processes

MDPI

Review

Thermochemical Biomass Conversion for Sustainable Hydrogen Production: A Review of Techno-Economic Performance and Decarbonization Potential

Cristian Laverde-Albarracín [1,2], Sergio Nogales-Delgado [3,*], Juan Félix González-González [3], Sebastián Naranjo-Silva [4] and Jorge Maldonado-Correa [5]

1 Faculty of Engineering Sciences, Technical State University of Quevedo, Quevedo 120301, Ecuador; claverde@uteq.edu.ec
2 Postgraduate Studies Department, ECOTEC University, Km 13.5, Samborondón 092302, Ecuador
3 Department of Applied Physics, University of Extremadura, 06006 Badajoz, Spain; jfelixgg@unex.es
4 Industrial Process Facilitation Department, Ministry of Production of Ecuador, Amazonas Av., Quito City 170519, Ecuador; hector.sebastian.naranjo@upc.edu
5 Technological and Energy Research Center (CITE), National University of Loja, Loja 110111, Ecuador; jorge.maldonado@unl.edu.ec
* Correspondence: senogalesd@unex.es

Abstract

Hydrogen is a strategic energy carrier for decarbonizing hard-to-abate sectors; however, current production remains fossil-based, while the economics and utilization of renewable electrolysis depend strongly on the availability and variability of low-carbon electricity. Thermochemical biomass conversion offers a complementary route because biomass can be stored, dispatched, and sourced from residues, wastes, and bioeconomy streams. This study systematically reviews the thermochemical pathways for sustainable hydrogen production, integrating technical performance, feedstock suitability, process upgrading, techno-economic feasibility, life-cycle impacts, and decarbonization potential. Following a PRISMA-based methodology, 111 core studies were included in the systematic review, while 26 review articles were analyzed separately as the supporting literature. Unlike previous reviews that primarily centered on technology- and reactor-level comparisons, the present synthesis places particular emphasis on the economic and deployment conditions governing biomass-to-hydrogen feasibility, including LCOH, plant scale, feedstock logistics, purification boundaries, and carbon-management assumptions. Gasification appeared in 96 core studies and showed the strongest maturity evidence among the reviewed thermochemical pathways, including pilot-scale integrated operation with downstream gas cleaning, water–gas shift, and hydrogen purification, although numerical TRL values were not consistently reported. Reported H_2 concentrations ranged from approximately 8–16 vol% in conventional air/oxygen gasification and 30–60 vol% in steam-based gasification. Advanced capture-assisted systems achieved 78–81.1 vol% H_2, while pilot-scale purification reached 98.6 vol%. Reported economic values varied substantially across metric definitions, plant scales, currencies, and system boundaries. Accordingly, LCOH, minimum selling price, and hydrogen production cost were treated as distinct metrics, and original currencies and economic reference years were retained when available rather than pooled into a single cross-study cost range.

Keywords: biomass gasification; sustainable hydrogen; thermochemical conversion; techno-economic assessment; life-cycle assessment; carbon capture and storage; circular economy

Check for updates

Academic Editor: Abhijeet Singh

Received: 24 August 2026
Revised: 24 September 2026
Accepted: 2 October 2026
Published: 29 October 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

1. Introduction

Global energy systems remain strongly dependent on fossil fuels despite the accelerated deployment of renewable energy technologies in recent decades. The rapid industrialization of emerging economies, population growth, urban expansion, digitalization, and increasing electrification of industrial and transportation sectors continue to drive global energy demand upward. According to recent international energy assessments, global energy consumption increased significantly during the last decade, with oil, coal, and natural gas still accounting for the dominant share of the global energy mix despite substantial investments in renewable energy infrastructure [1,2]. Although renewable electricity generation from solar and wind sources has expanded rapidly, fossil fuels continue to underpin industrial production, transportation, petrochemical manufacturing, fertilizer synthesis, and large-scale thermal power generation. Consequently, global energy-related CO_2 emissions have remained at historically high levels, exceeding 38 Gt in recent years, highlighting the limitations of current decarbonization trajectories and the complexity of achieving climate neutrality within highly interconnected industrial systems [1,2]. Beyond the structural dependence on fossil resources, modern energy systems are increasingly exposed to external disruptions associated with geopolitical conflicts, climate variability, supply chain fragility, and infrastructure constraints. These challenges reinforce the need for diversified, resilient, and low-carbon energy systems capable of improving both energy security and environmental sustainability [3,4]. Consequently, alternative energy carriers that support decarbonization while reducing dependence on fossil resources have attracted growing scientific and industrial interest [5–7].

Among these alternatives, hydrogen has emerged as one of the most promising energy carriers for enabling deep decarbonization across hard-to-abate sectors, including steelmaking, heavy transportation, ammonia production, refining, and chemical manufacturing. Hydrogen has the highest gravimetric energy density among common fuels; however, its very low volumetric energy density under ambient conditions represents a major limitation for storage and transportation. Consequently, compression, liquefaction, or conversion into chemical hydrogen carriers is generally required, increasing energy consumption, infrastructure requirements, and overall system costs [8,9]. Nevertheless, despite its increasing relevance within climate mitigation strategies, current global hydrogen production remains overwhelmingly dependent on fossil fuels. Recent estimates indicate that approximately 95–96% of worldwide hydrogen production is still generated through carbon-intensive pathways, particularly steam methane reforming (SMR), partial oxidation, and coal gasification [9,10].

Steam methane reforming remains the dominant industrial hydrogen production technology due to its technological maturity, relatively high conversion efficiency, established infrastructure, and comparatively low production cost [11–13]. In the SMR process, methane reacts with steam at elevated temperatures to produce synthesis gas rich in hydrogen and carbon monoxide, followed by water–gas shift reactions that further increase hydrogen yield. Despite its industrial attractiveness, this route generates substantial CO_2 emissions and reinforces long-term dependence on natural gas supply chains [8,11]. Furthermore, fossil-based hydrogen systems contribute to "carbon lock-in" dynamics, where the economic competitiveness and existing infrastructure of methane-derived hydrogen delay the large-scale adoption of renewable alternatives [14].

The implications of fossil-based hydrogen production extend far beyond the energy sector because hydrogen is also a critical feedstock for synthetic ammonia and nitrogen fertilizer production. Conventional Haber–Bosch synthesis depends heavily on hydrogen derived from natural gas through SMR, linking fertilizer production directly to fossil fuel markets [12,13,15,16]. Since ammonia production is highly energy-intensive, fluctua-

tions in natural gas availability and price volatility can propagate throughout agricultural commodity markets and global food systems. Consequently, rising gas prices or supply disruptions may substantially increase fertilizer costs, affecting agricultural productivity, food affordability, and economic stability at multiple scales [12,13,17]. These interconnections demonstrate that fossil-based hydrogen systems create systemic vulnerabilities that extend beyond energy security into the broader water–energy–food nexus.

Several technological strategies have been proposed to reduce the environmental impact of conventional hydrogen production systems. Process intensification, heat recovery integration, sorption-enhanced reforming, electrified reforming, carbon capture and storage (CCS), and renewable natural gas utilization have demonstrated potential for improving process efficiency and reducing net carbon emissions [13,18–20]. Nevertheless, these approaches still fundamentally depend on methane-based infrastructures and fossil-derived feedstocks. Therefore, although natural gas may temporarily function as a transitional fuel supporting energy system flexibility and low-carbon hydrogen deployment [21], its structural limitations and associated carbon emissions highlight the urgent need for fully renewable and resilient hydrogen production pathways.

Renewable-powered water electrolysis represents a key pathway for low-carbon hydrogen production when coupled with renewable electricity sources such as solar, wind, geothermal, or hydropower [22–25]. Alkaline water electrolysis (AWE), proton exchange membrane electrolysis (PEM), and solid oxide electrolysis cells (SOEC) are among the principal technologies currently investigated, while their integration with renewable energy systems can contribute to greenhouse-gas mitigation and broader energy-system decarbonization [22,23,26,27]. However, the economic and operational performance of electrolysis-based hydrogen remains dependent on renewable-electricity availability, storage, grid integration, infrastructure requirements, and capital costs [26–31]. Therefore, although renewable electrolysis is a fundamental component of future low-carbon energy systems, complementary renewable pathways capable of supporting dispatchable and feedstock-based hydrogen production remain relevant [27,28]. Within this scenario, biomass-derived hydrogen has emerged as a highly promising complementary pathway capable of addressing some limitations associated with electricity-driven hydrogen systems. Biomass represents a chemically stored renewable resource that can support dispatchable hydrogen production; however, it is not inherently easy or inexpensive to transport. Low bulk density, variable moisture content, seasonal availability, dispersed collection points, heterogeneous particle size, and degradation during storage may substantially increase handling, preprocessing, storage, and transportation costs. Consequently, the economic feasibility of biomass-to-hydrogen systems depends on feedstock densification, regional supply radius, plant location, decentralized preprocessing, and reliable long-term supply chains [32–37]. Biomass resources include agricultural residues, forestry by-products, municipal organic waste, industrial residues, algae, sewage sludge, and lignocellulosic feedstocks, many of which remain underutilized despite their substantial energy potential [29–32].

