyst Project achieved a 15% increase in hydrogen yield over traditional methods [66].Energy Optimization: Techniques to manage variable renewable energy inputs, such as dynamic operational strategies and advanced control systems, are reducing system inefficiencies.

Integration with Other Renewable Energy

The integration of green hydrogen production with renewable energy systems offers a pathway to more resilient and sustainable energy systems:

Intermittency Challenges: Addressing the variable nature of solar and wind energy requires innovations in energy storage and hybrid system design. Hydrogen Storage and Fuel Cells: Combining electrolysis with hydrogen storage systems and fuel cells helps stabilize grids and provides backup power during peak demand. Case studies like the Gamma Project highlight a 20% reduction in grid instability due to hydrogen-based storage solutions. Photovoltaic-Electrolyzer Systems: Direct integration of solar photovoltaic systems with water electrolyzers has shown promise for maximizing efficiency and reducing infrastructure costs. The Delta System in California reduced production costs by 10% through this integration [66].

Path Forward

To overcome the existing challenges in biomass-based hydrogen production, a multifaceted approach combining policy, technology, and market-based solutions is essential. Key strategies include:

Advancing Technologies: Investment in research and development (R&D) is crucial to enhance the efficiency, reliability, and scalability of conversion technologies such as gasification, pyrolysis, and fermentation. Particular emphasis should be placed on catalyst development to reduce tar formation during gasification, which currently limits operational efficiency and increases maintenance costs. Infrastructure Development: Building robust logistics and distribution networks is necessary to reduce costs related to feedstock

Received: 23-05-2025 - **Accepted**: 20-07-2025 - **Published**: 26-07-2025

collection, preprocessing, and transportation. Future efforts should incorporate AI-driven supply chain models to optimize logistics, minimize carbon footprints, and improve the overall sustainability of biomass supply chains. Financial Mechanisms: Economic incentives such as subsidies, carbon credits, or feed-in tariffs must be implemented to make biomass-to-hydrogen pathways financially competitive against fossil-based hydrogen production. These mechanisms can lower investment risks and attract private sector participation.
Sustainability Standards: Developing and enforcing certification systems and sustainability standards will ensure responsible sourcing of biomass feedstocks, mitigating adverse effects on biodiversity, soil quality, and water resources.
Awareness and Education: Raising awareness among policymakers, industry stakeholders, and the public about the benefits and technical feasibility of biomass-based hydrogen production is vital to fostering acceptance and encouraging collaborative efforts [71]. By addressing these challenges and leveraging the renewable, abundant nature of biomass, this energy vector could play a pivotal role in accelerating the global transition toward a sustainable hydrogen economy.

Future Research Priorities
Catalyst Development for Gasification: Research focused on novel catalysts that minimize tar formation during biomass gasification can significantly enhance system efficiency and reduce operational downtime, improving the economic viability of the technology.
Logistics Optimization via AI-Driven Supply Chain Models: Implementing artificial intelligence and machine learning algorithms to optimize feedstock collection, preprocessing, and distribution can reduce costs and environmental impacts, thereby improving the overall sustainability of biomass-to-hydrogen value chains.

Limitations
This review excludes fossil-based hydrogen production pathways, such as grey hydrogen from steam methane reforming (SMR), thereby limiting direct techno-economic and environmental comparisons between biomass-based green hydrogen and conventional fossil-derived hydrogen options. Future comprehensive assessments incorporating these pathways are recommended for a holistic evaluation.

Conclusion
This study confirms that biomass waste is a scalable and regionally adaptable feedstock for green hydrogen production. To unlock its full potential, the following priorities must be addressed: Advancing Technology: Enhance conversion efficiencies through innovative processes and novel materials, such as advanced catalysts and integrated hybrid systems. Policy and Incentives: Establish robust policy frameworks to lower production costs, support targeted research and pilot projects, and promote widespread adoption of biomass-based hydrogen technologies. Sustainability Practices: Mitigate ecological risks through responsible resource management and implementation of sustainability certification systems to preserve biodiversity and ecosystem health. Future research efforts should emphasize optimizing supply chain logistics, advancing catalyst technologies, and conducting pilot-scale demonstrations to bridge the gap between laboratory research and commercial viability. Governments: Support pilot programs, enforce sustainability regulations, and incentivize investments to ensure environmentally responsible and economically viable biomass hydrogen production. Industries: Focus on scaling up investments in technologies such as gasification and anaerobic digestion for efficient waste valorization and hydrogen production. Researchers: Investigate hybrid approaches—for example, integrating solar energy with biomass conversion systems—to achieve significant improvements in overall energy efficiency and system resilience.

Conflict of interest. Nil

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Received*: 23-05-2025 -* ***Accepted****: 20-07-2025 -* ***Published****: 26-07-2025*