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Techno-economic and life-cycle assessments of biomass thermochemical conversion into gaseous fuels

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Abstract

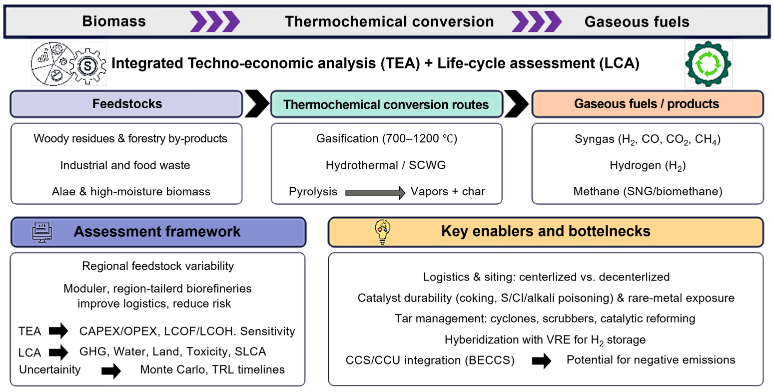
This review provides a comprehensive analysis of techno-economic and life-cycle assessments (TEA and LCA) for biomass thermochemical conversion processes that yield gaseous fuels such as syngas, hydrogen, and methane. The study analyzes core issues, including the influence of feedstock diversity, technological maturity, major cost factors, carbon reduction potential, and environmental outcomes of thermochemical conversion approaches. Research was systematically gathered with an emphasis on works that integrate TEA and LCA for comparative evaluation. An analysis of the production processes shows that both the characteristics of biomass feedstocks and local supply chain logistics critically affect process efficiency and cost-effectiveness. Persistent challenges include catalyst degradation and the integration of carbon capture and storage, which significantly impact technical feasibility and costs. LCA demonstrates that, when paired with effective carbon capture, several conversion pathways can result in net negative greenhouse gas emissions, although modeling and data uncertainties remain. The review highlights the promise of modular, locally adapted biorefineries underpinned by strong policy support, calling for methodological standardization and technological innovation to drive progress toward decarbonized fuel production.

Keywords: Biomass, Thermochemical conversion, Techno-economic analysis, Life-cycle analysis, Gaseous fuels

Highlights

- Bridges TEA and LCA to map biomass-to-gas climate and cost trade-offs.
- Shows biomass hydrogen and methane can outgreen fossil fuels with smart design.
- Links carbon pricing and tech readiness levels to real project bankability.
- Surfaces social, regional and food–fuel tensions in scaling gaseous biofuels.

Graphical abstract



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Introduction

Energy production and consumption play a crucial role in the world's scientific, economic, and social environment that humanity has constructed throughout time[1]. The contemporary economy is primarily propelled by energy, with a worldwide energy demand of roughly 13,973 million tons of oil equivalent (Mtoe). By 2019, 85% of global energy demand was met by fossil fuels[2]. In recent decades, the growing demand for fossil fuels, urbanization, and modernization have led to a significant increase in the emissions of greenhouse gases (GHG). The atmospheric carbon dioxide (CO_2) concentration increased from approximately 280 ppm before the Industrial Revolution to approximately 418.9 ppm in 2023[3]. The atmospheric CO_2 concentration is projected to reach around 570 ppm by the end of this century[4].

Consequently, there has been an estimated rise in the global mean temperature of 0.85 °C since the 18th Century[5]. In an effort to ameliorate the potentially disastrous effects of global warming, the Intergovernmental Panel on Climate Change (IPCC) has recommended limiting temperature increases to 2 °C, with a preferable target of 1.5 °C by the end of the current century[6]. The task of reducing CO_2 emissions is a challenging and enduring endeavour. As recommended in the fifth edition of the IPCC, a comprehensive transformation of worldwide energy supply systems, lifestyles, and dietary requirements is necessary. The depletion of fossil fuels is also a serious concern[7]. It is imperative to persist in commercializing low-carbon and carbon-neutral resources for chemicals, energy, materials, and technologies to facilitate the adoption of low-carbon pathways. The 2016 Paris Agreement underscores the need for a phased reduction in fossil fuel dependency, targeting a 50% reduction in CO_2 emissions through the increased integration of renewable energy sources[8]. Biomass has emerged as a promising feedstock in this transition due to its carbon neutrality. It has been reported that 80%–90% GHG emissions can be reduced by replacing fossil fuels with biomass[9]. The shift from a carbon economy of fossil fuel-dependent to a bio-based fuel is anticipated to undergo a gradual and ongoing transformation in the next few decades, with a consequential impact on all processing industries[10].

In the future, a bio-based alternative is expected to supplant the petrochemical product tree. The transition in raw materials should be perceived as an opportunity to restructure the industrial chain by utilizing renewable raw feedstocks to create novel products rather than as a potential hazard[10]. The utilization of bio-based carbon in biomass processes is characterized by its sustainability and renewability, resulting in a near carbon-neutral outcome. The implementation of suitable residue management strategies can result in a carbon-negative process. The emergence of bio-based fuels can be attributed to the availability of resources, advances in science and technology, and favourable policies.

Unlike other renewable energy sources such as wind, solar, geothermal, or hydropower, biomass is unique in its capacity to store carbon-based chemical energy. It serves as a readily available resource for biofuel production, aligning with global policy efforts to decarbonize the transportation sector. Initially, biofuel policies focused on first-generation biofuels derived from food crops such as corn, sugarcane, and canola. However, concerns over indirect land-use change (iLUC), GHG emissions, and food security have prompted a shift toward second- and third-generation biofuels, derived from non-food biomass sources such as agricultural residues, algae, and woody biomass[11]. Advanced synthetic biofuels offer the advantage of higher energy yields while preventing negative ecological and socio-economic side-effects such as high GHG emissions through indirect land-use change (iLUC)[11], or the competition manifested in the food-vs-fuel debate.

Recent policy frameworks, such as the European Union's Renewable Energy Directive (2018/2001), impose strict limitations on biofuels with a high iLUC risk[12]. Similarly, the ReFuelEU Aviation initiative, as part of the EU Fit for 55 Package, promotes second- and third-generation biofuels as sustainable alternatives for decarbonizing the aviation sector[13]. Globally, governments are implementing policies to accelerate the adoption of advanced biofuels. The U.S. Renewable Fuel Standard (RFS) mandates annual volume targets for four fuel categories: (a) cellulosic biofuel, (b) biomass-based diesel, (c) advanced biofuel, and (d) renewable fuel[14]. China has also implemented and supported renewable energy production, such as solar, wind, and biomass, including gasification, liquefaction, and direct combustion[15]. In 2023, the global power production was sourced 26% from coal, 32% from petroleum, 23% from natural gas, and 14% from renewables[16]. These data underscore the urgent need to scale up bio-based energy solutions to achieve a sustainable energy transition.

As the global energy landscape evolves, the demand for renewable and low-carbon fuels is projected to rise substantially. With continuous advancements in technology and policy frameworks, second-generation biofuels are gaining momentum as a promising pathway toward sustainable and environmentally friendly energy solutions. However, accurately assessing their feasibility and advantages over conventional fossil fuels requires scientifically rigorous and data-driven methodologies[17]. Life-cycle assessment (LCA) and techno-economic analysis (TEA) play a crucial role in evaluating novel biofuel technologies by systematically analyzing their socioeconomic, environmental, and technical feasibility[18]. LCA focuses on quantifying environmental aspects such as GHG emissions, energy consumption, and resource utilization, while TEA assesses economic viability by estimating production costs, investment requirements, and market competitiveness.

A key focus of these assessments lies in the production phase, where LCA and TEA aid in optimizing design parameters and estimating the market price of value-added biofuel products. Before large-scale investment in emerging biofuel technologies, funding agencies and policymakers require a thorough evaluation of both environmental performance and economic feasibility. This is particularly critical for thermochemical conversion processes, which must demonstrate commercial viability before widespread adoption. When conducting LCA for biomass thermochemical conversion processes, explicitly addressing uncertainties is critical for ensuring robust and reliable results[19]. Three primary types of uncertainty commonly considered are parameter uncertainty, model uncertainty, and scenario uncertainty. Integrating systematic uncertainty and sensitivity analysis through methods like Monte Carlo simulations provides transparency and enhances the credibility and applicability of LCA findings. This approach supports informed decision-making by clearly communicating the potential variability and limitations inherent in LCA studies[20].

Biomass, as a renewable feedstock, is broadly categorized into lignocellulosic sources such as wood, straw, and grass, and non-lignocellulosic sources like sludge, algae, and oil[21]. Compared to coal, as listed in Table 1, biomass typically has higher moisture content, increased volatile matter, elevated oxygen content calculated by the difference from ultimate analysis results, and lower carbon content, all of which influence the choice of conversion pathways[22−26]. Several methods transform biomass into fuels or chemicals, including thermochemical pathways[27] (i.e., combustion, pyrolysis, gasification, and hydrothermal treatment) and

Table 1 Proximate and ultimate analysis of various types of biomass[22–26]

Biomass	Proximate analysis (%, as received basis)			Ultimate analysis (%, dry ash-free basis)				
	Ash	Moisture	Organic fraction	C	H	N	S	O
Wood	1.8	19.8	78.4	50.8	6.1	0.3	0.1	42.7
Legume straw	9.8	1.6	73.7	43.3	5.6	0.6	0.1	50.4
Apricot stone	8.5	0.2	75.1	44.4	5.7	0.4	0.0	49.5
Hornbeam shell	9.5	2.3	78.8	41.8	5.4	0.60	0.0	52.3
Hornbeam sawdust	0.5	8.8	78.1	45.2	6.6	0.0	0.0	48.2
Rice husk	12.9	1.1	70.5	42.0	5.4	0.4	0.0	39.3
Straw	6.4	12.7	80.9	48.9	5.9	0.8	0.2	43.9
Safflower	2.2	5.7	80.8	60.5	9.8	3.1	0.0	27.4
Sludge	25.7	32.5	41.8	50.2	7.1	5.6	1.8	34.9
Manure	17.2	43.6	39.2	50.2	6.5	6.5	0.9	34.6
Vegetable oils	0.0	0.0	100.0	75.4	11.7	0.0	12.9	0.0

biochemical pathways (i.e., anaerobic digestion and fermentation)[28]. Thermochemical conversion processes operate at higher temperatures, allowing for shorter reaction times and nearly complete degradation of biomass components[28]. Some of these processes require catalysts, particularly in tar cracking and reforming, to improve efficiency. The primary products of thermochemical conversion include gaseous fuels such as syngas from gasification and hydrothermal gasification, and liquid biofuels such as bio-oil from pyrolysis and hydrothermal liquefaction, both of which require upgrading to meet fuel standards.

Biochemical conversion, including anaerobic digestion and fermentation, primarily produces liquid biofuels and biogas, which can also undergo refinement to obtain high-value biofuels. While both thermochemical and biochemical conversion technologies share similarities with traditional oil refinery processes, further research and development of H_2-rich processes, such as water gas shift (WGS) reaction, are necessary to improve their economic competitiveness against fossil fuels[29]. As biofuels are increasingly recognized as viable alternatives to fossil-based energy[30], optimizing their production processes and enhancing their commercial feasibility will be critical to accelerating their adoption. The thermochemical conversion pathways involved in biomass-to-biofuel transformation are illustrated in Fig. 1.

The performance and economics of biomass thermochemical conversion are strongly influenced by the inherent variability of feedstocks, especially in tropical and arid regions. Biomass sourced from tropical climates such as sugarcane bagasse, oil palm residues, and fast-growing grasses typically exhibits very high moisture content, often exceeding 50% by weight, as well as significant variability in ash content and mineral composition[21]. High moisture content imposes substantial additional energy demands for drying prior to gasification or pyrolysis, directly increasing operating costs and reducing net system efficiency. In many cases, the parasitic load for drying tropical biomass can represent 15%–30% of total process energy, potentially undermining the overall energy balance if waste heat or low-grade renewable energy is not available[21]. Regional feedstock characteristics thus have direct techno-economic implications, affecting energy yield, process design, capital expenditure (e.g., for robust handling and cleaning equipment), and supply chain configuration. Integrating robust LCA and TEA frameworks with local feedstock assessment is essential for accurately predicting system performance and economic feasibility in both tropical and arid environments.

TEA is a widely used methodology for assessing the financial viability of emerging technologies, while LCA evaluates their environmental impact. These evaluations are typically conducted using specialized software (e.g., Aspen, OpenLCA, and SimaPro) that simulates the environmental consequences of a process based on key input parameters, including process variables, energy consumption, and material flows. While numerous studies have focused on the production of liquid biofuels, fewer have examined the socioeconomic and environmental implications of biomass thermochemical conversion into gaseous biofuels.

This review specifically investigates the thermochemical conversion of various biomass feedstocks into gaseous biofuels, namely: (a) bio-based hydrogen, (b) bio-based methane, and (c) bio-based syngas. It provides a comprehensive analysis of the technical and economic feasibility of these processes alongside their

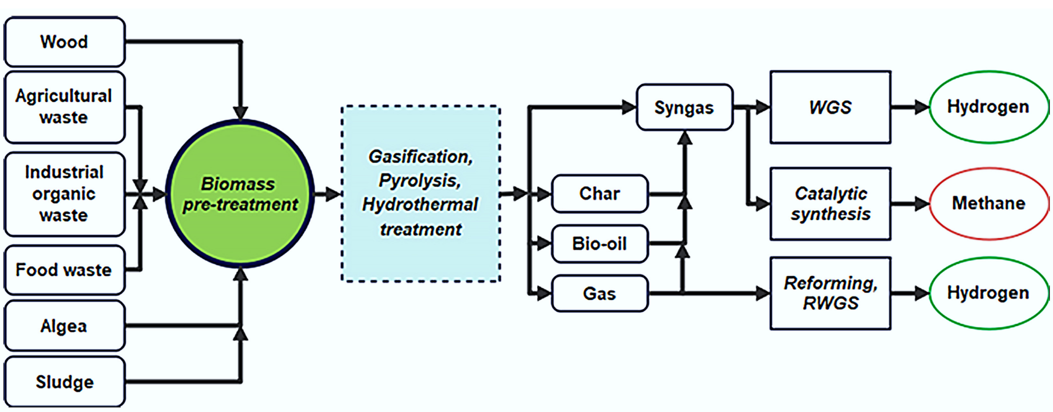

Fig. 1 Schematic flowchart for thermochemical conversion of biomass into syngas, bio-oil, and char.

environmental implications. By integrating TEA and LCA, this study aims to identify research gaps for guiding future research and tackling challenges in developing technologies for producing gaseous fuels by thermochemical conversion from biomass.