Thermochemical biomass conversion provides several pathways for producing hydrogen-rich gas, including gasification, pyrolysis, steam reforming, hydrothermal gasification, and supercritical water gasification (SCWG) [29,33]. Among these routes, biomass gasification is one of the most mature and widely investigated because of its feedstock flexibility, scalability, and compatibility with downstream hydrogen-upgrading technologies [29,30,33]. Steam- and oxygen-assisted configurations can enhance hydrogen-rich syngas production, whereas hydrothermal and supercritical-water routes are particularly relevant for high-moisture feedstocks that would otherwise require energy-intensive drying [29,30,33].

Current developments increasingly focus on process intensification through catalytic conversion, water–gas shift integration, CO_2 sorption, staged reactors, gas cleaning, and hydrogen separation to improve hydrogen yield, purity, and overall process efficiency [34,38–40]. These advances demonstrate that the performance of biomass-to-hydrogen systems depends not only on the primary thermochemical conversion step but also on the integration of downstream upgrading and purification processes.

Recent research has increasingly focused on integrating thermochemical biomass conversion with renewable electrolysis systems to improve process efficiency and overall sustainability. Hybrid systems combining photovoltaic-powered electrolysis with biomass gasification have demonstrated significant synergies, particularly through the reutilization of oxygen generated during electrolysis as a gasifying agent in oxy-steam gasification systems [34,35]. Consequently, biomass and electrolysis are increasingly viewed not as competing pathways but as complementary technologies capable of enabling more resilient and integrated renewable hydrogen systems [34,35].

In addition to their energy advantages, biomass-to-hydrogen systems strongly align with circular economy principles because they enable waste valorization, resource recovery, and decentralized carbon management [15,18,19,30–32]. Agricultural residues, forestry waste, industrial by-products, and municipal organic waste can be valorized through waste-to-energy pathways to produce useful energy carriers, while supporting improved waste management and reducing the environmental impacts associated with disposal [36]. Furthermore, integrating biomass conversion systems with carbon capture technologies, biochar stabilization, and renewable electricity inputs may enable low-carbon or even carbon-negative hydrogen production pathways [18,30,31]. These characteristics position thermochemical biomass conversion as a potentially strategic component within future sustainable and circular energy systems.

Nevertheless, despite substantial progress in recent years, several technical, economic, and operational barriers continue to limit the large-scale deployment of biomass-derived hydrogen systems. Feedstock heterogeneity, variable moisture content, ash accumulation, tar formation, catalyst deactivation, reactor fouling, gas cleaning requirements, logistics complexity, and uncertain techno-economic feasibility remain critical challenges [29,33]. Although numerous reviews have examined individual aspects of biomass-to-hydrogen technologies, including gasification, catalytic reforming, and reactor optimization, few studies have integrated techno-economic performance, life-cycle environmental assessment, bioenergy with carbon capture and storage BECCS integration, hydrogen purification, renewable hybridization, and scalability within a single systematic framework. Bioenergy with carbon capture and storage (BECCS) combines biomass conversion with the capture, transport, and permanent geological storage of biogenic CO_2. When biomass regrowth, upstream supply-chain emissions, capture efficiency, CO_2 transport, and storage permanence are properly accounted for, BECCS may result in net-negative life-cycle emissions. However, carbon-negative performance cannot be assumed solely because biomass and carbon capture are used; it must be demonstrated through transparent life-cycle carbon accounting [41–43]. Although several previous reviews have compared thermochemical pathways for biomass-derived hydrogen production, their primary emphasis has generally been on conversion technologies, reactor performance, catalysts, and hydrogen-rich syngas production. Consequently, the novelty of the present review does not lie in introducing a new thermochemical pathway or in repeating a technology-by-technology comparison. Instead, it provides a systematic, system-level assessment with particular emphasis on the economic and deployment conditions governing the feasibility of these technologies. The analysis integrates hydrogen performance with CAPEX, OPEX, LCOH, plant scale, feedstock logistics, purification requirements, financial assumptions, life-cycle carbon in-

tensity, CCS/BECCS integration, and technology readiness across 111 original studies. By linking technical performance with economic, environmental, and deployment-related boundaries, this review aims to identify not only how biomass-to-hydrogen technologies perform, but also the conditions under which specific pathways may become technically, economically, and environmentally viable at relevant deployment scales. Furthermore, the review identifies current research gaps, scale-up challenges, and future opportunities for integrating biomass conversion technologies into resilient, circular, and sustainable hydrogen production systems.

2. Materials and Methods

2.1. Study Design and Literature Search

This study was conducted as a Systematic Literature Review (SLR) focused on thermochemical biomass conversion for sustainable hydrogen production. The review was developed and reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) framework to ensure methodological transparency, reproducibility, and rigorous evidence selection [37]. The methodological structure was additionally informed by systematic review frameworks adapted for engineering-oriented research, which organize the review process into planning, conducting, and reporting phases [38]. Given the multidisciplinary nature of biomass-derived hydrogen systems and the heterogeneity of feedstocks, reactor configurations, operating conditions, hydrogen purification technologies, economic assumptions, and life-cycle boundaries, a structured thematic synthesis was adopted rather than a quantitative meta-analysis. The methodological approach was also aligned with recent PRISMA-compliant reviews in renewable-energy and advanced-energy research [44,45].

The review was guided by six research questions:

RQ1: What are the main thermochemical biomass conversion pathways investigated for sustainable hydrogen production, and how do they differ in terms of maturity, process integration, and hydrogen-oriented performance?

RQ2: Which biomass feedstocks are most suitable for thermochemical hydrogen production, and how do feedstock properties influence pathway selection, pretreatment requirements, hydrogen yield, and syngas quality?

RQ3: What technical performance indicators are reported for biomass-based hydrogen systems, including H_2 yield, H_2 concentration, H_2 recovery, final H_2 purity, syngas composition, conversion efficiency, operating conditions, and purification requirements?

RQ4: What techno-economic indicators are reported for biomass-derived hydrogen systems, including CAPEX, OPEX, LCOH, payback period, NPV, IRR, TRL, cost drivers, and sensitivity parameters?

RQ5: What environmental and decarbonization indicators are used to evaluate biomass-derived hydrogen systems, including LCA boundaries, carbon intensity, CO_2 mitigation potential, CCS/BECCS integration, and carbon-negative performance?

RQ6: What are the principal technological barriers, process-integration opportunities, scale-up challenges, and future research directions for large-scale deployment of sustainable biomass-derived hydrogen systems?

A systematic literature search was performed in Scopus, Web of Science (WoS), and IEEE Xplore because of their broad coverage of energy engineering, hydrogen systems, thermochemical conversion technologies, and environmental assessment. The search strategy combined predefined keyword groups and Boolean operators related to biomass feedstocks, hydrogen production, thermochemical conversion, and techno-economic or environmental assessment. The semantic structure of the search strategy and keyword categorization adopted for the systematic literature review is summarized in Table 1.

Table 1. Semantic search structure and keyword categorization adopted for the systematic literature review.

Layer	Category	Search Terms
SL 1	Biomass	(“biomass” OR “lignocellulosic biomass” OR “agricultural residues” OR “forestry residues” OR “municipal biowaste” OR “sewage sludge” OR “algal biomass” OR “microalgae” OR “macroalgae” OR “seaweed”)
SL 2	Hydrogen Production	AND (“green hydrogen” OR “hydrogen production” OR “biohydrogen”)
SL 3	Thermochemical Conversion	AND (“gasification” OR “pyrolysis” OR “steam reforming” OR “supercritical water gasification” OR “thermochemical conversion”)
SL 4	Techno-economic and Environmental Assessment	AND (“LCOH” OR “CAPEX” OR “OPEX” OR “techno-economic analysis” OR “life cycle assessment” OR “LCA” OR “BECCS” OR “carbon capture” OR “decarbonization”)

Based on the semantic structure presented in Table 1, the principal integrated search script was developed as shown in Table 2. This query provided the core retrieval framework for identifying scientific literature related to thermochemical biomass conversion pathways for sustainable hydrogen production.

Table 2. Integrated search script used for the systematic literature review query.

Database	Search Field/Syntax	Complete Search String
Scopus	TITLE-ABS-KEY	TITLE-ABS-KEY ((“biomass” OR “lignocellulosic biomass” OR “agricultural residues” OR “forestry residues” OR “municipal biowaste” OR “sewage sludge” OR “algal biomass” OR “microalgae” OR “macroalgae” OR “seaweed”) AND (“green hydrogen” OR “hydrogen production” OR “biohydrogen”) AND (“gasification” OR “pyrolysis” OR “steam reforming” OR “supercritical water gasification” OR “thermochemical conversion”) AND (“LCOH” OR “CAPEX” OR “OPEX” OR “techno-economic analysis” OR “life cycle assessment” OR “LCA” OR “BECCS” OR “carbon capture” OR “decarbonization”))
Web of Science Core Collection	TS=	TS = ((“biomass” OR “lignocellulosic biomass” OR “agricultural residues” OR “forestry residues” OR “municipal biowaste” OR “sewage sludge” OR “algal biomass” OR “microalgae” OR “macroalgae” OR “seaweed”) AND (“green hydrogen” OR “hydrogen production” OR “biohydrogen”) AND (“gasification” OR “pyrolysis” OR “steam reforming” OR “supercritical water gasification” OR “thermochemical conversion”) AND (“LCOH” OR “CAPEX” OR “OPEX” OR “techno-economic analysis” OR “life cycle assessment” OR “LCA” OR “BECCS” OR “carbon capture” OR “decarbonization”))
IEEE Xplore	All Metadata	((“biomass” OR “lignocellulosic biomass” OR “agricultural residues” OR “forestry residues” OR “municipal biowaste” OR “sewage sludge” OR “algal biomass” OR “microalgae” OR “macroalgae” OR “seaweed”) AND (“green hydrogen” OR “hydrogen production” OR “biohydrogen”) AND (“gasification” OR “pyrolysis” OR “steam reforming” OR “supercritical water gasification” OR “thermochemical conversion”) AND (“LCOH” OR “CAPEX” OR “OPEX” OR “techno-economic analysis” OR “life cycle assessment” OR “LCA” OR “BECCS” OR “carbon capture” OR “decarbonization”))

The principal database search was executed on 16 January 2026 and covered publications from 2010 up to that date. The complementary technical searches were conducted using the same database-specific search fields and predefined eligibility criteria, while omitting the SL4 techno-economic/environmental block. During the revision stage, a supplementary literature update was conducted on 20 June 2026 using Scopus, Web of Science Core Collection, and IEEE Xplore to identify newly published studies within the same review scope, with particular attention to microalgae, macroalgae, seaweed, integrated water–gas shift systems, and multigeneration configurations. Records identified during this update were screened using the same inclusion and exclusion criteria applied to the principal search and, when eligible, were incorporated into the final set of 111 core studies rather than analyzed as a separate dataset. In addition to the integrated search script shown in Table 2, complementary technical searches were conducted without the SL4 techno-economic/environmental block to retrieve studies focused primarily on technical performance, process integration, and hydrogen purification.

During the revision stage, a targeted supplementary update was conducted in June 2026 to identify newly published peer-reviewed studies relevant to the review scope, including studies on microalgae, macroalgae, seaweed, integrated water–gas shift systems, and multigeneration configurations. Earlier foundational studies identified through backward reference screening were also retained when they met the predefined eligibility criteria. These supplementary records were incorporated into the thematic synthesis and documented in the study-level evidence matrix to preserve methodological transparency and traceability.

2.2. Eligibility and Study Selection

Peer-reviewed English-language journal articles indexed in Scopus, Web of Science, or IEEE Xplore were considered eligible when they addressed hydrogen production through thermochemical biomass conversion and reported at least one relevant technical, techno-economic, environmental, process-integration, hydrogen-purification, or carbon-mitigation indicator. Full-text availability was required. Studies focused exclusively on biochemical hydrogen production, catalyst chemistry without system-level energy analysis, or topics without explicit relevance to hydrogen production were excluded. Duplicate records, inaccessible full-text articles, grey literature, institutional reports, patents, unpublished theses, editorials, conference summaries, opinion papers, and commentaries lacking an explicit methodology were also excluded [37].

The study-selection process followed the PRISMA 2020 workflow [37] and comprised four stages: identification, screening, eligibility assessment, and final inclusion. Records retrieved from the selected databases were exported to a reference-management system for duplicate removal, followed by title-and-abstract screening according to the predefined eligibility criteria. Potentially relevant studies subsequently underwent full-text assessment, and articles that did not meet the inclusion criteria were excluded from the final evidence base. The methodological sequence is summarized in Figure 1.

Title-and-abstract screening and subsequent full-text eligibility assessment were initially performed by one reviewer using the predefined inclusion and exclusion criteria. A second reviewer independently verified the eligibility decisions, particularly for potentially ambiguous records. Any discrepancies were discussed until consensus was reached before final inclusion or exclusion. This verification procedure was used to reduce selection bias and improve the reproducibility of the study-selection process.

After duplicate removal, 4874 records underwent title-and-abstract screening. A total of 4740 records were excluded at this stage because they did not meet the predefined scope and eligibility criteria, leaving 134 reports for full-text retrieval and eligibility assessment. All 134 reports selected for full-text assessment were successfully retrieved. Following full-text evaluation, 23 reports were excluded because they did not satisfy the predefined eligibility criteria: eight were outside the thermochemical biomass-to-H_2 scope, six focused exclusively on catalysts without system-level hydrogen assessment, five lacked sufficient hydrogen-production relevance or quantitative system-level data, and four failed to meet other predefined eligibility criteria. This resulted in 111 original studies included in the final systematic evidence base.

The final systematic evidence base comprised 111 original studies, while 26 review articles were retained separately as supporting literature for contextualization, comparison with previous reviews, and research-gap identification. The review articles were not merged with the primary evidence base used for the systematic synthesis. The quantitative study-selection and classification process is presented in the PRISMA flow diagram in Figure 2.

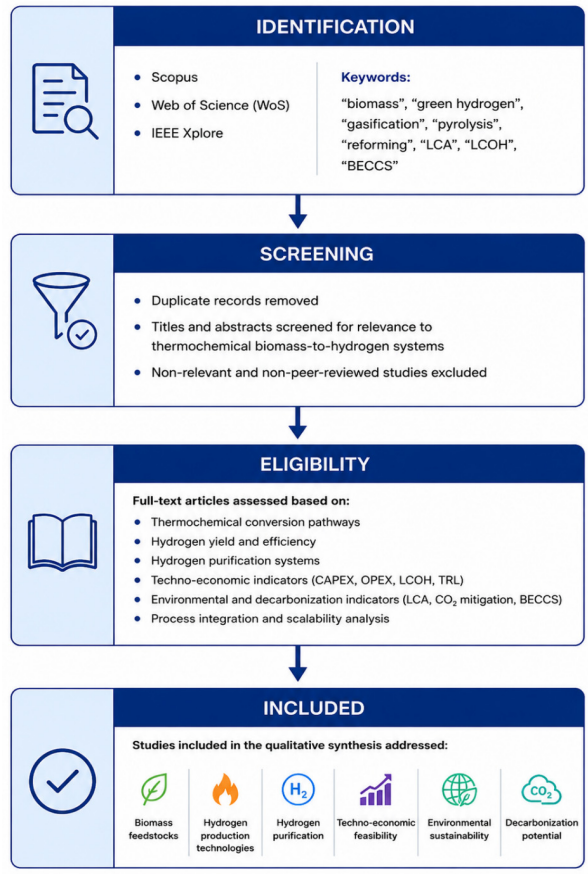


Figure 1. PRISMA-inspired workflow for the systematic review of thermochemical biomass-to-hydrogen studies.