Several review articles on biomass thermochemical conversion processes have recently been published. Adeniyi et al.[31] evaluated biochar derived from leaves, discussing different thermochemical conversion techniques and key properties influencing its environmental uses (feedstock characterization). Ighalo[32] examined thermochemical methods for transforming bio-wastes into eco-friendly sorbents, focusing on their water decontamination capabilities (environmental sustainability). Jha et al.[33] reviewed various biomass resources and corresponding thermochemical technologies, highlighting their efficiency and selectivity toward specific products (biomass resource overview). Muh et al.[34] systematically analyzed thermochemical conversion processes for producing fuels and valuable chemicals from biomass, emphasizing optimization strategies for improving yields (process and technology assessment). Lee et al.[35] summarized the latest catalytic advancements in thermochemical biomass conversion, specifically addressing enhancements in biofuel production efficiency (catalyst development and TEA). Das et al. reviewed different biomass thermochemical conversion methods and compared product yield and quality[36]. The various processes produce different amounts of products. Lewandowski et al. presented the thermochemical conversion model as a function of biomass temperature, pressure, and heating rate. The author articulated that combustion emissions can be compensated for by high-temperature gasification of biomass using steam[37]. While several existing articles focus primarily on the technological aspects, they often overlook the importance of TEA and LCA. This review addresses that shortcoming by thoroughly analyzing thermochemical routes for producing syngas, H_2, and methane from biomass, with a particular focus on their environmental impacts and economic performance.

Recent review articles have primarily emphasized individual aspects, such as technological advancements[35,36], specific gaseous fuel production pathways[38], or general biomass-to-energy processes[39,40]. For example, Das et al. extensively reviewed advancements in algal biomass conversion without comprehensive economic or life-cycle perspectives, and Lee et al. addressed catalytic thermochemical conversions but did not include detailed economic and sustainability evaluations[35,36]. Arregi et al.[38] primarily focused on H_2 production technologies, with limited coverage of socioeconomic impacts and regional variability of biomass feedstocks.

Patel et al.[39] conducted an integrated review of lignocellulosic biomass conversion pathways, but the work did not incorporate detailed socioeconomic and technology readiness level (TRL) analyses. Similarly, Kumar & Vyas.[40] reviewed various gasification methods, emphasizing technological progress without extensively addressing detailed techno-economic scenarios, lifecycle impacts, or socioeconomic implications. Recent reviews by Ignat et al.[41] and Kaloudas et al.[21] provided insights into land-use conflicts and socio-environmental challenges but lacked comprehensive techno-economic modeling and LCA integration. A comparison has been made with the recent review papers, as given in Table 2. Table 2 benchmarks prior reviews across six lenses: gaseous fuels, integrated TEA, integrated LCA, TRL, socioeconomics, and regional feedstocks, and added a final column (key limitations) to make gaps explicit.

This review fills these gaps by presenting an extensive comparative analysis that includes:

• Robust integration of TEA and LCA methodologies across multiple gaseous biofuel production routes.

• Detailed analyses of economic scenarios under varying carbon pricing schemes.

• Comprehensive assessment of TRLs and commercialization prospects for biomass-to-gas technologies.

• In-depth exploration of socioeconomic implications, including labor conditions, community impacts, and food-vs-fuel debates.

• Consideration of regional variability, specifically addressing moisture and ash content impacts in tropical and arid zones.

This review goes beyond prior summaries by providing a decision-oriented synthesis that jointly treats TEA, LCA, TRL, socioeconomics, and regional feedstock constraints for thermochemical routes to syngas, H_2, and CH_4. This holistic approach not only helps inform better decision-making but also emphasizes the significance of these innovations in supporting the global energy transition. Incorporating TEA and LCA into biomass biofuel production processes provides a clear path toward more sustainable energy

Table 2 Comparative summary with recent review papers relevant to biomass thermochemical conversion

Review study	Gaseous fuels	Integrated TEA	Integrated LCA	TRL analysis	Socioeconomic analysis	Regional feedstock consideration	Key limitations
Das et al.[36]	Syngas	Partial	No	No	No	No	No integrated TEA + LCA; no TRL/socioeconomics.
Lee et al.[35]	Syngas	No	No	No	No	No	Lacks TEA/LCA synthesis and deployment context.
Arregi et al.[38]	Hydrogen	Partial	Partial	Limited	No	No	Partial TEA/LCA with pre-2020 datasets; limited TRL mapping; excludes SNG.
Patel et al.[39]	Syngas, hydrogen	Partial	Yes	No	No	Limited	Mixed system boundaries; no TRL analysis, no regional feedstock economics.
Kumar et al.[40]	Syngas	Partial	Partial	No	No	No	Absent TRL and socioeconomic lenses.
Ignat et al.[41]	Bioenergy (general)	No	Yes	No	Yes	Yes	Not a thermochemical-process review; no TEA.
Kaloudas et al.[21]	Bioenergy (general)	No	Partial	No	Partial	Yes	Limited LCA depth and no TEA integration.
This review	Syngas, hydrogen, methane	Yes	Yes	Comprehensive	Yes	Comprehensive	Thermochemical-to-gas focus with harmonized TEA/LCA, integrated TRL and socioeconomic/ regional lenses.

solutions. A comprehensive study illustrating the relationship between biomass-based gaseous fuels and the energy transition can further enhance the understanding of these complex dynamics. Such a study can serve as a tool to communicate the importance of these biofuels in reducing carbon emissions and enhancing energy security, aligning with global sustainability objectives.

Preliminary considerations related to biomass supply chain and their sustainability

Expanding biomass supply chains can significantly influence socio-economic dynamics and alter land-use patterns, particularly when transitioning agricultural lands from food production to bioenergy crops. One critical concern is the well-documented food-vs-fuel debate, which arises when fertile land traditionally used for cultivating food crops is redirected toward biomass production for energy purposes. Recent studies have raised substantial concerns about potential negative implications for food availability, food prices, and nutritional security, especially in vulnerable regions already facing food shortages[42]. This competition can exacerbate food insecurity by driving up prices and limiting access to essential crops, underscoring the importance of strategic planning to balance bioenergy development with food security objectives.

Moreover, biomass energy supply chains can influence local and regional labor markets. Bioenergy projects have the potential to create numerous employment opportunities in agriculture, harvesting, transport logistics, processing, and distribution. However, these opportunities are frequently seasonal, characterized by low wages and often precarious working conditions, unless supported by robust labor standards and protective regulations. Recent analyses emphasize that meaningful socioeconomic benefits from biomass production require policy frameworks to secure fair labor conditions, adequate income, and improved livelihoods, particularly in rural and economically disadvantaged areas[43].

Land-use changes driven by biomass expansion pose additional sustainability risks. Converting forests, grasslands, and other ecosystems into energy crop plantations can have profound ecological impacts, including biodiversity loss, soil erosion, nutrient depletion, and altered water cycles. Recent literature emphasizes that intensive biomass cultivation without proper safeguards may lead to deforestation and habitat destruction, undermining long-term ecological and climate benefits[44]. Sustainable land-use strategies such as agroforestry, integrated crop–livestock systems, and the use of marginal or degraded lands are recommended to mitigate these impacts. Policymakers and industry stakeholders are increasingly encouraged to adopt holistic, landscape-level planning and sustainability certification schemes that balance bioenergy production with ecosystem conservation and food production objectives.

Incorporating comprehensive socioeconomic and environmental assessments within biomass supply chain planning and development is thus crucial. Such assessments ensure balanced trade-offs, promote sustainable agricultural practices, safeguard community livelihoods, and ultimately support equitable and environmentally sustainable bioenergy transitions.

Cross-study differences in functional unit (e.g., per MJ-LHV vs per Nm^3-CH_4), system boundary (gate-to-gate vs cradle-to-grave; treatment of biogenic CO_2, land-use change), co-product handling (allocation vs system expansion), LCIA method (e.g., ReCiPe2016 vs TRACI 2.1), and data/temporal representativeness (electricity mixes, background databases) can shift absolute and relative results, limiting comparability and threatening both internal (method consistency) and external (transferability) validity[45]. To mitigate this, the approach: (i) tag each study's functional unit (FU), boundary, LCIA method, and data year; (ii) normalize TEA figures to a common currency year and finance/scale assumptions by referencing established frameworks (Zimmermann TEA/LCA guideline; DOE H2A; NREL TEA practice); and (iii) report ranges with explicit method notes where harmonization is not possible[46]. Prior harmonization efforts show that aligning such assumptions materially reduces unexplained variance, enhancing the decision usefulness of synthesized results.

Syngas production from biomass

The market for syngas as an intermediate in the chemical industry is anticipated to increase as a precursor to bulk chemicals, including methanol and biofuels from the Fischer–Tropsch process[47]. Biomass-derived syngas is primarily obtained through gasification. This process involves subjecting biomass to high temperatures (typically 700–1,200 °C) under limited oxygen or air conditions. Gasifying high-carbon-content solids like biomass produces synthesis gas, mainly composed of H_2, CO, CO_2, CH_4, water vapor, N_2, and undesirable tars as impurities[48]. High-quality syngas is characterized by a low tar content, a high H_2 content, and a low nitrogen concentration.

Various biomass feedstocks, including wood, agricultural residues, municipal solid waste (MSW), and energy crops like switchgrass or miscanthus, can be utilized for syngas production. Before gasification, biomass is typically dried and ground into small particles. The syngas production capacities of different feedstocks are illustrated in Fig. 2[7]. As shown, coal exhibits the highest syngas production capacity, exceeding 35,000 MWh, whereas petcoke and biomass/waste yield the lowest amounts.

Inside the gasifier, biomass undergoes a series of chemical reactions to produce syngas. Biomass-derived syngas offers significant advantages over fossil fuel-based methods, including reduced reliance on non-renewable resources and lower GHG emissions. It plays a crucial role in power generation through gas turbines, fuel cells, and steam turbines. Additionally, syngas serves as a key feedstock for producing H_2 and various chemicals, such as urea, ammonia, methanol, dimethyl ether, and Fischer–Tropsch diesel, reinforcing its economic importance[49]. Beyond energy production, utilizing biomass feedstocks supports local agriculture and forestry industries, fostering economic growth within communities. The

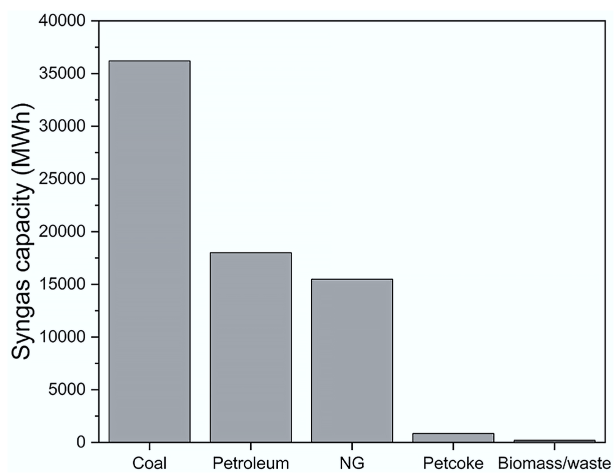

Fig. 2 Syngas production capacities of various feedstocks. Redraw based on the data from Ahmad et al. [7].

quality and yield of syngas are critical in determining its practical applications. Several factors influence its composition, including gasifier type, operating conditions, pressure, space velocity, gasifying agents, feedstock properties, particle size, and catalyst efficiency[48]. Optimizing these parameters is essential for producing high-quality syngas with minimal contaminants, such as tar and nitrogen, while maximizing H_2 content. Advances in gasification technologies continue to enhance efficiency, solidifying syngas as a cornerstone of sustainable energy and chemical production.

Techno-economic analysis of bio-based syngas

The TEA of syngas, bio-based H_2, and bio-based methane production from biomass typically involves the following steps, as listed in Table 3.

The successful commercialization of biomass thermochemical conversion technologies is heavily influenced by their current TRLs, which provide a standardized scale to gauge technological maturity. These levels range from TRL 1 (basic research) to TRL 9 (fully commercial systems). For biomass-based gaseous fuel systems, most technologies operate within the TRL 3–8 range, with only a few reaching sustained commercial viability, as listed in Table 4.

The configuration of biomass conversion systems, whether centralized or decentralized, plays a critical role in the economic and environmental performance of biofuel production. Logistics—including feedstock collection, transportation, storage, and pre-processing—account for a substantial share of both the cost and emissions associated with biomass-based systems[57]. Therefore, the system layout significantly influences the feasibility of thermochemical conversion technologies and applies broadly to all biomass-to-gas systems.

In recent years, numerous studies have focused on developing advanced technologies to enhance the utilization of renewable energy sources in response to climate change and the corresponding policies aimed at its mitigation. Biomass gasification is a promising pathway for producing energy, chemicals, and H_2, offering a sustainable alternative to fossil-fuel-based processes. However, evaluating the TEA of these systems is critical, as multiple factors influence economic viability and energy efficiency. These factors include biomass quality, feedstock transportation, process efficiency, operational costs, and market conditions[58].

Colantoni et al. conducted a financial feasibility analysis of biomass-based combined heat and power (CHP) systems at three different scales: 100 kWth, 1 MWth, and 10 MWth. This study used a bubbling fluidized bed reactor, and the feedstock comprised various biomass types. Indicators such as Net Present Value (NPV), Internal Rate of Return (IRR), and Pay Back Period(PBP) were utilized in an economic feasibility analysis. The sensitivity of NPV was also compared through a risk analysis using the Monte Carlo Simulation. It was found that the most influential economic model parameters for sensitivity analysis were the biomass cost, the amount of synthesis gas, and the price of electricity sold. The probability of a system having a positive NPV ranged from 66% to 90%, and it increased with the size of the system. It has been established that using regionally procured biomass as a raw material and acquiring an energy green certificate from the resultant syngas would qualify the undertaking as a triumph[59].