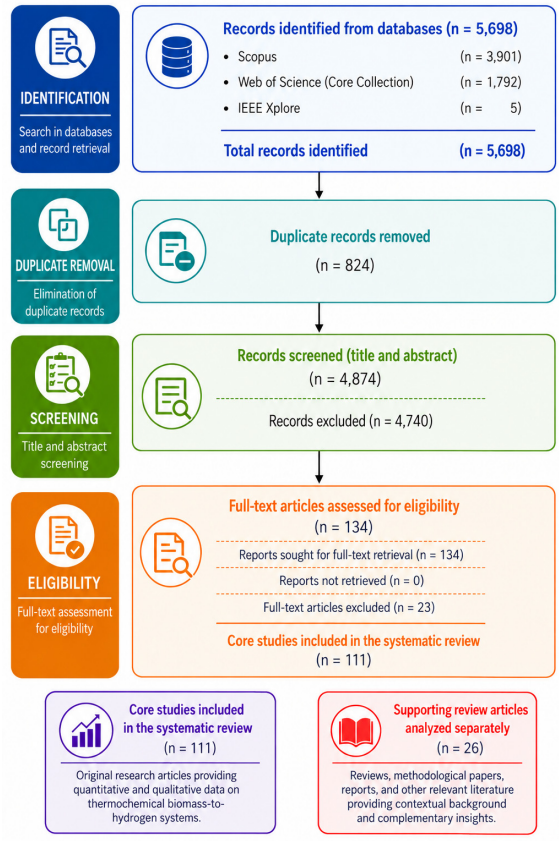


Figure 2. PRISMA 2020-based flow diagram of the study selection and classification process.

2.3. Data Extraction and Evidence Synthesis

A standardized evidence-extraction framework was used to systematically collect and classify information from the selected studies. The extracted variables covered general study information; biomass type and characteristics; thermochemical conversion pathway and reactor configuration; operating conditions; H_2 yield, H_2 concentration, syngas composition, H_2 recovery, final H_2 purity, and conversion efficiency; techno-economic indicators such as CAPEX, OPEX, LCOH, payback period, and TRL; environmental indicators including CO_2-equivalent emissions, life-cycle assessment results, carbon-reduction potential, and BECCS integration; and system-integration characteristics such as carbon capture, renewable hybridization, heat recovery, and process intensification.

For study-level transparency, reproducibility, and traceability, the complete evidence-extraction matrix for the 111 core studies is provided in Supplementary Table S1. The matrix includes bibliographic information, feedstock or system classification, thermochemical pathway, process-integration strategy, evidence type, study scale, hydrogen-performance indicators, techno-economic and environmental assessment coverage, CCS/BECCS integration, and mapping to the corresponding manuscript sections and main-text tables.

Data extraction was initially performed by one reviewer using the predefined evidence-extraction framework. A second reviewer subsequently verified the extracted information against the original articles, with particular attention to quantitative technical, techno-economic, environmental, and hydrogen-purification indicators. Any inconsistencies or ambiguous data were rechecked in the source article and resolved through discussion and consensus before inclusion in the final evidence matrix. This verification procedure was applied to improve consistency, reduce extraction errors, and strengthen the reliability of the synthesized evidence.

Evidence synthesis was conducted at two complementary levels. First, descriptive synthesis was used to identify publication trends, dominant thermochemical pathways, geographical distribution, feedstock prevalence, and frequently reported performance indicators. Second, structured thematic synthesis was conducted for gasification systems, pyrolysis and reforming pathways, supercritical-water gasification, hydrogen purification technologies, techno-economic feasibility, life-cycle environmental impacts, BECCS integration, renewable hybrid configurations, and scalability challenges. Comparative analyses were emphasized only when studies reported sufficiently comparable operating conditions and performance metrics.

Because the evidence base exhibited substantial heterogeneity in biomass feedstocks, reactor designs, operating conditions, economic assumptions, functional units, life-cycle boundaries, and carbon-accounting methodologies, a unified quantitative meta-analysis was not considered appropriate. Restricting the review to English-language peer-reviewed articles may also have excluded relevant regional studies and industrial reports, while rapidly evolving pilot-scale developments may not yet be fully represented in the indexed scientific literature. Nevertheless, the adopted approach provides a structured and reproducible framework for critically synthesizing thermochemical biomass-to-hydrogen systems.

To account for differences in study design, scale, validation, and reporting quality, an evidence-confidence assessment was incorporated into the study-level evidence matrix. Because the reviewed evidence includes experimental studies, process simulations, techno-economic assessments (TEA), life-cycle assessments (LCA), and pilot-scale demonstrations, a single conventional risk-of-bias tool was not considered appropriate for all study types. Instead, evidence confidence was evaluated according to four common criteria: (i) methodological transparency and reproducibility; (ii) validation or empirical support appropriate to the study design; (iii) representativeness of the investigated scale and oper-

ating conditions; and (iv) completeness of assumptions, system boundaries, uncertainty, and sensitivity reporting. Studies were classified as High, Moderate, or Low confidence. High-confidence studies showed strong methodological reporting, appropriate validation, and experimentally or operationally supported conditions; Moderate-confidence studies provided adequate methodological information but had limitations in validation, scale, duration, or uncertainty assessment; and Low-confidence studies relied primarily on conceptual or equilibrium modeling, limited validation, poorly documented assumptions, or incomplete system boundaries. This classification was used to contextualize the quantitative synthesis rather than as an additional exclusion criterion, and the study-level confidence rating is reported in Supplementary Table S1.

3. Results and Discussion

3.1. Overview of the Analyzed Literature and Comparison with Previous Reviews

The final evidence base was organized to distinguish between original research articles used for the main systematic synthesis and review articles used as supporting literature for contextualization and gap identification. As shown in Figure 2, records were retrieved from Scopus, Web of Science Core Collection, and IEEE Xplore, followed by duplicate removal, title-and-abstract screening, and full-text eligibility assessment. This process resulted in 111 core studies included in the systematic literature review and 26 supporting review articles analyzed separately to compare previous review scopes, methodological approaches, and thematic limitations.

The 111 core studies constitute the primary evidence base for analyzing thermochemical conversion pathways, biomass feedstocks, hydrogen production performance, techno-economic indicators, life-cycle impacts, decarbonization potential, and process integration strategies. In contrast, the 26 review articles were not merged with the primary evidence base, but were examined separately to position the present review within the existing literature and identify unresolved gaps related to BECCS integration, hydrogen purification, renewable hybridization, scalability, and systematic methodology.

To comprehensively address the research questions (RQ1–RQ6), a comparative analysis of the main review studies on thermochemical biomass conversion for hydrogen production was conducted. As shown in Table 3, this analysis enables not only the identification of current technological and scientific advances, but also the recognition of the principal methodological, techno-economic, environmental, and scalability limitations that still persist in the field.

Table 3. Comparative analysis of related review studies on thermochemical biomass conversion pathways for sustainable hydrogen production and their principal methodological, techno-economic, and sustainability limitations.

Reference	Main Focus	Thermochemical Pathways	Techno-Economic Analysis	LCA/ Decarbonization	BECCS Integration	Hydrogen Purification	PRISMA	Main Limitations Identified
Ghodke et al. [46]	Catalytic gasification for H_2-rich syngas	Catalytic gasification, plasma, microwave, solar, pyrolysis-gasification	Partial	Limited	No	Partial	No	Focused on catalysts and H_2-rich syngas; limited quantitative TEA/LCA comparison.
Lanjekar et al. [47]	Hydrogen from biomass thermochemical conversion	Gasification, pyrolysis, reforming, SCWG	Partial	Partial	Limited	Partial	No	Broad review; limited integration of TEA, LCA, purification, and BECCS in one framework.
Bolívar Caballero et al. [48]	Syngas reforming from biomass	Reforming, gasification-derived syngas	No	Partial	Partial	Partial	No	Mini-review; not focused exclusively on H_2 production or full sustainability assessment.

Table 3. *Cont.*

Reference	Main Focus	Thermochemical Pathways	Techno-Economic Analysis	LCA/ Decarbonization	BECCS Integration	Hydrogen Purification	PRISMA	Main Limitations Identified
Motta et al. [39]	Syngas cleaning and conditioning	Gasification, tar reforming, WGS, cleaning	Partial	Partial	Limited	Yes	Bibliometric compo-nent	Not centered only on green H_2; focuses more on gas cleaning than complete H_2 systems.
Arregi et al. [40]	Comparison of thermochemi-cal H_2 routes	Steam gasification, SCWG, pyrolysis, bio-oil reforming	Partial	Partial	Limited	Partial	No	Strong pathway comparison, but older; limited recent BECCS/AI/ML and LCOH developments.
Salam et al. [49]	Biomass gasification and H_2 purification	Gasification	Limited	No	No	Yes (PSA, membranes, WGS)	No	Focused mainly on gasification processes and purification systems without integrated sustainability or economic assessment.
Cao et al. [50]	Biomass gasification and catalytic systems	Steam gasification, SCWG	Limited	Partial	No	Partial	No	Primarily focused on catalytic gasification and operating conditions without system-level techno-economic integration.
Dou et al. [51]	Thermochemical hydrogen production technologies	Pyrolysis, gasification, reforming, chemical looping	Limited	Partial	Partial	Limited	No	Emphasis on catalysts and thermochemical mechanisms rather than integrated decarbonization and scalability assessment.
Alptekin et al. [52]	Catalytic biomass gasification	Gasification	Partial	Partial	No	Limited	No	Catalyst-centered review with limited discussion of integrated hydrogen systems and life-cycle sustainability.
Wang et al. [53]	Biomass hydrogen production with bibliometric analysis	Gasification, pyrolysis, reforming, fermentation	Partial	Limited	No	Limited	Bibliometric approach	Focused primarily on publication trends and hotspot analysis without detailed process integration assessment.
Bartoli et al. [54]	Biomass gasification for hydrogen production	Gasification	Yes	Partial	Limited	Limited	No	Focused mainly on gasification technologies without broader integration of hybrid renewable systems and circular bioeconomy strategies.
Minh et al. [55]	Hydrogen-rich syngas and sustainability	Gasification, pyrolysis	Yes	Partial	Partial	Partial	No	Strong system-level integration, but still focused predominantly on gasification-oriented syngas production.
Goel et al. [56]	Biomass chemical looping gasification	Chemical looping gasification	Partial	Yes	Yes	Partial	No	Focused on syngas quality and oxygen carriers; H_2 purification and LCA/TEA not fully integrated.
Huang et al. [57]	Carbon capture and impurity removal for high-purity H_2	Gasification, pyrolysis, SCWG, chemical looping	Partial	Yes	Partial	Yes	No	Focuses on impurities and purification; less emphasis on feedstock variability and economic scalability.
Setiabudi et al. [58]	Bio-oil steam reforming to H_2	Pyrolysis + bio-oil reforming	Partial	Limited	No	Partial	No	Strong catalyst focus; limited system-level TEA/LCA and BECCS integration.
Pandey et al. [59]	State-of-the-art thermochemi-cal biomass-to-H_2	Gasification, pyrolysis, SCWG, reforming	Partial	Limited	No	Partial	No	Broad but older; limited BECCS, LCA and recent optimization tools.
Zhang et al. [60]	Exergy review of steam gasification	Steam gasification	No	Limited	No	Limited	No	Focused on exergy only; lacks broader economic, LCA, and BECCS evaluation.
Zhang et al. [61]	SCWG from exergy perspective	SCWG	No	Limited	No	Limited	No	Specialized exergy focus; limited TEA, purification and decarbonization analysis.

Table 3. *Cont.*

Reference	Main Focus	Thermochemical Pathways	Techno-Economic Analysis	LCA/ Decarbonization	BECCS Integration	Hydrogen Purification	PRISMA	Main Limitations Identified
Vuppaladadiyam et al. [62]	Pyrolysis routes for green H_2	Conventional, advanced and emerging pyrolysis	Partial	Partial	Limited	Partial	No	Focuses on pyrolysis; less coverage of gasification, SCWG and integrated H_2 purification chains.
Valizadeh et al. [63]	Green H_2 via biomass gasification	Catalytic gasification	Partial	Partial	Limited	Partial	No	Strong gasification/catalyst focus; limited quantitative synthesis of LCOH, LCA and BECCS.
Singh et al. [64]	Pretreatment effects on bio-H_2	Pretreatment + gasification/pyrolysis	Partial	Partial	Partial	No	No	Focuses on feedstock conditioning; not a full biomass-to-H_2 system review.
Ahmed et al. [65]	Modeling and computational design	Biomass gasification	Partial	No	No	Limited	No	Older modeling review; no modern AI/ML, BECCS or LCA integration.
He et al. [66]	Hydrothermal/ SCWG of sewage sludge	Hydrothermal gasification, SCWG	Partial	Limited	No	Limited	No	Strong on wet biomass/sludge; limited modern TEA, LCA and purification discussion.
Kumar and V. Strezov [67]	Bio-oil upgrading and H_2 production	Pyrolysis, HTL, steam reforming	Partial	Partial	No	Partial	No	Broader bio-oil upgrading focus; H_2 is one application, not the only central axis.
Tavares Borges et al. [68]	Technical, economic, environmental and bibliometric review	Biomass gasification	Yes	Yes	Partial	Yes	No	Strong global/Brazilian potential; limited full PRISMA-style systematic screening.
Ceron et al. [69]	Hybrid CLG with biomass and mineral-rich oil shale	Chemical looping gasification	Partial	Yes	Yes	No	No	Includes fossil/mineral-rich oil shale; should not be treated as pure green H_2 evidence.

Table 3 confirms that technology comparison itself is not a new contribution, since several previous reviews have already examined gasification, pyrolysis, reforming, supercritical water gasification, chemical looping, and related biomass-to-hydrogen pathways. The remaining research gap lies instead in the limited integration of technological performance with economic feasibility and deployment conditions. In particular, previous reviews have rarely examined within a common evidence framework how plant scale, feedstock cost and logistics, hydrogen purification requirements, CAPEX and OPEX assumptions, LCOH boundaries, carbon capture, life-cycle performance, and technology readiness jointly influence the apparent competitiveness of biomass-to-hydrogen pathways. The present review was therefore structured to address this system-level economic and deployment gap rather than to provide another purely technological comparison.

Across the 26 prior reviews, several conclusions remain consistent: gasification is generally identified as the most mature thermochemical route; catalyst selection, tar control, and gas cleaning are recurrent technical challenges; hydrothermal and supercritical-water pathways are particularly relevant for wet feedstocks; and downstream syngas upgrading is required to obtain high-purity hydrogen. These conclusions are consistent with the present evidence base and confirm that the principal technological trends of biomass-to-hydrogen conversion are already well established in the literature.

The present review extends this established technological knowledge by linking reactor-level H_2 performance with water–gas shift and purification requirements, LCOH and financial assumptions, feedstock logistics, life-cycle carbon intensity, carbon-capture performance, technology readiness, operational durability, and deployment scale across 111 original studies. This integrated perspective enables the discussion to move beyond identifying which technologies are most frequently investigated and toward determin-

ing the technical, economic, environmental, and deployment conditions under which individual pathways may be considered viable.

3.2. Evidence-Based Synthesis of the Research Questions

The first level of synthesis was structured around the six research questions defined in the methodology. This approach was adopted to avoid limiting the discussion to keyword frequency or publication occurrence. Instead, the selected studies were interpreted according to pathway maturity, feedstock suitability, H_2 yield, H_2 concentration, syngas composition, H_2 purification requirements, LCOH, CAPEX, OPEX, GWP, CCS/BECCS integration, carbon intensity, and scale-up barriers.

The quantitative evidence was interpreted together with the study-level evidence-confidence classification reported in Table S1. Greater interpretive weight was assigned to experimentally validated systems, pilot-scale evidence, transparent TEA/LCA assessments, and validated process models, whereas results derived primarily from conceptual configurations, equilibrium simulations, short-duration experiments, or incompletely reported system boundaries were interpreted more cautiously. Therefore, numerical extremes were not considered inherently representative of pathway performance solely because they constituted the highest or lowest reported values.

Table 4 provides an integrated synthesis of the research questions and connects each question with quantitative and critical evidence extracted from the 111 core studies. The table is intended to function as an evidence map for the subsequent sections: technical performance is discussed in Section 3.3, techno-economic performance in Section 3.4, feedstock suitability and scale-up barriers in Section 3.5, life-cycle emissions and decarbonization performance in Section 3.6, and integrated future priorities in Section 3.7.

Table 4. Evidence-based synthesis of the research questions.