Table 3 A summary of parameters need to be considerd for conducing techno-economic analysis of syngas, bio-based H_2, and bio-based methane production from biomass

Step	Syngas	Bio-based hydrogen	Bio-based methane	Comparison	Ref.
Biomass feedstock characterization	Moisture content, ash content, and heating value	Moisture content, ash content, and heating value	Moisture content, ash content, and heating value	Similar	[50–52]
Process design	Gassifiaction: Feedstock properties and the desired syngas composition,gasifier type, operating conditions, and gas cleaning methods	Gasification process design: feedstock properties, gasifier type, operating conditions, gas cleaning, H_2 separation	Drying, pyrolysis, and gasification: feedstock properties, gasifier type, operating conditions, gas cleaning	Key difference: drying for methane; H_2 separation for H_2	[50]
Product gas composition analysis	Analyzed to determine its suitability for downstream applications	Analyzed for H_2 purity and downstream applications	Analyzed for downstream applications	Similar, with H_2 requiring additional purity analysis	[50]
Capital cost estimation	Based on the process design, equipment specifications, and installation costs	Based on process design, equipment, H_2 separation unit, installation costs	Based on process design, equipment, installation costs	Similar, with H_2 including additional costs for H_2 separation	[50]
Operating cost estimation	Feedstock costs, energy costs, and maintenance costs	Feedstock, energy, H_2 separation, maintenance costs	Feedstock, energy, maintenance costs	Similar, with H_2 including H_2 separation costs	[50]
Revenue estimation	From the sale of the syngas or downstream products	From bio-based H_2 or downstream product sales	From bio-based methane or downstream product sales	Similar	[50]
Sensitivity analysis	Evaluate the impact of changes in key parameters, such as feedstock prices and product prices, on the economic viability of the process.	Evaluates impact of feedstock and product price changes on viability	Evaluates impact of feedstock and product price changes on viability	Similar	[50]

Table 4 Technology readiness levels (TRL) of the technologies for producing biomass-based gaseous fuels

Technology	Fuel type	Current TRL	Key barrier	Estimated commercialization timeline	Ref.
Bubbling fluidized bed gasifier	Syngas	7–8	Tar control, catalyst degradation	3–5 years	[53]
Steam reforming of bio-oil	H_2	5–6	Catalyst cost, scalability	5–8 years	[38]
Sorption-enhanced gasification	H_2	4–5	Process integration, CO_2 handling	8–10 years	[54]
Supercritical water gasification (SCWG)	Syngas/H_2	4–5	High pressure equipment cost, limited demo data	8–12 years	[55]
Biomass methanation	Methane	6–7	Ni-based catalyst deactivation, cost estimating	5–7 years	[56]

Catalyst deactivation is a critical challenge in biomass thermochemical conversion, directly affecting system performance and economics. Common mechanisms include coke deposition, sintering, and poisoning from sulfur, chlorine, or alkali metals in feedstocks. Nickel-based catalysts, widely used for reforming and methanation, are particularly susceptible to carbon deposition, requiring regular regeneration and impacting operating costs[60]. Additionally, the reliance on rare or precious metals such as cobalt, rhodium, or ruthenium in advanced catalyst systems raises concerns about resource availability, supply chain risks, and increased capital expenditures[61]. Research is thus focusing on developing robust, earth-abundant alternatives and strategies to prolong catalyst life, such as doped supports and periodic oxidative regeneration. Comprehensive TEA should incorporate catalyst replacement intervals, regeneration costs, and market volatility of rare metals to accurately assess process sustainability.

Sarafraz et al.[62] investigated the economic feasibility of a chemical looping gasification system using liquid indium as an oxygen carrier for syngas production. A TEA was conducted to evaluate cost-effectiveness and levelized energy costs under different pricing scenarios based on real-world market indices. The study analyzed a system capable of processing 110 t/d of carbon feedstock, optimizing process parameters to achieve a syngas quality score of approximately 0.5. The cost breakdown for the chemical looping gasification process with liquid metal oxide carriers (CLG-LMOC) is presented in Fig. 3[62]. It was determined that liquid metal handling represented a significant cost component, accounting for 49% of total equipment cost. Furthermore, fuel costs comprised 57.51% of the total annual cost, while equipment operation accounted for 40%.

The cost breakdown shown in Fig. 3 is derived from a specific case study by Sarafraz et al.[62], which analyzed a chemical looping gasification system using a liquid medium as an oxygen carrier. It reflects the economic conditions, market indices, and operational factors particular to the studied region. Although the distribution of cost components, such as liquid metal handling (49%) and reactor operations (18%) offers valuable insights, it may not be universally applicable to regions with differing market conditions or feedstock prices. Variables like local energy costs, labor expenses, raw material availability, and regional regulations can significantly affect the cost structure. Therefore, while this breakdown is informative, it should not be broadly generalized without considering local contexts.

These findings underscore the importance of optimizing process conditions and reducing high-cost elements to improve the economic feasibility of biomass gasification. Integrating advanced gasification techniques and policy incentives, such as carbon credits and renewable energy subsidies, could further enhance the viability of biomass-based syngas production systems.

The supercritical water gasification (SCWG) method has received much attention in recent years due to its high energy conversion efficiency and environmental benefits. Meanwhile, the SCWG does not require a separate drying stage, saving cost and space. Additional economic evaluation is necessary to encourage the widespread development and commercialization of SCWG. In 1999, Amos refined the syngas produced at the starch waste SCWG plant using a complex membrane purification device[63]. The economic assessment found that the membrane unit accounted for over 35% of the total equipment cost. Table 5 provides an economic assessment of syngas production via SCWG.

Brandenberger et al. investigated the production of synthetic natural gas (SNG) via microalgal SCWG[55]. Their findings indicated that feed concentration was the most influential factor affecting SNG production costs. Under optimistic hypothetical conditions, where the SCWG plant had a microalgae treatment capacity of 86,500 t/d, the estimated cost range for SNG was USD$79–USD$129 /GJ. However, despite these advancements, the cost of SNG remains higher than that of conventional natural gas, limiting its current economic feasibility[64].

Several gasification technologies are employed for syngas production from biomass, but only the double fluidized bed (DFB) steam gasification technology has reached commercial-scale operation. Although extensive research and demonstration projects have been conducted, no full-scale commercial plants are currently operational. Numerous demonstration projects are in progress or in the planning phase, including GoBiGas, BioTfueL, Stracel BTL, Ajos BTL, Woodspirit, Enerkem's ethanol demonstration plant, and the TIGAS project[65]. These projects utilize different gasification technologies to produce various products, including liquid and gaseous fuels such as BioSNG and H_2.

Plasma gasification exhibits considerable promise for syngas production from biomass. Ramos & Rouboa[50] reported a net energy output of 816 kWh/t of biomass, with conversion efficiencies ranging from 20% to 45%, substantially higher than the 2.7% efficiency of conventional gasification[66]. Additionally, the technology achieves a mass reduction rate of 90 wt.% and generates an annual revenue of approximately USD$3.2 million, demonstrating its economic feasibility for syngas production[66].

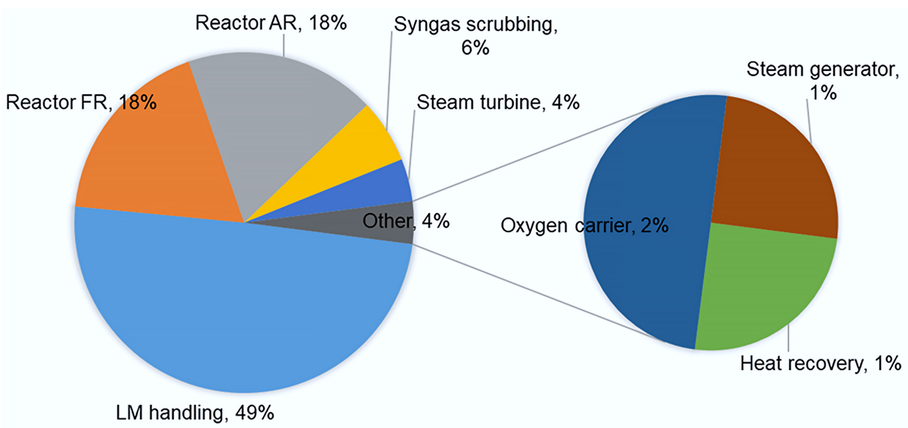

Fig. 3 Price breakdown for syngas production by chemical looping gasification process with liquid metal oxide carriers (CLG-LMOC). Redraw based on the data from Sarafraz & Christo[63].

Table 5 Economic analysis of various SCWG processes for syngas production

Year	Category	Targeted product	Indicator	Feedstock	Capacity	Result	Ref.
2011	Fixed capital investment: 53.4 MUSD TCI: 64.06 MUSD	CH_4 and H_2	Annual net income	Waste sludge	481 kg/h H_2	Annual profit will be highest at USD$3.78 /kg H_2 selling price	[67]
2012	Construction cost: USD$16,169 /ha Labor cost: USD$30,787 /ha/yr TPC: USD$110,270 /ha/yr	Syngas	Syngas production cost	Microalgae	86,500 t/d	Updated syngas cost: USD$79–USD$129 /GJ	[55]
2014	Indirect cost, O.C., Depreciation cost	Syngas	Break-even prices for syngas, electricity	Sugarcane Bio-refinery residues	1 kg/h syngas yield	The break-even syngas price is lower than USD$32.40 /MWh is profitable	[68]

One of the key advantages of these gasification technologies is their high conversion efficiency, which can reach up to 70%[65]. However, challenges remain, particularly regarding H_2 production, which requires further infrastructure development. While the transportation sector is gradually transitioning toward electric vehicles and H_2 fuel, widespread adoption will take decades. As a result, hydrocarbons are expected to remain the dominant fuel source for the foreseeable future. Despite previous setbacks and industry failures, it is crucial to further develop syngas production technologies to reduce costs and improve economic viability.

Life-cycle assessment of bio-based syngas

The LCA of bio-based syngas production offers an in-depth analysis of its environmental impacts, focusing on critical sustainability indicators such as GHG emissions, acidification potential, eutrophication potential, and water usage. A detailed LCA evaluates the environmental consequences of syngas production across its entire life-cycle, encompassing biomass cultivation, harvesting, gasification, purification, and end-of-life waste management. The environmental performance of bio-based syngas is shaped by multiple factors, including the type of biomass feedstock, energy requirements, gasification technology, and overall process efficiency. By pinpointing environmental hotspots through LCA, opportunities for improvement can be identified, such as increasing energy efficiency, adopting carbon capture technologies, and sourcing biomass sustainably. Additionally, a comparative analysis between bio-based and fossil-derived syngas highlights the former's potential benefits, particularly in reducing carbon emissions and enhancing overall environmental sustainability. Performing an LCA for bio-based syngas production yields essential insights for policymakers, researchers, and industry stakeholders, supporting the shift toward more sustainable and eco-friendly energy systems. The LCA is typically divided into the following stages, as listed in Table 6.

Syngas, which is H_2-rich, is considered one of the cleanest energy sources, producing the fewest GHGs. Several studies have investigated the environmental impact of producing H_2-rich syngas from various biomass types[69]. Biomass pyrolysis produces the highest CO_2 equivalent emissions among the thermo-catalytic processes for producing H_2-rich syngas[70]. Yet, due to variations in machinery, process conditions, and feedstocks, it is impossible to compare the environmental impact of these various processes directly. According to Dufour & Moreno, the CO_2 equivalent emissions can be decreased by combining the water-gas-shift reaction with the reforming process[71].

Carpentieti et al.[73] studied the LCA of an integrated biomass gasification combined cycle (IBGCC) for the production of syngas. The LCA demonstrates the significant environmental benefits of biomass utilization, including mitigating GHG emissions and preserving natural resources. With a fixed CO_2 removal efficiency of

Table 6 A summary of LCA steps of syngas, bio-based H_2, and bio-based methane production from biomass thermochemical conversion

LCA step	Syngas	Bio-based hydrogen	Bio-based methane	Comparison/note	Ref.
Biomass feedstock acquisition and preprocessing	Land, water, and energy use for growth, harvesting, transport, drying; GHG and biodiversity impacts	As syngas; effects depend on H_2 pathway selected (gasification, steam reforming)	As syngas; for biogas/biomethane, includes anaerobic digestion of waste or crops	All rely on sustainable sourcing and transport minimization; cropping practice crucial	[72]
Conversion/ process stage	Gasification emissions (CO_2, CO, tars, particulates); electricity/fuel use	Gasification plus water-gas shift, H_2 separation (membranes, PSA); added energy and chemicals	Anaerobic digestion/followed by upgrading and possible methanation; methane slip and biogenic CO_2	H_2 route has higher process emissions and energy use; methane route increases risk of fugitive CH_4 emissions	[72]
Product gas upgrading/ cleaning	Acid gas removal (CO_2, H_2S), tar cleanup, waste disposal impacts	H_2 purification to fuel cell or pipeline standards; impacts from separation units	Upgrading biogas to biomethane purity (> 95% CH_4); methane slip is critical LCA factor	All require energy-intensive cleanup; H_2 and biomethane purity requirements drive additional impacts	[72]
Distribution and use	Pipeline or local use; GHG savings depend on substitution (e.g., replacing fossil syngas)	Similar; GHG impact determined by end use (fuel, chemical); negative emissions possible with carbon capture and storage (CCS)	Grid injection or CNG; methane leakage and efficiency affect net GHG savings	Biogenic routes generally yield lower GHG than fossil, but only if methane slip and H_2 purification are managed efficiently	[72]
End-of-life/waste management	Ash, char, tar reuse/disposal, water effluents; possible recycling or reuse of byproducts	Similar, plus wastes from H_2 separation materials	Digestate use in agriculture, residual CO_2 streams from upgrading	H_2 and methane pathways introduce separation wastes; all routes can benefit from optimal byproduct valorization	[72]
Overall GHG and environmental performance (summary)	Significant GHG reduction vs fossil syngas, especially when using bio-waste; some trade-offs in land/water use	H_2 from biomass + CCS can be net negative GHG; LCA depends on full-system boundaries	Biomethane can achieve deep decarbonization if methane slip minimized and digestate reused	Best LCA results from waste-based feedstocks, strong methane management, CCS integration for negative emissions	[72]

80%, modelling an IBGCC + $DeCO_2$ yielded an intriguing 33.94% cycle efficiency and specific CO_2 emissions of 178 kg CO_2/MWh. Due to the low efficiency of the IBGCC + $DeCO_2$ and the significant impact of energy crop cultivation, the results for the other indicators indicate values that are slightly higher than the ICGCC + $DeCO_2$[73]. For system-scale LCA, modeled BECCS yields ~850–900 kWh per tCO_2 captured, while DAC requires ~350–600 kWh and ~5.4–7.1 GJ heat per tCO_2; net-negative cases imply ~0.3–1.1 $GtCO_2$/yr storage (−0.85) and ~4 $GtCO_2$/yr (−3.9) in 2050 EU scenarios[74].

The environmental impact of syngas production through air, steam, and CO_2-enhanced gasification was analyzed by Parvez et al.[75]. The study showed that CO_2-enhanced gasification had fewer adverse environmental effects than traditional gasification. When considering the environmental impact of a process, CO_2 emissions are typically a primary concern. While CO_2-enhanced gasification had a lower energy footprint than conventional gasification, it resulted in larger consequences in the middle-ground category, particularly in terms of human toxicity and marine ecotoxicity. As shown in Fig. 4, conventional biomass gasification had a greater effect on resource consumption, whereas its impact on human health and ecosystems was less significant[75].

Ramos & Rouboa[50] underscore the potential of plasma gasification for syngas production from biomass, highlighting its environmental and economic advantages through a life cycle thinking (LCT) approach that encompasses LCA, life-cycle costing (LCC), and social life-cycle assessment (S-LCA). From an LCA standpoint, plasma gasification of biomass yields a global warming potential (GWP) ranging from −31 to 422 kg CO_2 equ., which is comparable to conventional gasification (27 to 104 kg CO_2 equ.) and pyrolysis (−1 to 151 kg CO_2 equ.)[76].

Shen et al. measured particulate matter (PM) emissions in CO_2-enhanced biomass gasification, finding a 75.4% reduction in PM emissions at a 15% CO_2 addition[77]. An environmental investigation using Aspen Plus software also revealed that CO_2-enhanced biomass gasification reduced environmental impacts compared to traditional biomass gasification, especially regarding human toxicity and ecotoxicity[75]. Gu & Bergman[78] conducted an LCA of GHG emissions from electricity generated by syngas produced from woody biomass. Their study found that the conversion of woody biomass into medium-energy syngas in a high-temperature, low-oxygen environment, followed by combustion to produce electricity, had a significantly lower global warming potential than energy from bituminous coal (1.08 kg CO_2-eq/kWh) or conventional natural gas (0.72 kg CO_2-eq/kWh), with a global warming impact value of just 0.142 kg CO_2-eq/kWh[78].

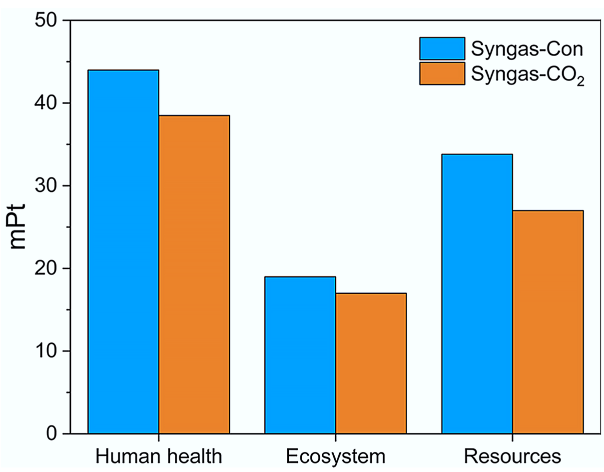

Fig. 4 Environmental impact caused-conventional biomass gasification (Syngas-Con) and CO_2-enhanced biomass gasification (Syngas-CO_2). Redraw based on the data from Parvez et al.[76].

Voultsos et al. assessed the proposed cogeneration biomass gasification facility in Thessaly, Greece, for its energetic and environmental performance using a combination of process modelling and the LCA technique. When the gasification model was expanded to a 1 MW_{el} and 2.25 MW_{th} CHP facility, its Global Warming Potential (GWP) and Cumulative Demand for Non-Renewable Fossil Energy were analyzed as part of a 'cradle-to-gate' LCA. Plant operation was found to lower GHG emissions by around 0.6 kg CO_2-eq/kWh_{el} and save roughly 10 MJ/kWh_{el} of non-renewable energy under all test conditions[79].

Integrating LCA with LCC analysis for bio-based syngas production enables a holistic evaluation, balancing environmental impacts like GHG emissions with economic costs, ensuring sustainable and cost-effective energy solutions. The LCC analysis of thermochemical syngas production from biomass provides a comprehensive economic assessment of this renewable energy process, covering feedstock acquisition, plant construction, operation, and eventual decommissioning. Thermochemical syngas production primarily involves biomass gasification, where lignocellulosic materials such as forestry residues, agricultural wastes, or energy crops are converted into a gaseous mixture of CO, H_2, and CO_2 at high temperatures (typically 700–1,000 °C)[80]. Capital costs are a major component of the LCC, with gasification facilities requiring investments of USD$500–USD$1,500 per kW of installed capacity, depending on the gasifier type (e.g., updraft, downdraft, or fluidized-bed), plant scale, and ancillary systems such as gas cleaning and heat recovery units[81]. Feedstock costs dominate the LCC, ranging from USD$30 to USD$100 per dry ton, accounting for 50%–70% of total expenses due to harvesting, transportation, and preprocessing needs such as drying and grinding[82]. Operational and maintenance (O&M) costs contribute an additional 10%–20% to the LCC, driven by energy inputs for gasification (often 15%–25% of total energy demand), gasifier maintenance, and the replacement of tar-reforming catalysts, which can cost USD$5–USD$15 per kg[83]. Environmental factors, including ash disposal and potential carbon credits, also influence the LCC, with a carbon price of USD$20–USD$50 per ton of CO_2-equ. potentially yielding savings of USD$0.02–USD$0.10 per m^3 of syngas through emissions offsets[84]. TEA and LCA comparison of different technologies for syngas production is given in Table 7.

Across studies, levelized costs pivot on feedstock logistics and gas cleanup, while LCA swings with electricity mix and methane/tar management. CCS and waste-based feedstocks frequently flip GWP from positive to near-neutral/negative. At TRL 7–8 (indirect steam gasification), near-term wins lie in tar control and heat integration; policy levers (e.g., carbon price, renewable gas credits) strongly affect bankability. Decision-relevant range: syngas GWP improves most when the cleanup energy is low-carbon and when co-products (biochar) are valorized.

The results of the LCA and LCC can be used to identify areas where improvements can be made to reduce the environmental impact of syngas production from biomass. For example, the LCA may identify opportunities to reduce energy consumption, switch to renewable energy sources, or improve waste management practices. Overall, the LCA of syngas production from biomass provides essential information for decision-makers, stakeholders, and investors to evaluate the environmental sustainability of the process and make informed decisions about its implementation. Hence,

Table 7 Comparison of syngas production cost and GWP for different technologies

Process type	Feedstock/context	Syngas production cost (USD$/GJ)	GWP (kg CO_2-eq per kg syngas)	Ref.
Indirect steam DFB gasification	Woody biomass	–	~2–5 depending on electricity GWI	[85]
Stand-alone biomass syngas plant	Lignocellulosic biomass	8.22–6.73	–	[86]
Pulp-mill integrated biomass gasification	Forest residues	17	–	[87]
Mill-gas separation (COG H_2 + BOFG CO) to syngas	Steel mill off-gases	–	0.7–3.6 (pathway and electricity carbon intensity dependent)	[88]
Micro-scale biomass gasification	Various residues	5–54	–	[89]

enhancing the production process is a viable option for reducing CO_2 equivalent emissions.

Hydrogen production from biomass

The development of sustainable fuels is critical for addressing the global challenges of climate change, energy security, and transitioning to a low-carbon economy. H_2 is widely considered a highly efficient and environmentally friendly energy carrier because only water is produced from H_2 combustion. It is a carbon-free energy carrier and has the highest known energy density among common fuels, at 142 kJ/gal[90]. H_2 energy has the potential to decarbonize several sectors, including industry, transportation, and energy storage. Worldwide, H_2 production might reach 10 EJ/year in 2050, up from 7.7 EJ/year in 2017[91]. Figure 5 shows the primary application regions of H_2, which include China (29%), North America (17%), the Middle East (13%), and others (42%)[92]. Furthermore, the H_2 industry is expected to grow at an annual rate of 5%–10% in the coming years, primarily due to its use in oil refineries for processing heavy oil fractions and its anticipated role in the transportation sector or as an energy carrier[93]. Currently, 96% of the produced H_2 is based on non-renewable resources[94]. Natural gas (62%) and oil reforming (0.5%) are the most common methods, followed by coal gasification (21%). According to Fig. 5, the production of H_2 through water electrolysis accounts for a mere 0.4%[92].

Biomass is emerging as a promising sustainable feedstock for H_2 production, harnessing thermochemical processes such as steam gasification, supercritical steam gasification, bio-oil reforming, and pyrolysis[38]. Globally, approximately 181.5 billion tons of lignocellulosic and agricultural biomass are produced; however, a minor proportion of this biomass undergoes processing and repurposing, resulting in substantial quantities of organic waste (equivalent to 40%–50% of its initial mass) being deposited into the environment[95]. Today's food systems result in massive volumes of wasted food; the United States (U.S.) alone produces over 50 Mt of food waste per year[96]. Employing renewable biomass materials in H_2 production mitigates their inherent uncontrolled decomposition and the environmental risk of climate change[97]. This approach aligns with broader trends in sustainable fuel development, where bio-based H_2 is increasingly seen as a crucial component in achieving a net-zero future. By linking biomass conversion technologies to the H_2 economy, this paper offers insights into how sustainable fuels can play a pivotal role in the broader energy transition.

Importance of bio-based hydrogen

The thermochemical conversion of biomass offers a sustainable and carbon-neutral method for H_2 production, tackling two significant issues: decreasing reliance on fossil fuels and reducing GHG emissions. The production of H_2 from biomass presents a promising avenue for reducing carbon emissions in sectors that are challenging to electrify, including heavy industry and long-distance transport. The incorporation of H_2 into energy systems plays a vital role in achieving the ambitious climate goals established by international accords like the Paris Agreement, which seeks to restrict global warming to 1.5 °C. In this context, the capacity of biomass conversion technologies to produce low-carbon H_2 via sustainable methods emerges as a crucial element of future energy systems[98].

The global shift towards an H_2 economy is accelerating, particularly with Europe at the forefront of this movement. The H_2 strategy of the European Union, especially within the framework of the RePowerEU plan, presents a detailed roadmap aimed at deploying 40 GW of electrolyzers by 2030 for the production of renewable H_2, emphasizing the integration of H_2 across multiple sectors[99]. Nonetheless, a significant challenge in the production of green H_2 through electrolysis is the reliance on renewable electricity, which may not consistently be accessible in adequate amounts. H_2 production from biomass presents a valuable approach by utilizing a renewable feedstock that can function autonomously or alongside

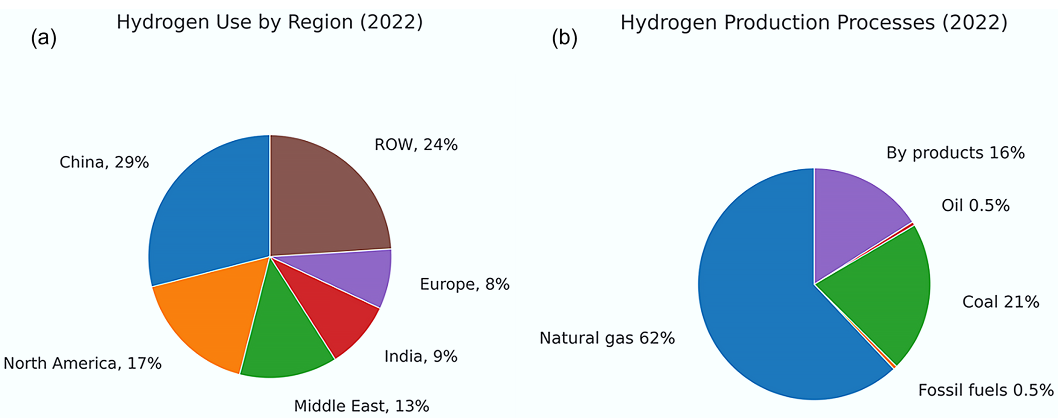

Fig. 5 **(a)** Major application regions, and **(b)** production processes of H_2 in 2022. Redraw based on the data from IEA[93].

renewable electricity, thereby guaranteeing a consistent H_2 supply. Furthermore, integrating biomass conversion with carbon capture and storage technologies can significantly improve its environmental impact, facilitating negative emissions and aiding in the achievement of net-zero objectives[100].

The environmental advantages of biomass-derived H_2 production are significant, especially in contrast to traditional H_2 production techniques. The conventional method of producing H_2, mainly via steam methane reforming (SMR) of natural gas, leads to considerable CO_2 emissions. Conversely, thermochemical processes utilizing biomass, especially when combined with carbon capture and storage, can lead to a net decrease in CO_2 emissions, thereby rendering H_2 produced from biomass carbon-negative[101]. This holds particular significance in the realm of challenging sectors like cement, steel, and chemicals, where H_2 can serve as a substitute for fossil fuels, thereby diminishing their carbon emissions. In the industrial sector, H_2 is becoming a crucial tool for decarbonization, and biomass conversion is poised to significantly contribute to fulfilling the H_2 needs of these industries[102].

The significance of H_2 in the transportation sector is growing, especially for applications where battery-electric solutions prove impractical, including long-haul trucking, shipping, and aviation. Hydrogen fuel cells, utilizing H_2 derived from biomass, offer a zero-emissions alternative to diesel engines in these sectors, contributing to global initiatives aimed at lowering transport emissions[103]. Studies indicate that hydrogen fuel cells provide greater energy density and range than battery-electric options, rendering them more appropriate for heavy-duty and long-range uses. Additionally, H_2 produced from biomass can be incorporated into current infrastructure, minimizing the necessity for expensive new energy systems[101].

A notable benefit of biomass-based H_2 production is its potential for implementation in areas where renewable energy sources such as wind and solar are scarce. Biomass is abundantly accessible in numerous regions globally, presenting a compelling opportunity for decentralized H_2 production, especially in rural and agricultural areas. This approach can strengthen energy security by decreasing reliance on imported fossil fuels and ensuring a consistent, locally sourced energy supply. Furthermore, the production of H_2 from biomass has the potential to enhance rural economic development by establishing new markets for agricultural residues and various organic waste materials[102]. This method promotes a circular economy by transforming waste into valuable energy resources, which is in line with global sustainability objectives.

From an economic standpoint, the viability of converting biomass through thermochemical processes into H_2 is gaining significant competitiveness. The review emphasizes that advancements in thermochemical processes, including enhancements in gasification efficiency and the incorporation of carbon capture and storage (CCS), are reducing the costs associated with H_2 production from biomass[1]. When external factors like carbon pricing and environmental benefits are taken into account, biomass-based H_2 demonstrates the potential to compete with alternative H_2 production methods, such as electrolysis. Furthermore, the advancement of hybrid systems that integrate biomass conversion with renewable energy sources has the potential to significantly improve the cost-effectiveness and sustainability of H_2 production[104].

The incorporation of H_2 into the broader energy framework, especially via power-to-H_2-to-power systems, presents a noteworthy opportunity for H_2 derived from biomass. In these systems, surplus renewable electricity is utilized to produce H_2 via electrolysis, allowing for storage and subsequent conversion back into electricity during periods of low renewable production. H_2 derived from biomass can enhance this strategy by offering a consistent supply that remains unaffected by weather variability, thereby ensuring the reliability and stability of the energy system[98]. The adaptability of biomass-derived H_2 positions it as a significant resource for stabilizing variable renewable energy sources such as wind and solar.

As progress continues, the advancement of sustainable fuels, such as H_2, will remain a crucial priority for policymakers, experts, and industries across the globe. The review highlights biomass thermochemical conversion as an essential element of the future H_2 economy. With the increasing scale of H_2 production from renewable sources, biomass is set to be a vital component in supporting various H_2 production methods, thereby contributing to a diverse and robust energy supply[52]. The ongoing progress in biomass conversion technologies, along with favorable policies and investments, will be crucial for unlocking the full potential of biomass-based H_2 in meeting global decarbonization objectives.

The techno-economic potential for biomass thermochemical conversion into H_2 is gaining competitiveness as a result of technological advancements and improved process efficiency. Considering the implications of carbon pricing and the environmental advantages associated with negative emissions, biomass-derived H_2 emerges as a competitive option against alternative H_2 production techniques, including electrolysis and steam methane reforming with carbon capture and storage[52]. This production pathway also generates economic opportunities in rural regions, enabling the conversion of agricultural and forestry residues into valuable energy products, thereby fostering economic development and job creation[101]. This is in accordance with worldwide initiatives aimed at facilitating a fair shift to a low-carbon economy, ensuring that the advantages of clean energy are distributed equitably[98].