RQ	Key Evidence	Main Finding
RQ1—Thermochemical pathways	Gasification appears in 96/111 core studies. Other pathways include SCWG, pyrolysis, and bio-oil reforming (Table S1).	Gasification is the dominant route in the evidence base and shows the strongest maturity evidence, whereas alternative pathways remain relevant for wet feedstocks, difficult wastes, and advanced H_2/CO_2 management.
RQ2—Feedstock suitability	Lignocellulosic/woody/forestry biomass: 75/111; agricultural residues: 43/111; mixed co-feedstocks: 28/111; MSW/RDF/biowaste: 27/111; bio-oil/intermediates: 20/111; wet streams: 17/111; algae/microalgae: 10/111 (Table S1).	Dry lignocellulosic biomass favors gasification; wet streams favor SCWG/hydrothermal routes; MSW/RDF favors waste/plasma gasification; bio-oil favors catalytic reforming.
RQ3—Technical performance	Air/oxygen gasification: ~8–16 vol% H_2; steam gasification: ~30–60 vol% H_2 [70–72]; advanced capture-assisted systems: ~78–81.1 vol% H_2 [73,74]; final purification: 98.6 vol% [72] and 99.99 mol% H_2 [75].	Raw syngas and final purified H_2 must be distinguished; WGS and downstream separation strongly affect final H_2 purity.
RQ4—Techno-economic performance	Reported costs range from 1.94 USD/kg H_2 to 13.75–19.09 USD/kg H_2 [76,77], 2.72 EUR/kg H_2 to 16.30–24.45 EUR/kg H_2 [78,79], and 3.16 GBP/kg H_2 without CCS to 4.17–5.40 GBP/kg H_2 with BECCS [41].	Cost is strongly affected by scale, feedstock, purification, CCS/BECCS, logistics, and system boundaries.
RQ5—LCA/decarbonization	Life-cycle results range from net-positive to carbon-negative configurations [41,80]. CO_2 capture reaches approximately 90–92% in advanced waste-to-H_2 systems [75].	Carbon performance depends on LCA boundaries, auxiliary energy, logistics, H_2 purification, and CCS/BECCS integration.
RQ6—Barriers and scale-up	Main recurring issues: feedstock heterogeneity/logistics (50 studies), TEA/LCOH uncertainty (43), tar/gas cleaning (38), and catalyst/oxygen-carrier stability (22) (Table S1).	Scale-up requires integrated feedstock supply, stable conversion, gas cleaning, H_2 purification, CO_2 management, competitive cost, and pilot validation.

Note: Feedstock categories are non-mutually exclusive because individual studies may evaluate more than one feedstock type.

The synthesis in Table 4 shows that gasification-based systems constitute the dominant pathway in the evidence base, but this dominance should not be interpreted as universal superiority. Gasification appears in conventional fixed-bed, fluidized-bed, pressurized, dual-stage, catalytic, steam, oxy-steam, sorption-enhanced, chemical-looping, molten-salt-mediated, plasma-assisted, and BECCS-integrated configurations [41,43,70–75,79–144]. However, the evidence also demonstrates that gasification alone generally produces H_2-rich

syngas rather than fuel-grade H_2. Therefore, downstream gas cleaning, tar reforming, WGS, CO_2 removal, drying, compression, PSA, membrane separation, or in situ carbon capture are required to obtain purified hydrogen [70–72,81,82,92,103,107,111,130,131,136].

The quantitative values presented in Table 4 summarize the range and variability observed across the reviewed evidence base rather than representing isolated best-performing studies. Detailed study-level results and operating conditions are subsequently presented in Tables 5–8 and in the complete evidence matrix (Table S1).

Table 5. Quantitative technical performance of thermochemical biomass-to-H_2 pathways.

Conversion Pathway	Feedstock	Configuration	Operating Conditions/Scale	Quantitative Performance	Technical Implication
Gasification	Wood chips	Downdraft gasifier + gas cleaning + WGS + PSA	15 kWh pilot; 20 kg wood chips; PSA storage at 55 bar	H_2 concentration in producer gas: 14–16 vol%; H_2 concentration after WGS: 30–33 vol%; final H_2 purity after PSA: 98.6 vol%; CO conversion: 94.85%; H_2 recovery: about 95%	Shows that gasification requires gas cleaning, WGS, and PSA to produce high-purity H_2 [72].
Chemical looping gasification	Pine sawdust	CaO-CLG with in situ CO_2 capture and tar reduction	Solid circulation rate: 1.04 kg/m^2/s	H_2 concentration: 78 vol%; H_2 yield: 451.11 mL H_2/g biomass; minimum CO_2 concentration: 4.98%; tar concentration: 2.48 g/Nm^3	CaO improves H_2 production, captures CO_2, and supports tar reforming [74].
Gasification + staged WGS	Wood residues; food waste	Aspen Plus equilibrium model + HT/LT WGS	Optimal gasification near 850 °C; SBR 0.55–0.65	Relative increase in H_2 production after WGS: 90.3% for wood residues and 54.8% for food waste; CO reduction: up to 93.8%	WGS is essential for upgrading raw syngas toward H_2-rich gas [81].
Gasification with CO_2 capture	Rice husk	Biomass gasification with in situ CO_2 capture	Equivalence ratio: 0.15–0.25	H_2 yield: increased from 37 to 41 g H_2/kg biomass; syngas yield: increased from 2.1 to 2.45 Nm^3/kg biomass	Moderate ER improves H_2 and syngas yield, but excessive oxidation can reduce gas quality [82].
Sorption-enhanced gasification	Biomass	CeO_2-modified $CaO/Ca_{12}Al_{14}O_{33}$ bifunctional material	10 cyclic tests	Average H_2 concentration: 81.1 vol%; H_2 yield: 124 mL H_2/g biomass; H_2 concentration and H_2 yield were 17.4% and 47.3% higher, respectively, than with the unmodified material	Modified CaO-based sorbents enhance WGS/SMR activity and cyclic stability [73].
Waste gasification	MSW + biomass; MSW + mixed plastic waste	Steam gasification + CaO + carbon capture	Steam:feed = 2:1; CaO:feed = 0.92:1 and 0.4:1	H_2 yield: 141.8 g H_2/kg feed for MSW + wood and 201.9 g H_2/kg feed for MSW + mixed plastic waste; final H_2 purity: 99.99 mol%; CO_2 capture: 90–92%	Waste co-gasification can increase H_2 output, but LCA and fossil-carbon accounting must be explicit [75].
Plasma gasification	Refractory organic solid waste	Plasma gasification + reforming + WGS + PSA	1111.88 °C; ER 0.089; S/W 0.788; S/C 1.45	H_2 yield: 347.04 g H_2/kg dry waste; H_2 production efficiency: 65.71%; total energy efficiency: 61.34%	Technically suitable for difficult wastes, but electricity and exergy demand must be considered [83].
Pyrolysis and reforming	Corn-waste bio-oil	Two-stage pyrolysis + Ni-Fe/PCH catalytic steam reforming	Pyrolysis: 500 °C; reforming: 800 °C; 170 h stability test	Reported H_2 yield: 58.8%; reported conversion: 87.3%; stable operation over 170 h	Bio-oil reforming is promising when catalyst stability and coke control are achieved [145].
Conventional/ steam gasification	Lignocellulosic biomass	Gasification chain for purified H_2	Air/oxygen vs. steam gasification comparison	H_2 concentration in air/oxygen-derived syngas: 8–16 vol%; H_2 concentration in steam-gasification syngas: 30–60 vol%	Steam gasification provides H_2-richer syngas but still requires downstream upgrading [70,71].
Catalytic gasification	Algal biomass	Catalytic gasification with CaO/Ni/Zn-based material	851 °C; catalyst loading: 16.4 wt%; reaction time: 28.8 min	H_2 concentration: 48.95 mol%; H_2 yield: 37.8 g H_2/kg biomass	Algal biomass can produce H_2-rich gas, but species, catalyst selection, mineral content, and gas cleaning remain decisive [91].
Integrated pyrolysis–gasification	Cladophora glomerata, Chlorella vulgaris, and Gracilaria gracilis	Pyrolysis/steam gasification followed by staged WGS depending on feedstock and route	Approximately 600–900 °C	Experimental H_2 concentration: 43.94–48% for Cladophora, 52% for Chlorella, and 42% for Gracilaria; simulated H_2 concentration: approximately 50–52.3%	Feedstock species and WGS integration strongly influence final H_2 concentration [146].

Note: H_2 yield values were harmonized to g H_2/kg feedstock whenever the reported data allowed direct conversion. Volumetric yields and percentage-based yields were retained in their original form when a mass-based conversion could not be performed without additional assumptions. H_2 concentration refers to the hydrogen fraction in raw or upgraded gaseous streams, whereas H_2 purity refers specifically to the hydrogen fraction in the final separated product after downstream purification. H_2 recovery refers to the fraction of hydrogen entering a separation or upgrading unit that is recovered in the hydrogen-rich product stream. Conversion efficiencies are reported according to the basis specified in the original studies and are not treated as equivalent to H_2 yield, H_2 concentration, H_2 recovery, or final H_2 purity. H_2 yield values were harmonized to g H_2/kg feedstock whenever the reported data allowed direct conversion. Volumetric yields and percentage-based yields were retained in their original form when a mass-based conversion could not be performed without additional assumptions.

The table also confirms that feedstock suitability is a route-selection criterion rather than a simple classification variable. Woody and lignocellulosic biomass are mainly associated with gasification, WGS, PSA, CCS, BECCS, exergy analysis, and techno-economic assessment [41,70–72,81,82,87–90,92–95,97,102–114,123,134–136,140,141,147]. Agricultural and agro-industrial residues, including rice straw, soybean straw, canola straw, olive pomace, citrus peels, palm residues, corn waste, maize husk, rice husk, oil palm fiber, and palm rachis, are distributed across steam gasification, oxy-steam gasification, pyrogasification, SCWG, bio-oil reforming, co-pyrolysis, chemical looping, TEA, and LCA studies [77,78,129,138,139,145,148–152]. Wet feedstocks, including sewage sludge, oily sludge, algae, microalgae, food waste, and other high-moisture residues, are more closely associated with SCWG, hydrothermal gasification, alkaline pyrolysis, and integrated wet-route systems. Plasma gasification has been investigated for selected algal and waste-derived feedstocks, although feedstock conditioning and drying requirements depend on the specific process configuration [72,76,77,79,86,89,91,104,115–123,146,147,149,153–162].

The quantitative evidence summarized in Table 4 further indicates that performance comparison must be conducted at the system level. Integrated gasification–WGS modeling increased H_2 production by 90.3% for wood residues and 54.8% for food waste while reducing CO by up to 93.8% [81]. Pilot-scale gasification followed by WGS and PSA upgraded producer gas from 14–16 vol% H_2 to 30–33 vol% H_2 after WGS and finally to 98.6 vol% H_2 after PSA [72]. CaO-assisted chemical looping and sorption-enhanced systems reported H_2 concentrations around 78–81.1 vol%, H_2 yield values of 451.11 mL H_2/g biomass or 124 mL H_2/g biomass, reduced CO_2 concentration, and tar reduction [73,74]. Waste-to-H_2 configurations reported up to 141.8 g H_2/kg feed for MSW–wood and 201.9 g H_2/kg feed for MSW–mixed plastic systems, with final H_2 purity of 99.99 mol% and CO_2 capture around 90–92% [75].

From an economic perspective, Table 4 highlights strong cost dispersion. USD-denominated studies reported values from 1.94 USD/kg H_2 under favorable plant-gate assumptions to 13.75–19.09 USD/kg H_2 in remote-community scenarios, whereas EUR-denominated studies reported values from 2.72 EUR/kg H_2 to 16.30–24.45 EUR/kg H_2 [76–78]. From an environmental perspective, the same synthesis shows that biomass-derived H_2 should not be automatically classified as green. Systems without CCS may remain net-positive emitters, whereas CCS-/BECCS-integrated configurations can achieve low-carbon or carbon-negative performance depending on system boundary, electricity mix, capture rate, storage assumptions, and carbon accounting [41–43,70,71,80,85,102,106,108,117,122,129,135,137,141,144,148,150,156,163–169].

Overall, Table 4 shows that the key scientific question is not whether biomass can be converted into H_2-rich gas, but under which feedstock, reactor, purification, techno-economic, CCS/BECCS, and LCA conditions biomass-derived hydrogen becomes technically reliable, economically competitive, and environmentally credible.

The evidence indicates that pathway dominance should not be interpreted as technological superiority. Gasification is the most frequently studied route because of its maturity and feedstock flexibility, but the most appropriate pathway depends on moisture content, ash chemistry, impurity profile, required H_2 purity, carbon-capture configuration, plant scale, and final application. Therefore, the main insight derived from the evidence is that feedstock–route matching, rather than publication frequency, should be used as the primary decision criterion for selecting biomass-to-hydrogen technologies.

3.3. Technical Performance of Thermochemical Biomass-to-H_2 Pathways

3.3.1. Thermochemical Transformation Mechanisms

Thermochemical conversion of the organic fraction of biomass into hydrogen-containing gas involves a sequence of interacting decomposition, gasification, reforming, and shift reactions. During pyrolysis, biomass is initially converted into permanent gases, condensable vapors and tars, and solid char. Subsequent char gasification with steam ($C + H_2O \rightleftharpoons CO + H_2$) and carbon dioxide ($C + CO_2 \rightleftharpoons 2CO$), together with steam reforming of methane and light hydrocarbons ($CH_4 + H_2O \rightleftharpoons CO + 3H_2$), contributes to the formation of H_2- and CO-rich syngas. These reactions are predominantly endothermic and are generally favored by elevated temperatures. In contrast, the water–gas shift reaction ($CO + H_2O \rightleftharpoons CO_2 + H_2$) is exothermic and plays a central role in increasing the hydrogen fraction while reducing residual CO. Methanation, carbon deposition, and complete oxidation compete with these hydrogen-oriented pathways under specific operating conditions [34,38–40].

Temperature is a key operating variable because it influences the relative contribution of devolatilization, char gasification, reforming, water–gas shift, and oxidation reactions, and therefore affects H_2 yield and syngas composition. The reviewed evidence shows that the effect of temperature cannot be interpreted independently from the gasifying agent, steam-to-biomass ratio, equivalence ratio, feedstock composition, catalyst formulation, and residence time [84,87,90,93,109,110,123,130,140,147]. For example, gasification coupled with staged water–gas shift has been evaluated near 850 °C [81], catalytic gasification of algal biomass at 851 °C produced 48.95 mol% H_2 and 37.8 g H_2/kg biomass [91], and plasma gasification of refractory organic waste operated at approximately 1111.88 °C, reaching 347.04 g H_2/kg dry waste [83]. These results indicate that higher operating temperature may promote conversion and reforming, but the resulting hydrogen performance remains strongly dependent on the overall reactor and process configuration.

The organization of the gasification process within the reactor is equally important because reactor configuration determines how biomass, heat, gasifying agents, catalysts, sorbents, and intermediate products interact during conversion. The reviewed studies include downdraft, fixed-bed, fluidized-bed, pressurized, dual-stage, catalytic, sorption-enhanced, and chemical-looping configurations, demonstrating that hydrogen production is governed by both reaction chemistry and reactor architecture. In a pilot downdraft configuration, producer gas containing 14–16 vol% H_2 was subsequently upgraded through water–gas shift and PSA to 98.6 vol% H_2 [72]. Staged systems also demonstrate the importance of spatially separating conversion and upgrading steps: two-stage pyrolysis and catalytic steam reforming of corn-waste bio-oil operated at approximately 500 and 800 °C, respectively, and achieved 58.8% H_2 yield with stable operation over 170 h [145]. Similarly, CaO-assisted chemical-looping configurations combine reaction and CO_2 capture within an integrated solid-circulation environment, reaching H_2 concentrations of approximately 78 vol% [74]. These examples show that reactor staging, gas–solid contacting, and integration of reforming, shift, and capture functions can substantially influence hydrogen-oriented performance.

Figure 3 provides a schematic overview of the principal thermochemical biomass-to-hydrogen pathways identified in the reviewed literature and the downstream upgrading stages required to obtain high-purity hydrogen. The scheme integrates biomass pretreatment, gasification, pyrolysis–reforming, supercritical water or hydrothermal conversion, and chemical-looping or sorption-enhanced routes with subsequent gas cleaning, water–gas shift, CO_2 separation, and final purification by pressure swing adsorption or membrane technologies.