Techno-economic analysis of bio-based hydrogen

The sustainability of the H_2 economy and the future of clean energy hinge on the development of adaptive and environmentally benign methods for H_2 production. As discussed in TEA of bio-based syngas, H_2 production technologies such as steam reforming and sorption-enhanced gasification (SEG) remain in mid-development stages (TRL 4–6), affecting their current economic viability and scalability. The configuration of biomass conversion systems, whether centralized or decentralized, plays a critical role in the economic and environmental performance of biobased H_2 production, as discussed in a previous section. Traditional H_2 production methods, such as steam methane reforming (SMR) of natural gas and coal gasification, are increasingly unsuitable for a circular economy due to their energy-intensive processes and high carbon emissions, which amount to approximately 830 million tons per year[105]. As the global demand for H_2 rises, especially in the context of decarbonization strategies, the need for alternative production methods has become pressing. The utilization of renewable resources, particularly organic residual biomasses such as food wastes, lignocellulosic agricultural residues, and forestry waste, offers one of the most promising alternatives to these conventional methods[106].

For H_2 to be commercially viable as a clean fuel, it is essential that its production methods are both sustainable and cost-competitive. The scalability and processing reliability of bio-based H_2 production are crucial to reducing production costs and driving broader adoption. Several factors contribute to the overall economics of bio-based H_2, including: (a) substrate/feedstock and pretreatment costs, (b) production costs of H_2, (c) downstream purification and processing costs, (d) storage and transportation costs, and (e) distribution costs[107]. While thermochemical H_2 production technologies such as gasification and pyrolysis are productive and can yield high-purity H_2, they are often not economically viable without significant improvements in energy efficiency due to their high energy consumption[106].

H_2 commercialization has progressed considerably due to advances in various production technologies. These include water electrolysis, steam reforming, and coal gasification, each of which has been extensively applied in industrial settings[108]. However, as H_2 production from biomass is explored more extensively, it has been found that the cost of H_2 produced through gasification of biomass remains relatively high compared to conventional methods. For example, a study by Liu et al. reported that the levelized cost of hydrogen (LCOH) from MSW gasification was USD$3.04/kg, while the cost for waste wood gasification was slightly lower at USD$2.77/kg. This study considered several feedstock scenarios to determine the most economically viable H_2 production option, as detailed in Table 1. However, the LCOH associated with biomass conversion into H_2 was found to be approximately three times higher than conventional MSW gasification methods[109]. Catalyst deactivation and rare-metal cost considerations previously discussed in the syngas TEA section are also highly relevant here, particularly for steam reforming and water-gas shift reactions.

Further analysis revealed that LCOH for MSW gasification was calculated at GBP 2.22 /kg, and for waste wood gasification, it was GBP 2.02 /kg. This cost disparity underscores the economic challenge faced by biomass-derived H_2. Liu et al. evaluated five different scenarios for H_2 production: (S1) gasification of MSW, (S2) gasification of waste wood, (S3) dark fermentation of wet waste or sludge, (S4) combined dark and photo fermentation of wet waste or sludge, and (S5) steam methane reforming (SMR) of natural gas. Among these, biomass-based H_2 production through gasification (S1 and S2) was more expensive compared to SMR, but dark fermentation (S3) and combined fermentation (S4) showed some potential for reducing costs, particularly when compared to more conventional methods[109].

The techno-economic feasibility of SEG for H_2 production was also investigated. Santos & Hanak[54] found that this method led to a higher LCOH of USD$6.3 /kg, significantly higher than the traditional steam gasification process, which had an estimated LCOH of USD$3.402 /kg. The impact of carbon pricing on the economic performance of H_2 production methods was also considered. In the case of SEG, the avoided CO_2 emissions cost was USD$144.77 /t$CO_2$, assuming no gate fee and tax imposition. However, with the introduction of a carbon pricing mechanism at USD$49.89 /t$CO_2$, the cost of CO_2 emissions decreased to USD$113.526 /t$CO_2$[54]. This finding highlights the sensitivity of biomass-based H_2 economics to carbon pricing, and its potential for further cost reductions as policies to curb emissions are enacted. The impact of gasification temperature on H_2 product yield and process efficiencies is shown in Fig. 6.

The pyrolysis process, another thermochemical method for converting biomass into H_2, also presents an alternative to gasification. Pyrolysis offers advantages such as lower operating temperatures and the potential for producing valuable byproducts, but like other thermochemical processes, it still faces challenges in terms of cost competitiveness with more established H_2 production methods. The economics of pyrolysis-based H_2 production, while promising, require further investigation and optimization, especially concerning the integration of CCS to mitigate the environmental impact.

However, the production of H_2 via biomass pyrolysis is still in the early stages, with a TRL between 3.5 and 4.2 (laboratory scale). This relatively low TRL reduces production efficiency and increases associated costs[110]. To enhance the scalability of the process, improving H_2 yields from biomass would be crucial for reducing both capital and operating expenditures.

Capital expenditures (CAPEX) for biomass pyrolysis encompass both direct costs, such as instrumentation, equipment type, installation location, and electrical control systems, as well as indirect costs, which include construction and engineering expenses[111]. Operating expenditures (OPEX), on the other hand, include variable costs such as biomass feedstock transportation, raw material pricing, chemicals, and energy consumption. Additionally, fixed costs, such as administrative, labor, and maintenance expenses for the pyrolysis plant, must also be considered[111].

A TEA study on the hydropyrolysis of woody biomass for biofuel production estimated the minimum fuel selling price (MFSP) at USD$1.64 /kg (in 2007 U.S. dollars), with an annual output of 79 gallons of liquid fuels per ton of lignocellulosic feedstock[112]. In a similar analysis, the fast pyrolysis of corn stover to produce H_2 yielded a production cost between USD$2.1 and USD$3.09 per kilogram of H_2, with CAPEX at USD$287 million and annual OPEX at

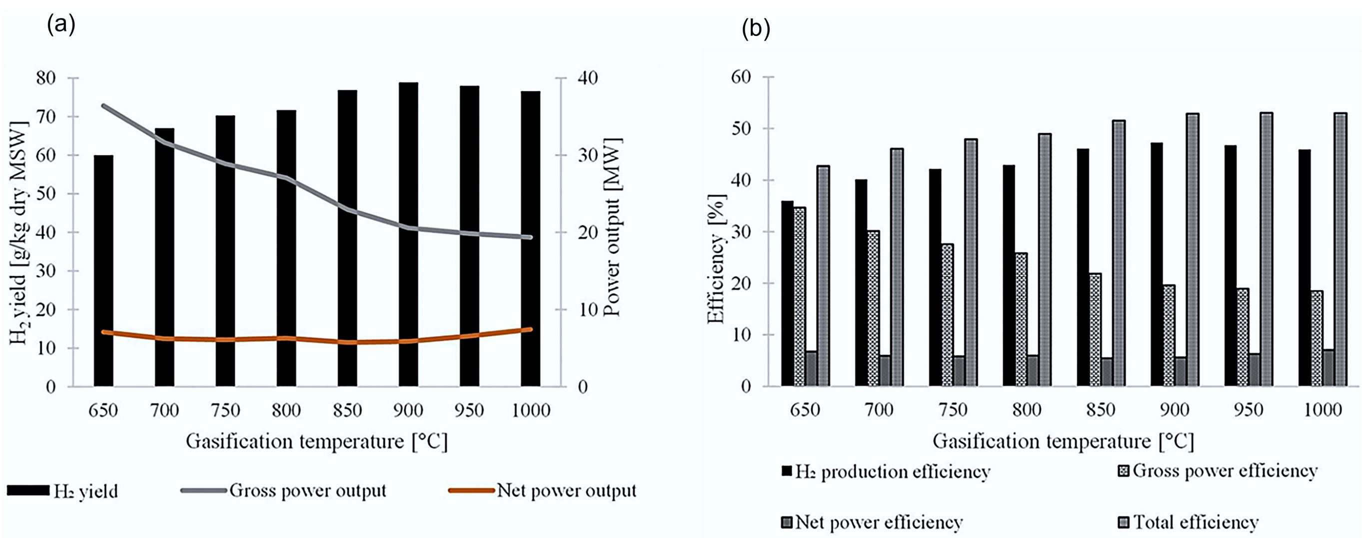

Fig. 6 The influence of gasification temperature on H_2 product yield and process efficiencies[54].

USD$109 million. The simulation results also demonstrated a strong correlation between the production cost and the price of biomass feedstock[113].

H_2 production costs must be below or close to USD$0.3 /kg H_2, or about the same as the cost of gasoline (USD$2.5 /GJ), to increase the commercial feasibility of a production method[114]. While microalgae are a costly biomass feedstock, they provide a sustainable means of producing H_2, but there is currently very little information about the technology's economic and environmental viability. The cost of producing biofuels from microalgae residue is dependent on the method of upgrading employed, namely mechanical dewatering (with an operational expenditure of USD$120.8 M per year and capital expenditure of USD$409 M) or thermal drying (with an annual operational expenditure of USD$145.8 M and a capital expenditure of USD$346 M). The resulting biofuels are priced between USD$1.49 per liter and USD$1.80 per liter[115]. A summary of H_2 production costs from biomass and fossil resources, including levelized cost, GWP, and capital expenditures, is provided in Table 8.

The world's largest economies, particularly China, the United States, Japan, and India, have been pivotal in supporting the development of H_2 fuel production[122]. China, as the leading market for bio-H_2, anticipates that the sector's production value will reach USD$157.44 billion by 2025, significantly outpacing the other major economies[123]. Japan, the United States, and India have made substantial investments, with projected contributions of USD$3.4 billion, USD$8.0 billion, and USD$25 billion, respectively, aimed at reducing the cost of sustainable H_2 to USD$1 /kg by 2030[124]. Additionally, nine countries from the European Union and other regions unveiled their H_2 strategies in 2020, including nations such as Australia, the Netherlands, South Korea, Germany, Portugal, Spain, Chile, and Canada, with another eleven countries following suit in 2021[125]. These significant investments by major global economies are expected to accelerate the development of bio-H_2 facilities and technologies, ultimately offering substantial returns and improving the economic viability of H_2 production.

The H_2 economy holds immense potential to mitigate GHG emissions and reduce pollution, thereby playing a crucial role in achieving the United Nations' Sustainable Development Goals (SDGs). By promoting the adoption of eco-friendly technologies and fostering environmentally conscious production methods, the H_2 economy contributes to environmental preservation and long-term sustainability[126]. If effectively implemented, this transition can support sustained economic growth while easing the burden on natural resources, establishing a solid foundation for social sustainability. However, for this to be realized, it is imperative to lower processing costs. This will require the continued development and scaling up of new technologies, such as integrated bioprocessing, to enhance the efficiency and economic feasibility of bio-H_2 production.

Life-cycle assessment of bio-based hydrogen

LCA is a crucial methodology for systematically evaluating the environmental, economic, and social impacts of products, processes, and activities, including H_2 production, biofuel synthesis, power generation, and energy systems. LCA provides a structured analytical framework that identifies both direct and indirect inputs and outputs, assesses energy and material flows, and quantifies environmental impacts throughout the entire life cycle of a product. This approach also helps identify potential areas for improvement in process optimization and policy implementation[127].

The LCA methodology is standardized under ISO 14040:2006 and ISO 14044, which define four key stages: (1) goal and scope definition, (2) life-cycle inventory analysis (LCI), (3) life-cycle impact assessment (LCIA), and (4) interpretation of results[128]. The goal and scope definition phase establishes the purpose of the LCA, system boundaries, functional unit, geographical scope, and temporal considerations. The LCI phase involves quantifying all material and energy inputs, emissions, and waste outputs across the system. The LCIA phase evaluates the potential environmental impacts associated with resource use, GHG emissions, and energy consumption. Finally, the interpretation phase ensures that the results align with the study's objectives and provides recommendations for process improvement and policy development.

A cradle-to-grave LCA of bio-based H_2 must consider multiple process steps, including raw biomass production, pretreatment, collection, transportation, syngas production, H_2 purification, distribution, and end-use applications. Each of these stages contributes to the overall environmental impact and energy efficiency of the H_2 production system[129]. A schematic diagram of the LCA approach is shown in Fig. 7.

The analysis indicates that in the near term, bio-H_2 produced through biomass gasification is unlikely to fully replace

Table 8 Techno-economic comparison of different H_2 production processes

Process type	Feedstock	Capital expenditure (M USD$)	Hydrogen production cost (USD$/kg)	Levelized cost of hydrogen (USD$/kg)	GWP (kg CO_2 eq/kg H_2)	Ref.
Biomass						
Gasification and steam reforming	Solid waste	399.2	2.26	3.04	4.4–7.72	[109,116]
	Waste wood	137.65	2	2.77	0.18–6.98 (−24.19 with CCS)	[109,116]
	Wood chips	12.5	1.83–2.35	n.a.	0.18–6.98 (−24.19 with CCS)	[116]
Dark fermentation	Wet waste, sludge	38.162	2.38	2.945	n.a.	[109]
Dark and photo fermentation	Wet waste, sludge	41.642	2.52	3.137	n.a.	[109]
Pyrolysis	Bio-nut shell, olive husk, black liquor, pulp and paper waste	264.6–361.6	1.21–2.57	n.a.	n.a.	[117]
Supercritical water gasification	Black liquor	72.37	1.51–3.89	n.a.	n.a.	[118]
Fossil resources						
SMR	Natural gas	215.4–302.65	0.77	1.45–2.56	10–16	[117]
SMR with CCS	Natural gas			2–2.4	3–10	[119,120]
Coal gasification	Coal	324.57	0.92–2.83	1.26	19.25–23	[117]
Coal gasification with CCS				1.51	4.85–11	[121]
Non-biobased renewables						
H_2 electrification	Renewable energy			2.9–6.7	0.49–6.63	[119,120]

conventional H_2 due to various economic and social barriers. Nonetheless, improving process efficiency can strengthen the sustainability of bio-H_2 production, addressing economic, environmental, and social factors. By employing cost-effective measures and leveraging carbon credits, conducting a thorough LCA of bio-H_2 production can support the global shift toward renewable energy systems and net-zero emission targets, as depicted in Fig. 8. Despite its potential, bio-H_2 production from biomass faces notable challenges, such as the need for expensive catalysts, the production of multiple by-products (including CO_2 and H_2), and, in some cases, liquid-phase by-products[93].

To overcome these limitations, expanding traditional LCA with a broader life cycle sustainability assessment (LCSA) is necessary. Unlike standard LCA, LCSA evaluates not only environmental impacts but also economic and social consequences. This comprehensive approach can reveal inefficiencies in operations, potential health risks, and pollution issues linked to bio-H_2 production[130]. Moreover, LCSA can promote improved resource management, community participation, knowledge exchange, safer living conditions, cost savings, responsible technology adoption, and infrastructure development.

Environmental impacts of bio-H_2 production are primarily assessed through two indicators: acidification potential (AP), mainly due to SO_2 emissions that contribute to acid rain, and GHG emissions, largely CO_2, associated with global warming potential[131]. A meta-analysis suggested that H_2 production from biomass can lower GHG emissions by up to 75% compared to the natural gas reforming process[132]. Valente et al.[116] aimed to standardize LCA studies to better compare AP, cumulative non-renewable energy demand (CEDnr), and GHG emissions. Their research showed that biomass-based H_2 production produces fewer GHG emissions, particularly when coupled with CCS, which can even achieve negative emissions due to carbon absorption during biomass growth. An overview of the global warming potential of various H_2 production pathways is shown in Table 8.

The H_2 was produced by using coal-to-H_2 (CTH) and biomass-to-H_2 (BTH) processes. When compared to producing H_2 from coal, biomass-to-H_2 methods score better on many relevant LCA indicators. The life cycle boundaries of the system include transportation, syngas synthesis, H_2 purification, and its applications. The energy consumption data for H_2 production indicate that H_2 produced from biomass requires roughly 25% less energy than H_2 produced from coal[133]. Furthermore, transporting H_2 through pipelines is a more eco-friendly option, as it minimizes GHG emissions[133]. However, the economic feasibility of bio-H_2 production from residual biomass remains uncertain. Despite the projected global market for H_2 reaching USD$130 billion by 2033[134], further advancements are necessary for bio-H_2 to become competitive with conventional H_2 production methods.

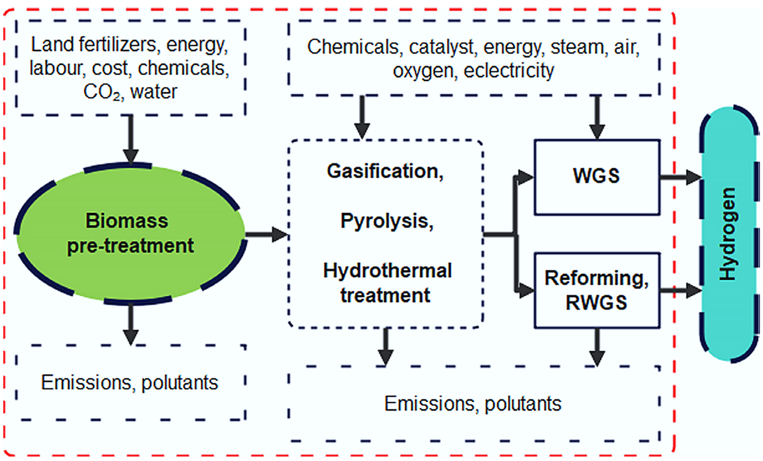

Fig. 7 Schematic diagram of LCA for thermochemical conversion of biomass into H_2.

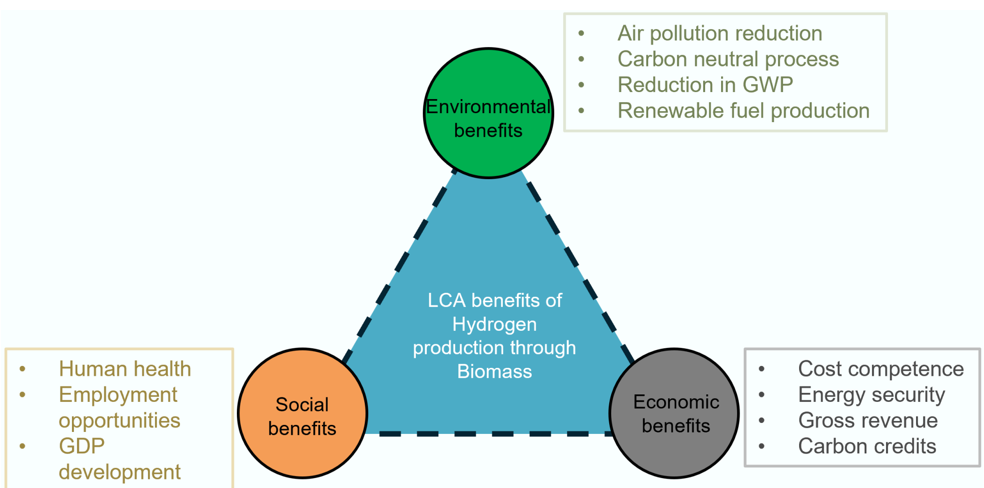

Fig. 8 Social, economic, and environmental benefits of H_2 production through biomass.

Combining LCA and LCC for bio-based H_2 production through thermochemical biomass conversion allows for a thorough assessment of both environmental impacts and economic feasibility, promoting efficient resource use and minimizing overall costs. The process typically involves biomass gasification to produce syngas, followed by water-gas shift reactions and H_2 purification (e.g., pressure swing adsorption or membrane separation) to produce high-purity H_2.

Gasification plants requiring investments of USD$1,000–USD$2,500 per kW of installed capacity. The cost depends on factors such as plant scale, gasifier type (e.g., fixed-bed, fluidized-bed, or entrained-flow), and auxiliary systems, including gas cleaning and separation units[81]. Feedstock costs are a dominant expense, typically ranging from USD$30 to USD$120 per dry ton, depending on the biomass source (e.g., woody residues, agricultural wastes, or dedicated energy crops). These costs account for 40%–60% of the total LCC due to expenses related to harvesting, transportation, and preprocessing[82]. Operational and maintenance (O&M) expenses contribute an additional 15%–25% to the LCC. Major cost drivers include energy requirements for biomass drying (20%–30% of total energy input), catalyst replacement for syngas upgrading (e.g., USD$10–USD$20 per kg for water-gas shift catalysts), and routine equipment maintenance[135]. Environmental considerations, such as ash disposal and carbon credit benefits, also affect the LCC. A carbon price of USD$20–USD$50 per ton of CO_2-equivalent could reduce costs by USD$0.05–USD$0.15 per kg through emissions offsets[84].

Compared to fossil-based H_2 production via steam methane reforming (USD$1.50–USD$2.50 per kg), thermochemical H_2 from biomass is more expensive, with LCC estimates ranging from USD$2.50–USD$5.00 per kg, reflecting higher feedstock and processing costs[52]. However, its life cycle GHG emissions are 50%–80% lower, providing a strong environmental advantage[84].

Biomass-based H_2 production can potentially reduce GHG emissions by up to 90%, depending on the production site's conditions and system boundaries. However, the effectiveness of this approach depends significantly on the type of biomass used. Utilizing high-yield biomass sources like eucalyptus can lead to better economic and environmental results[136]. Integrating advanced assessment methods like exergy analysis with LCA could provide more accurate insights into the sustainability of H_2 production pathways, helping to develop more efficient and sustainable technologies[137]. TEA is dominated by separation and purification and catalyst life; LCA is dominated by capture rate and electricity carbon intensity. Biomass-to-H_2 + CCS can be net-negative but requires durable WGS/PSA trains and steady feedstock. With current TRL ~4–6 for several routes, market access hinges on hydrogen offtake contracts and carbon policy; near-term pilots should target gate-fee feedstocks and heat recovery to compress LCOH ranges.

Methane production from biomass

Methane is recognized as a cleaner alternative to conventional fossil fuels such as oil and coal. It is commonly used as a fuel alongside Liquefied Petroleum Gas (LPG) in internal combustion engines[138]. In 2022, Europe emerged as the largest producer of bio-based methane, producing approximately 1.8 million tons annually[139]. Methane has diverse applications across residential and industrial sectors, including its use in transportation, electricity generation, and as a key component in fertilizer production[140].

The global methane market, which was valued at approximately USD$86.24 billion in 2022, is projected to reach USD$106.02 billion by 2028. This growth corresponds to a compound annual growth rate (CAGR) of 3.5% during the forecast period from 2022 to 2028[141]. Additionally, biogas, a significant source of renewable methane, has the potential to meet nearly 25% of the global renewable energy demand[142].

The adoption of biogas technology has seen substantial growth in recent years. In the European Union, the number of biogas plants increased from 10,508 in 2010 to approximately 19,000 by 2020, with 880 facilities specifically dedicated to biomethane production[143]. Similarly, in China, as of 2020, there were 172 biomethane plants and 3,150 biogas plants in operation[144].

By 2050, several European countries, including Germany, France, Spain, Poland, and Italy, are expected to contribute more than 50% of the total biomethane production capacity, as depicted in Fig. 9. The production potential in these countries is largely influenced by the availability of biomass resources, with larger land areas typically supporting higher methane yields[145].

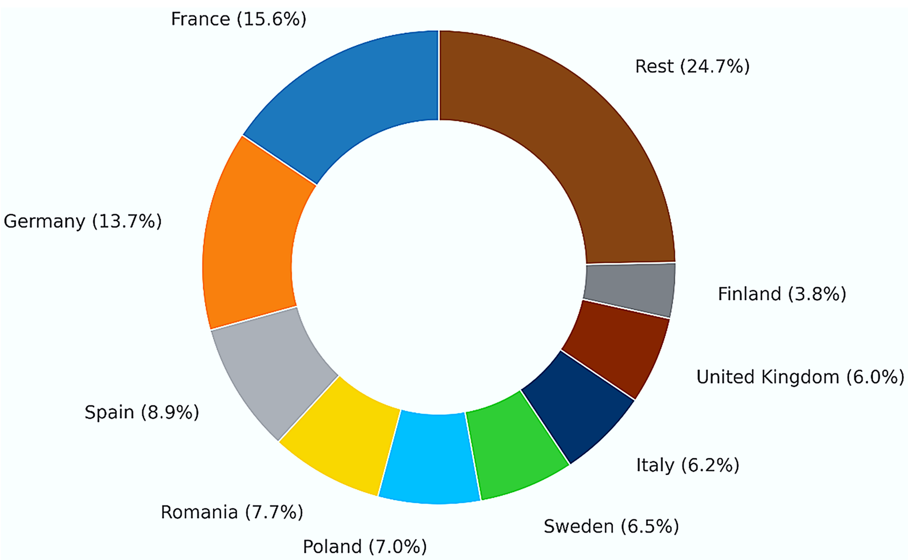

Fig. 9 Bio-based methane production in different countries. Redraw based on the data from Sulewski et al.[146].

A variety of feedstocks, including food waste, microalgae, agricultural residues, MSW, forestry by-products, animal manure, and energy crops, can be utilized for biogas production, further expanding the role of methane in the renewable energy landscape.

Techno-economic analysis of bio-methane

The thermochemical conversion of biomass into methane involves utilizing heat and chemical reactions to break down biomass and produce methane-rich gases. This process typically consists of three primary stages: drying, pyrolysis, and gasification. The resulting syngas undergoes cleaning and upgrading to maximize methane content. Evaluating the economic feasibility of this conversion requires analyzing factors such as total manufacturing costs, capital expenditures, and projected revenue. TEA frameworks incorporate key financial indicators, including return on investment (ROI), discounted payback period, net present value, and internal rate of return (IRR), to assess the profitability and risks associated with biomethane production[146]. Biomass methanation technologies are approaching higher TRLs (6–7), as outlined in the TEA of bio-based syngas, which supports their near-term potential but still demands targeted improvements in catalyst stability and system integration.

Several studies have investigated the biochemical conversion of biomass into biomethane, providing insights into process efficiencies and cost implications[147,148]. The techno-economic comparison of syngas, bio-based H_2, and bio-based methane production from biomass is given in Table 9. Syngas production, typically achieved through fluidized bed gasification, offers operational flexibility but is less efficient (32%–53%) compared to bio-H_2 (69% lower heating value (LHV) efficiency) and biomethane (70.98% system efficiency)[149]. In contrast, biomethane production via methanation achieves high carbon recovery (69.8%) but is hindered by the expense of catalysts[149].

Key economic considerations include initial capital investment in infrastructure and equipment, operational costs such as feedstock procurement, labor, and maintenance, as well as revenue generation from methane sales. The choice of feedstock significantly influences process economics, with woody biomass, agricultural residues, and dedicated energy crops being the primary materials used in gasification-based methane production[39]. Catalyst deactivation and rare-metal cost considerations previously discussed in the syngas TEA section are also highly relevant here, particularly for methanation processes.

The chemical composition and energy content of different biomass feedstocks, as presented in Table 1, play a crucial role in determining product yield and overall economic feasibility. Hernández et al.[150] conducted a comparative analysis of biomethane production costs from various organic waste sources, including food waste, cattle manure, pig manure, and sewage sludge. Their findings indicated that food waste offered the most cost-effective pathway for biomethane production[150].

Capital costs for biomethane production facilities depend on plant scale, required equipment, and regional factors. Larger-scale plants necessitate more sophisticated and expensive equipment, whereas smaller operations may benefit from lower capital expenditures. Operating costs, on the other hand, are influenced by feedstock prices, labor wages, maintenance expenses, and other ongoing operational requirements. The profitability of methane production is further dictated by market demand and pricing, which can fluctuate based on regional natural gas availability and competition from alternative energy sources.

Conducting a TEA for thermochemical biomass conversion provides a comprehensive understanding of the cost-effectiveness of biomethane production. This analysis is essential for determining whether the process can achieve commercial viability and compete with conventional fossil fuels and other renewable energy alternatives.

Life cycle assessment of bio-based methane

Thermochemical biomass conversion for methane production can be evaluated for environmental impacts using LCA. This method allows for a comprehensive assessment of the entire process, starting from the feedstock production phase to the ultimate utilization of the methane. LCA provides insights into the sustainability of biomethane production by identifying key environmental impacts across various stages of the process.

As previously mentioned, multiple steps are involved in utilizing LCA to assess the thermochemical conversion of biomass. These include the production and transportation of feedstocks, the thermochemical conversion process, and the distribution and end-use of the methane once it has been converted. The environmental impacts of these stages can be analyzed by considering factors such as water and energy consumption, carbon emissions, and the release of other pollutants. For example, the production of biomass feedstock may involve the application of pesticides and fertilizers, which can negatively affect ecological balance and water quality. Additionally, CO_2 and other GHGs are released during both the feedstock processing and methane production phases, further influencing the overall carbon footprint of biomethane.

Beyond carbon emissions, the thermochemical conversion process itself may lead to the release of particulate matter and other effluents that can contribute to air pollution. However, biomethane is often regarded as a carbon-neutral fuel because the CO_2 emitted during its combustion is theoretically offset by the carbon absorbed by biomass during its growth phase. This balance makes biomethane a promising alternative to fossil-based methane when properly managed.

Table 9 Techno-economic comparison of syngas, bio-based H_2, and bio-based methane production from biomass

Parameter	Syngas	Bio-based hydrogen	Bio-based methane	Ref.
Production method	Gasification (fluidized/entrained bed)	Gasification + WGS reactors + pressure swing adsorption purification	Gasification + methanation (Ni-based catalysts)	[149]
Energy efficiency	32%–53% exergy efficiency	69% LHV efficiency (steam gasification)	70.98% system efficiency (with heat integration)	[149]
Yield	8–14 MJ/Nm^3 (LHV)	0.057–0.107 kg H_2/kg biomass	0.4–0.6 kg CH_4/kg biomass	[149]
Production cost	USD$0.05–USD$0.15 /m^3	USD$2.90–USD$3.54 /kg	USD$1.37–USD$1.47 /L liquid fuels (via biogas reforming)	[149]
Key cost driver	Gasifier type, O_2 consumption	Gas cleaning, WGS reactors, electrolysis	Methanation catalysts, drying energy	[149]
Carbon recovery	N/A	41%–69% (with CCS)	69.8% (via gasification + methanation)	[149]
Byproduct	Biochar, residual ash	CO_2	Biochar, CO_2 (with CCS)	[149]
TRL	TRL 7–8 (commercial gasifiers)	TRL 6–7 (pilot plants)	TRL 6 (demonstration-scale)	[149]

A comparative study of the GWP for 100 years of various renewable gas production pathways was provided[151]. The study demonstrated that biomethane can significantly reduce emissions when compared to fossil fuels[151]. However, it also highlighted that the results of LCA studies are highly dependent on the boundary conditions and methodological assumptions used in the analysis. The study further indicated that achieving a low GWP does not solely depend on the chosen biomethane production technology but is also influenced by several key factors. These include the storage of digestate in closed tanks for biomethane, the utilization of excess heat for bio-SNG, and the use of renewable electricity throughout the production chain. Properly implementing these factors can lead to a significant reduction in environmental impacts, making biomethane a more sustainable option.

An overview of emissions from different biomethane production processes is presented in Table 10, providing a comparative analysis of various production pathways and their associated environmental impacts. By integrating efficient resource management strategies and optimizing production conditions, biomethane can play a significant role in reducing GHG emissions while contributing to a cleaner and more sustainable energy system.

In addition, most studies that calculated the net energy ratio (NER)—the ratio of total process output energy to total input energy, as defined in Eq. (1)—concluded that the net energy gain was > 1. This finding underscores the significance of biofuels as viable energy sources[156]. Despite their advantages, biofuels present challenges, particularly concerning land use. Land transformation for biofuel production—whether from natural landscapes, agricultural areas, or urban regions—has been identified as a key environmental concern. While many studies have assessed the effects of land use, only a limited number have explicitly treated land use as a functional unit in their analyses[157]. Furthermore, the use of perennial energy crops has been highlighted as a promising strategy for reducing GHG emissions. However, this approach carries the risk of negatively impacting biodiversity by altering natural habitats[158].

$$NER = \frac{\sum Energy\ output}{\sum Energy\ input} \quad (1)$$

While biofuels can reduce GHG emissions, other studies highlight the importance of accounting for the water used in crop irrigation and biomass processing. These studies found that the water used in producing biofuels from cotton straws was less than that used in producing bio-oil for power but much higher than that reported for other sources of renewable energy (such as geothermal, solar photovoltaic, and wind power)[159]. Agricultural production of biomass accounted for 84.6% of all freshwater withdrawals globally[159].

When considering land use and water depletion impacts, waste-derived feedstocks may be more sustainable energy sources than energy crops. Using waste biomass for energy production could reduce the need for farmland, fertilizer, and agricultural water use. The zero-waste hierarchy (Refuse/redesign > Reduce > Reuse > Recycle > Material and Chemicals Recovery > Residuals Management > Unacceptable, e.g., Landfilling of Non-Stabilized Waste/ Energy Recovery) is also consistent with this method of handling waste biomass[160]. The LCA diagram of methane production from biomass is shown in Fig. 10.

The life-cycle cost analysis (LCCA) of thermochemical methane production from biomass provides a comprehensive evaluation of the economic implications across the entire process, from feedstock sourcing to plant decommissioning. Capital costs represent a significant portion of the LCC, with gasification and methanation systems requiring investments of USD$1,200–USD$2,800 per kW of installed capacity. The cost varies depending on plant size, gasifier type (e.g., downdraft or fluidized-bed), and downstream equipment such as gas cleaning units and methanation reactors[81]. Feedstock costs are a critical factor, typically ranging from USD$30–USD$120 per dry ton, depending on the type of biomass (e.g., woody biomass, agricultural residues, or energy crops). These costs generally account for 45%–65% of the total LCC due to procurement, transportation, and preprocessing requirements such as drying and size reduction[82]. Methanation economics hinge on Ni-catalyst stability and drying energy; LCA hinges on methane slip and digestate management where relevant. Routes are TRL 6–7, suited to regions with pipeline access and carbon crediting. Decision-relevant range: net GWP is most sensitive to slip control (< 1%–2%) and renewable electricity in upgrading.

The findings of the LCA and LCCA can inform strategies for mitigating the ecological footprint associated with the thermochemical conversion process. Implementing sustainable practices in feedstock production and promoting renewable energy sources are potential strategies to reduce GHG emissions.

Industrial R&D and case studies

The advancement of sustainable fuels has experienced considerable industrial investigation and innovation, especially in the thermochemical conversion of biomass into gaseous fuels like H_2, syngas, and methane. This section analyzes pilot projects, demonstrations, and insights gained from diverse initiatives globally, with a particular emphasis on the European Union, where numerous biofuel projects have faced technical, economic, and logistical hurdles. The insights gained from these experiences play a vital role in shaping the broader dialogue surrounding the techno-economic and environmental evaluation of biomass conversion technologies, as examined in this review paper.

Table 10 Techno-economic comparison of different SNG and biomethane production processes and their global warming potentials

Process type	Feedstock	Capital expenditure (M USD$)	SNG/biomethane production cost (USD$/MWh)	GWP 100 (kg CO_2 eq/MWh)	Ref.
Biomass					
Biogas to biomethane	Food waste	75.696	38.91	−168 to 316.8	[150]
	Food waste (scaled up 2×)	141.93	31.94	−168 to 316.8	[150]
	Cattle manure	62.016	130.34	−324 to −236	[150]
	Pig manure	55.518	215.55	−241.3 to 211.5	[150]
	Sludge	58.482	123.73	−52.6 to 16.9	[150]
Gasification and methanation	Solid biomass	62.12–131.1	−86.9 to 95.1 (assuming wood)		[152–155]
SCWG	Microalgae	Very optimistic: 82.8–147.6 optimistic: 284.4–464	n.a.		[55]

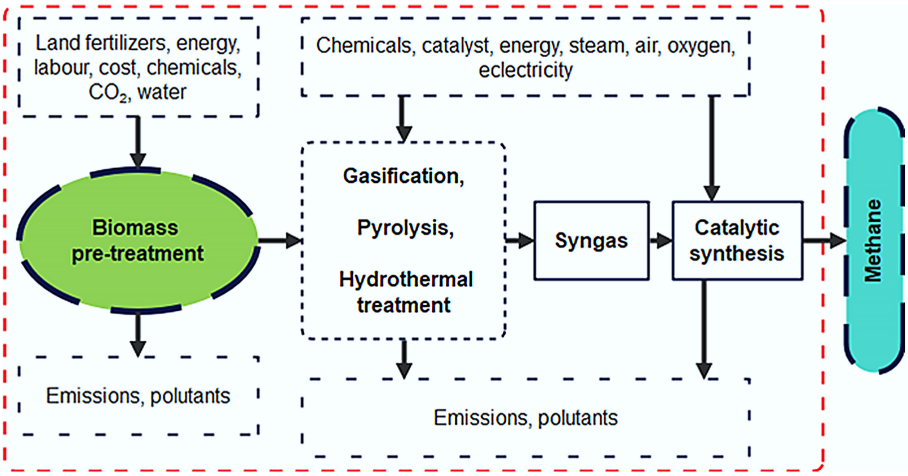

Fig. 10 LCA diagram of methane production from biomass.

Pilot plant case studies

Pilot-scale studies play a critical role in validating biomass thermochemical conversion processes, bridging laboratory research and commercial-scale implementation. The EU has led the way in biofuel studies, implementing numerous initiatives to advance biomass-based gaseous fuels. Nonetheless, several of these initiatives have encountered considerable challenges. The CHRISGAS project, which aimed at producing syngas from biomass through advanced gasification technologies, faced technical challenges concerning feedstock variability and the reliable production of high-quality syngas. This project emphasized the necessity for enhanced feedstock pretreatment and gas cleaning technologies to mitigate tar and other impurities, which are prevalent challenges in biomass gasification processes[51,52]. Additionally, the project's overall success was hindered by cost overruns and delays stemming from inadequate infrastructure for biomass collection and transport in specific regions of Europe[161].

A significant initiative, BioSNG, sought to showcase the production of SNG from woody biomass through gasification. The pilot plant located in Güssing, Austria, which commenced operations in 2008, effectively showcased the technical viability of transforming biomass into methane. Nonetheless, expanding the technology for commercial use uncovered economic hurdles, especially concerning elevated capital expenses and feedstock logistics[162]. Despite these challenges, the project yielded important insights into the possibilities of decentralized gasification plants, which may significantly contribute to local energy systems, particularly in rural or forested areas[163].

Numerous pilot projects in North America have concentrated on H_2 production from biomass. The NREL Thermochemical Pilot Plant in the United States serves as a prominent facility for demonstrating biomass-to-H_2 pathways. The facility employs biomass gasification, subsequent water-gas shift reactions, and CO_2 scrubbing to produce H_2 with a purity level appropriate for fuel cells[164]. The pilot plant has effectively demonstrated the process; however, challenges concerning H_2 separation and purification, along with the substantial energy requirements for the gasification process, continue to pose significant obstacles to commercial viability[165]. In Asia, Japan's Biomass Nippon Strategy has facilitated the establishment of multiple pilot plants in Asia that concentrate on converting local agricultural residues into gaseous fuels. The Osaka Gas Hydrogen Pilot Plant utilizes rice husks and other biomass feedstock for H_2 production through pyrolysis and steam reforming[166]. Despite advancements, a primary challenge in biomass thermochemical conversion remains the substantial capital costs associated with the construction and operation of these facilities. The Horizon 2020 initiative has funded various biofuel projects within the EU, indicating that while small-scale demonstration plants are successful, transitioning to commercial operations frequently necessitates further technological innovation to decrease costs[167].

A notable pilot-scale study was undertaken by VTT Technical Research Centre of Finland, utilizing a dual-fluidized bed gasifier operating at a thermal capacity ranging from approximately 0.5–1 MW. This plant conducted several extended test runs, each lasting 500–1,000 operational hours, consistently producing high-quality syngas from woody biomass feedstocks. Key achievements of this pilot included demonstrating prolonged catalyst effectiveness and successfully employing pressure swing adsorption (PSA) technology to achieve H_2 purity levels greater than 99.9%[168].

In a related effort, the Technical University of Denmark conducted a pilot biomass gasification project from 2020 to 2022. Their setup, designed to process about 100 kg of biomass per hour, incorporated WSG along with PSA purification units. The pilot achieved critical benchmarks, such as stable H_2 production and catalyst durability during test runs exceeding 800 h, thus validating the feasibility of this approach for future scale-up to demonstration-level operations[169].

Demonstration projects

At scales beyond pilot facilities, multiple demonstration projects have proven the practicality of biomass thermochemical conversion for industrial applications. One prominent example is the Gothenburg Biomass Gasification (GoBiGas) project in Gothenburg, Sweden, which was designed to convert forest residues into biomethane using indirect gasification. Active from 2014 to 2018, the GoBiGas plant operated at a thermal input of roughly 20 MW and delivered biomethane of sufficient purity for injection into the national gas grid. This project highlighted its ability to maintain consistent syngas and methane quality, uphold catalyst longevity, and achieve methane conversion efficiencies of 65%–70%. These outcomes collectively confirmed the process's technical and economic viability, even while encountering challenges such as controlling operational costs and managing plant complexity[170].

The GoBiGas project in Sweden is notable for its ambitious approach to methane production from biomass at an industrial scale. The initiative focused on producing biomethane from forest biomass through gasification technology, and the initial phase was successfully completed, yielding high-quality methane suitable for injection into the natural gas grid. Nonetheless, GoBiGas ceased operations in 2018 as a result of economic difficulties, such as elevated operational expenses and a lack of demand for biomethane within the Swedish energy sector[170]. Although the project achieved technical success, its economic viability was compromised by low natural gas prices and a lack of adequate market incentives for biomethane. The GoBiGas case highlights the critical role of policy support and market conditions in influencing the success of biofuel initiatives, even when technical challenges are addressed[170]. Similarly, the NER300 program, initiated by the European Commission to foster innovative low-carbon energy projects, yielded varied outcomes in the biofuels sector. Numerous initiatives, including the VärmlandsMetanol facility in Sweden, which sought to produce methanol from forest residues, faced challenges in progressing past the pilot stage because of financial and technical uncertainties. The VärmlandsMetanol project presents significant environmental advantages; however, it encountered considerable obstacles in securing long-term investment, primarily due to elevated capital costs and the inherent risks linked to scaling up the gasification process[171,172]. This highlights a persistent challenge associated with advanced biofuels: the high initial costs of biomass gasification technologies frequently hinder the attainment of financial sustainability, despite the evident environmental and technical advantages.

Another significant demonstration was the FlexiFuel-SOFC project, supported by EU funding and carried out between 2020 and 2023. This initiative combined adaptable biomass gasification technology with solid oxide fuel cells (SOFC), operating under a budget of approximately EUR€5 million. The project achieved notable progress by reliably generating both heat and electricity from diverse biomass sources. Major achievements included maintaining catalyst efficiency at high operating temperatures, implementing effective strategies for managing tar byproducts, and conducting thorough life-cycle and economic assessments. These advances demonstrated the potential of integrating biomass gasification and SOFCs for distributed, sustainable power generation[173].

Industrial scale-up challenges

Although pilot and demonstration projects have made significant progress, scaling up to full industrial level in biomass thermochemical conversion still presents numerous challenges. High capital and ongoing operational costs, especially those tied to catalyst renewal and intricate system design, continue to be primary obstacles. Issues like catalyst fouling from carbon deposits, poisoning by sulfur, and heat-induced deterioration can substantially increase maintenance expenses and disrupt plant operations. Arregi et al.[174] reported that, at commercial scale, the financial burden of catalyst replacement and regeneration could account for a significant portion of a facility's total operating costs.

The integration of CCS technologies presents a promising approach to enhance the environmental sustainability of biomass-to-gas projects. The BECCS concept, or Bioenergy with Carbon Capture and Storage, has been investigated in various pilot projects, notably the Drax BECCS Pilot in the UK, which aims to capture carbon emissions from biomass combustion and gasification processes[175]. The integration of CCS can substantially decrease net CO_2 emissions; however, the economic viability of these combined systems is uncertain due to the substantial costs associated with capture and storage infrastructure[176]. At a power-system scale, excluding sustainable biomass approximately doubles total costs by 2050; prohibiting CCS raises costs ~78%; the cost of CO_2 removal spans EUR€82–EUR€335 /tCO_2 (−0.85 Gt) but escalates to EUR€1,300–EUR€1,700 /tCO_2 in deep negative scenarios (−3.9 Gt), largely due to DAC electricity demand[74]. However, the inclusion of CCS imposes a significant energy penalty, typically resulting in a 10%–15% decrease in net electrical or fuel conversion efficiency due to additional energy requirements for CO_2 capture, compression, and transport[177,178]. This efficiency drop can reduce the overall plant output and increase both capital and operational costs. Despite this drawback, LCA studies consistently show that CCS substantially enhances the GHG mitigation potential of biomass gasification systems. When CCS is applied, net life-cycle GHG emissions can shift from near-neutral or modestly negative values (e.g., −100 to −300 kg CO_2-eq/MWh) to deeply negative (up to −800 kg CO_2-eq/MWh) depending on feedstock, capture rate, and supply chain configuration[179].

These trade-offs underscore the importance of holistic techno-economic and environmental assessments. While the efficiency penalty and increased cost are non-negligible, the potential to deliver large-scale CO_2 removal (CDR) may justify CCS deployment in policy environments valuing negative emissions[168]. The choice to integrate CCS should consider regional carbon pricing, biomass sustainability, and infrastructure readiness for long-term storage, as these factors critically affect net climate benefits and economic feasibility.

Role of biorefineries in producing sustainable gaseous fuel

Bio-refineries are essential for the sustainable production of gaseous fuels, including syngas, H_2, and methane, utilizing thermochemical conversion methods such as gasification, pyrolysis, and catalytic reforming. Integrated systems offer a comprehensive strategy for optimizing biomass utilization, enhancing efficiency, and minimizing GHG emissions[180]. Syngas, comprising H_2 and carbon monoxide, serves as the foundation for the production of fuels and chemicals. The GoBiGas project in Sweden effectively produced syngas through a dual fluidized bed gasification process, subsequently transforming it into synthetic methane (SNG) via catalytic methanation, demonstrating the multifunctionality of biorefineries in producing various energy carriers[181]. This method improves economic viability and environmental performance, illustrating the function of biorefineries in integrating various processes for increased efficiency.

Syngas production generally entails biomass gasification at higher temperatures with the inclusion of steam or controlled oxygen. Advanced gasification technologies, such as plasma-assisted gasification, have been utilized to enhance syngas quality by minimising tar formation and increasing H_2 content, as demonstrated in the Güssing biorefinery in Austria[53]. The economic feasibility of syngas production is influenced by elevated capital and operational costs, particularly concerning gasifier maintenance and syngas purification systems[52]. The quality of biomass feedstock influences both gasification efficiency and syngas yield. The BioSNG project faced challenges in maintaining consistent syngas quality due to the variability of biomass feedstock, which required the implementation of advanced pre-treatment technologies to stabilise input materials[162].

The production of H_2 from syngas generally entails the WGS reaction, in which CO_2 reacts with steam to produce additional H_2 and CO_2. This process enhances H_2 yield and is typically succeeded by CO_2 separation to achieve high-purity H_2[131]. The H2Future project in Austria illustrated H_2 production from biomass syngas by integrating biomass gasification with renewable electrolysis to enhance reactor conditions and minimize emissions[182]. This integration demonstrates techno-economic potential but underscores the necessity for substantial investment in advanced electrolysers and CO_2 capture systems to attain competitive costs[183,184]. The production of methane in biorefineries entails the catalytic methanation of syngas. Nickel-based catalysts are widely utilized for their efficiency and cost-effectiveness; nonetheless, catalyst deactivation poses a considerable challenge that impacts long-term economic viability[185]. The development of catalysts is a key area for improving methane production systems, with research focused on dual-functional and more robust catalysts to enhance stability and decrease operational costs[186].

System optimization in biorefineries is essential for enhancing the efficiency of syngas, H_2, and methane production. Advanced reactor designs and process control systems enable biorefineries to optimize conditions, minimize tar formation, and enhance gas quality[187]. The BioRefine-2G project demonstrated that steam-assisted gasification at regulated temperatures can enhance syngas quality, resulting in higher yields of H_2 and methane[188]. The findings correspond with existing research that highlights the necessity of advanced gas cleaning technologies, including plasma-assisted reactors and catalytic tar reforming, for the production of high-quality syngas appropriate for subsequent conversion into H_2 or methane[176].

The environmental sustainability of biorefineries is determined by the selection of feedstock, the efficiency of conversion processes, and the management of emissions. LCA indicates that biorefineries utilizing sustainably sourced feedstock, including agricultural and forestry residues, can markedly reduce GHG emissions in comparison to fossil-based systems[178]. The BEST initiative showed that methane production from agricultural residues can result in up to 85% reductions in GHG emissions compared to conventional natural gas[189]. Unsustainable biomass cultivation practices can result in indirect land-use changes (ILUC), potentially undermining the environmental advantages of biorefineries[190]. The incorporation of biochar production within gasification processes enhances sustainability through carbon sequestration and improved soil health, thereby supporting biorefinery systems[191].

Bio-refineries have incorporated carbon capture and utilization technologies to enhance emission reduction efforts. The Drax BECCS pilot project in the UK serves as a prime example, capturing CO_2 during biomass gasification and storing it underground, thereby achieving negative emissions[192]. Nonetheless, these systems increase overall costs because of the requirements for CO_2 capture, compression, and storage infrastructure[193]. TEA demonstrates that policy support, including carbon credits and subsidies, is crucial for ensuring the economic viability of these integrated systems[167].

Ramos & Rouboa[50] emphasized that plasma gasification within biorefineries not only yields gaseous fuels but also generates vitrified slag as a by-product, which can be repurposed as a secondary raw material in industries such as construction, aligning with circular economy principles[194]. The environmental benefits of this approach include reduced GHG emissions, with plasma gasification achieving a GWP of −31 to 422 kg CO_2-equ., contributing to decarbonization objectives[76]. Biorefineries employing plasma gasification can realize substantial economic benefits, with an annual revenue of USD$3.2 million and high conversion efficiencies (20%–45%) for gaseous fuel production[66]. However, challenges persist in standardizing LCSA methodologies, particularly for S-LCA, due to limitations in data availability and indicator selection[195]. Ramos & Rouboa[50] suggest that developing harmonized assessment frameworks and implementing supportive policies could enhance the adoption of plasma gasification in biorefineries, positioning them as a key component of sustainable gaseous fuel production from biomass.

Feedstock logistics represent a significant element influencing the economic and environmental outcomes of biorefineries. Decentralized biorefineries, such as those implemented in the GoBiGas and BioSNG projects, effectively reduce transportation distances, leading to lower costs and emissions[196]. Identifying biorefineries in proximity to biomass sources enhances economic viability by streamlining local biomass supply chains and minimizing the carbon emissions linked to long-distance biomass transportation[197]. The effectiveness of these models depends on the establishment of efficient systems for biomass harvesting, storage, and transportation to guarantee a stable and sustainable supply chain.

Regardless of technological progress, the substantial capital costs continue to pose a major obstacle to the expansion of biorefineries. Advancing scaling efforts necessitates additional innovations, especially in the realms of catalyst development and process efficiency[198]. Plasma-assisted catalysts demonstrate promise in enhancing conversion efficiency and lowering costs[39]. These advancements are essential for ensuring that H_2 and methane production from biomass can compete effectively with fossil fuel alternatives. The incorporation of renewable energy sources like wind and solar significantly boosts efficiency and lowers emissions. However, this strategy necessitates considerable investment, as evidenced by the H2Future project[199].

Future research perspectives

Integrated comparative assessment approach

There is currently a lack of a holistic assessment approach that integrates LCA and TEA across various biomass thermochemical conversion pathways for gaseous fuel production. Conducting comparative TEA and LCA analyses with methodological rigor would enable straightforward comparisons among different biomass conversion routes. Such analyses will improve understanding of both economic feasibility and environmental implications, facilitating informed decision-making regarding the optimal pathways.

Standardization in LCA

The variability in methods, standards, and functional units used in LCA analyses presents challenges for making meaningful comparisons across studies. Establishing a standardized and rigorous LCA framework, agreed upon by stakeholders, is essential to ensure coherence and reliability in sustainability assessments. This standardization should focus on enhancing transparency in research methodologies and the presentation of findings, thereby increasing the credibility and usefulness of LCAs as a comprehensive tool for sustainability evaluations.

Techno-economic and Life-cycle assessment of carbon capture and gasification

Further research is needed to conduct an integrated comparative examination of techno-economic and life-cycle aspects related to carbon capture and the thermochemical conversion of biomass via gasification to produce syngas. Such analyses hold the potential to mitigate environmental burdens from biomass utilization while reducing carbon emissions. Evaluating both the economic feasibility and environmental implications of these processes could lead to sustainable energy production and offer valuable insights into optimizing biomass utilization strategies and reducing carbon footprints.

CO_2 enhanced gasification process

The CO_2 enhanced gasification process has the potential to significantly reduce PM and carbon emissions. This process could play a crucial role in reducing environmental impacts and promoting more sustainable biomass conversion methods.

Advancements in catalyst technology

There is an urgent need for advancements in catalyst technology to reduce costs and improve process efficiency. Overcoming the challenges associated with expensive catalysts and the production of harmful by-products is crucial for advancing biomass thermochemical conversion technologies.

Optimization of biomass-to-hydrogen process chain

Future research should prioritize optimizing the entire biomass-to-H_2 process chain, including biomass pretreatment, gasification, syngas purification, and H_2 synthesis. This optimization would maximize resource utilization while minimizing environmental impacts, making the process more efficient and sustainable.

Advanced sustainability evaluation methodologies

Integrating advanced methodologies like exergy analysis with traditional LCA and economic assessment frameworks can provide a more comprehensive understanding of the economic, environmental, and societal implications of different H_2 production platforms. This approach will enhance the overall sustainability assessment of these technologies.

Exploration of novel biomass sources

Exploring novel biomass sources, such as eucalyptus and other high-H_2 gas-yielding types, should be a priority in future research. These sources could improve both the economic viability and environmental sustainability of biomass thermochemical conversion processes, making them more attractive options for large-scale deployment.

Interdisciplinary collaboration and innovation

Interdisciplinary collaboration and innovation-driven research are essential for unlocking the full potential of biomass thermochemical conversion technologies. These efforts will be vital in accelerating the transition toward a greener, carbon-neutral energy future.

This analysis comprehensively investigates the significance of biomass in the context of sustainable H_2 production, highlighting thermochemical methods such as gasification. This paper emphasizes the integration of biomass-based H_2 within the larger H_2 economy and energy transition, aligning with global decarbonisation objectives. It underscores the technology's capacity to foster diverse, resilient, and regionally equitable energy systems.

Conclusions

This review underscores the critical importance of transitioning from a fossil fuel-dependent economy to a sustainable, bio-based energy system in response to the escalating global energy demand and the pressing need to mitigate climate change impacts. It highlights the significant role of biomass as a renewable, carbon-neutral resource capable of reducing GHG emissions significantly when substituted for fossil fuels in energy production. The discussion points to the increasing reliance on intricate bio-renewable feedstocks and the potential of advanced second- and third-generation biofuels to address the challenges associated with first-generation biofuels, including indirect land use change. This review also acknowledges the global shift in policy frameworks towards supporting the production and utilization of these advanced biofuels, with a specific focus on the TEA and LCA methodologies as essential tools for evaluating the viability and environmental impacts of biofuel production technologies, especially for syngas, hydrogen, and methane production. By situating biomass within the broader context of renewable energy sources and emphasizing the necessity for scientific and reliable methodologies to assess biofuels' advantages, this review sets the stage for a detailed exploration of the techno-economic and environmental considerations of thermochemical conversion of biomass into gaseous fuels.

This review article delves into the comprehensive landscape of syngas production from biomass, underscoring its pivotal role as an intermediate for synthesizing many bulk chemicals and biofuels. It highlights the process of biomass gasification as a versatile method for syngas production, capable of utilizing a variety of feedstocks like wood, agricultural waste, and MSW. This process, characterized by its high temperatures and controlled oxygen environment, is poised for growth due to the global shift towards sustainable energy sources. Through the TEA, factors such as capital and operating costs, revenue potential, and sensitivity to market fluctuations are examined, providing a blueprint for economic viability. Moreover, the LCA presents an in-depth analysis of the environmental impacts associated with syngas production, from raw material extraction to waste disposal. It emphasizes the significant advantages of biomass gasification regarding GHG mitigation and reduced dependency on fossil fuels. The synergistic evaluation of TEA and LCA elucidates the multifaceted benefits of syngas production, including economic incentives and environmental stewardship.

The TEA and LCA of hydrogen and methane production from biomass thermochemical conversion underscore the potential and challenges of transitioning towards renewable energy sources. TEA reveals that while biomass thermochemical conversion processes are technologically diverse and evolving for hydrogen production, their economic viability hinges on improving process efficiencies, reducing capital and operating costs, and scaling up production. Compared to fossil fuel-based methods, the high cost of hydrogen production from biomass poses a significant barrier to commercialization despite the environmental benefits. LCA studies indicate that bio-based hydrogen can significantly reduce GHG emissions, highlighting its environmental advantage over conventional hydrogen production methods.

Similarly, the production of methane through the thermochemical conversion of biomass presents a promising pathway for renewable energy. TEA analyses emphasize the importance of selecting appropriate feedstocks and optimizing process designs to enhance economic feasibility. The environmental benefits, as illustrated by LCA, include reduced GHG emissions and the potential for sustainable feedstock management, especially when utilizing waste biomass. Both TEA and LCA underscore the necessity for innovation in process technology, efficient resource utilization, and the development of supportive policy frameworks to realize the full potential of bio-based syngas, hydrogen, and methane as pivotal components of a sustainable energy future.

Author contributions

The authors confirm contributions to the paper as follows: Muhammad Saddam Hussain led the conceptualization and methodology and wrote the original draft; Meng Shi contributed to data curation, formal analysis and visualization; Shiyu Zhang contributed to validation and writing, review and editing; Yeshui Zhang contributed to investigation, provision of resources and writing, review and editing; Xuan Bie contributed to writing, review and editing; Qinghai Li contributed to validation; Yanguo Zhang contributed to conceptualization; Sebastian Lubjuhn contributed to writing, review and editing; Sandra Venghaus contributed to supervision and writing, review and editing; Hui Zhou contributed to conceptualization, supervision and writing, review and editing. All authors reviewed the results and approved the final version of the manuscript.

Data availability

This article is a critical review and does not report any new primary data. All data and information discussed are drawn from previously published studies and publicly available sources, which are fully cited in the reference list. Additional clarifications can be obtained from the author upon reasonable request.

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Declarations

Competing interests

The author declares that there is no conflict of interest.

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