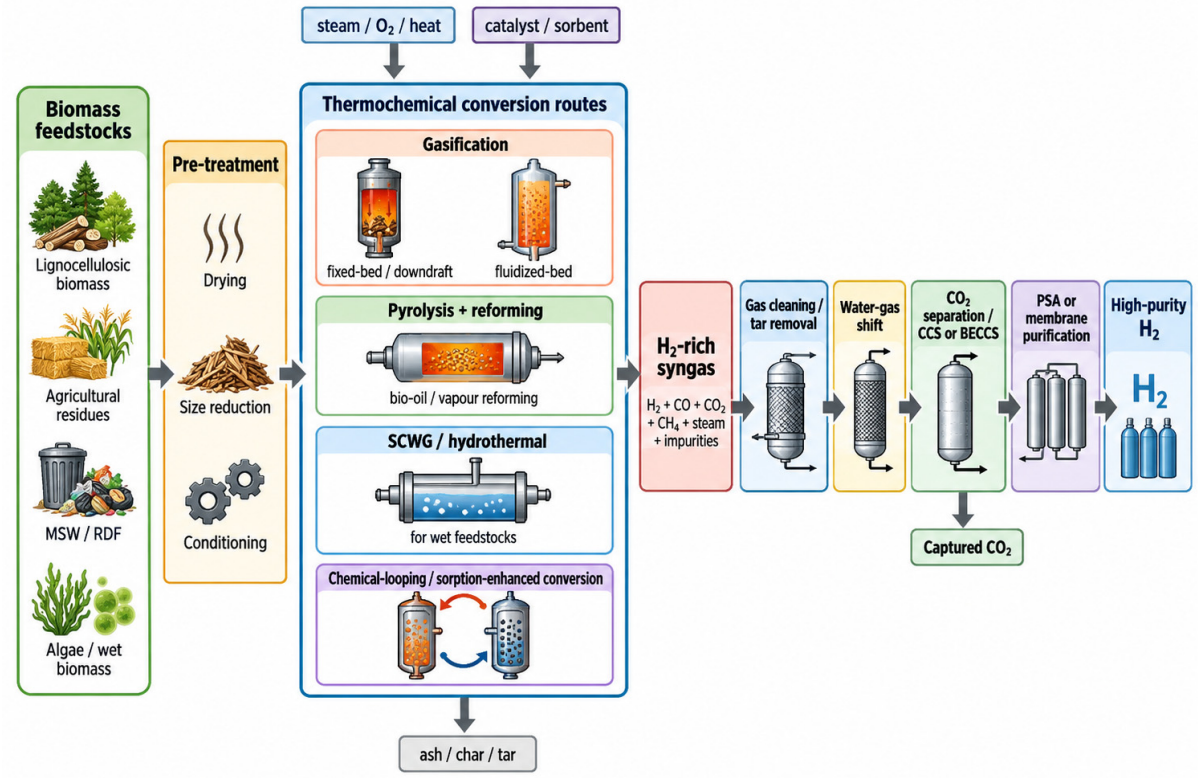


Figure 3. Schematic representation of the main thermochemical biomass-to-hydrogen conversion and purification stages identified in the reviewed literature.

3.3.2. Quantitative Technical Performance and Process Integration

Technical performance was evaluated through quantitative and system-level indicators, including H_2 yield, H_2 concentration, syngas yield, H_2/CO ratio, CO conversion, CH_4 conversion, CO_2 concentration, tar concentration, gas-cleaning requirements, WGS performance, PSA or membrane purification, energy efficiency, exergy efficiency, and operational stability. Across the 111 core studies included through the PRISMA-based selection process, gasification-based configurations dominate the technical evidence; however, performance varies substantially according to feedstock composition, reactor type, gasifying agent, temperature, pressure, equivalence ratio, steam-to-biomass ratio, catalyst or sorbent formulation, residence time, and downstream upgrading strategy [41,70–75,78–133,136,142–144,146,153,154].

To avoid ambiguity among the technical indicators reported across the reviewed studies, the following terminology was applied consistently throughout the synthesis. H_2 yield refers to the amount of hydrogen produced relative to a defined feedstock or process-input basis and is reported using the original study units, such as g H_2/kg biomass, mol H_2/kg feedstock, or Nm^3 H_2/kg feedstock. H_2 concentration refers to the fraction of hydrogen in a gaseous stream, typically expressed as vol% or mol%, and generally describes raw or upgraded syngas composition rather than the final purified product. H_2 recovery refers to the fraction of hydrogen entering a separation or upgrading unit that is recovered in the hydrogen-rich product stream. H_2 purity refers to the hydrogen fraction in the final separated product after downstream purification, such as pressure swing adsorption or membrane separation. Conversion efficiency refers to the extent to which a defined feedstock or reactant is converted during a specific process step; where available, the manuscript therefore specifies the corresponding basis explicitly, such as biomass conversion, CO conversion, or CH_4 conversion, rather than using the generic term "conversion" alone. These indicators were not treated as interchangeable.

Because many studies report different output levels, Table 5 was included to distinguish between gasifier-level performance, upgraded syngas performance, and final H_2 purity. This distinction is essential because raw producer gas, H_2-rich syngas, upgraded syngas, and purified hydrogen are not equivalent products. Conventional biomass gasification generally produces a mixture containing H_2, CO, CO_2, CH_4, steam, tar, particulates, and sulfur-, chlorine-, and nitrogen-containing impurities. Therefore, results based only on raw syngas composition should not be compared directly with results obtained after WGS, CO_2 capture, PSA, membrane purification, or other upgrading units [70–72,81,82,92,103,107,111,130,131,136].

In Table 5, the conversion pathway identifies the general thermochemical route, whereas the configuration describes the specific reactor arrangement, process integration, and downstream upgrading steps.

The evidence summarized in Table 5 shows that gasification should not be treated as a single homogeneous pathway. Air or oxygen gasification generally produces lower H_2 concentrations than steam or oxy-steam gasification because nitrogen dilution, partial oxidation, and lower steam reforming intensity limit H_2 enrichment. Baseline studies indicate that air/oxygen gasification may generate syngas with approximately 8–16 vol% H_2, while steam gasification can reach approximately 30–60 vol% H_2 under favorable conditions [70–72]. However, these values refer to syngas-level composition and do not represent final hydrogen purity.

The role of WGS and purification is particularly important. Akash et al. showed that staged WGS increased H_2 production by 90.3% for wood residues and 54.8% for food waste, while reducing CO by up to 93.8% [81]. Salam et al. provided pilot-scale evidence in which raw producer gas containing 14–16 vol% H_2 was upgraded to 30–33 vol% H_2 after WGS and finally to 98.6 vol% H_2 after PSA, with approximately 95% H_2 recovery [72]. These values demonstrate that fuel-grade H_2 is not determined by the gasifier alone, but by the complete process chain, including gas cleaning, CO conversion, moisture removal, compression, and final separation.

Operating conditions and feedstock properties strongly influence gasification performance. Doranehgard et al. showed that in situ CO_2 capture increased H_2 yield from 37 to 41 g H_2/kg biomass and syngas yield from 2.1 to 2.45 Nm^3/kg biomass as the equivalence ratio increased from 0.15 to 0.25, although excessive oxidation can reduce gas quality [82]. Thermodynamic, numerical, exergy, optimization, and machine-learning studies further show that gasification temperature, steam-to-biomass ratio, equivalence ratio, feedstock composition, and gasifying agent selection determine H_2 yield, syngas composition, LHV, H_2/CO ratio, carbon conversion, and exergy efficiency [84,87,90,93,109,110,123,130,140,147].

Advanced sorption-enhanced, CaO-assisted, chemical-looping, molten-salt-mediated, and solar-assisted configurations improve H_2 enrichment by integrating conversion with CO_2 capture, oxygen-carrier cycling, or heat integration. Yan et al. reported an average H_2 concentration of 81.1 vol% and an H_2 yield of 124 mL H_2/g biomass using CeO_2-modified $CaO/Ca_{12}Al_{14}O_{33}$, with H_2 concentration and yield increasing by 17.4% and 47.3%, respectively, compared with the unmodified material [73]. Udomsirichakorn et al. reported 78% H_2, 451.11 mL H_2/g biomass, a minimum CO_2 concentration of 4.98%, and tar content of 2.48 g/Nm^3 using CaO-based chemical looping gasification [74]. Other studies on gas-switching integrated gasification, molten-salt-mediated gasification, solar–biomass chemical looping, sorption-enhanced gasification, biomass chemical looping, and autothermal chemical looping confirm that H_2 enrichment and CO_2 capture can be integrated, but durability remains decisive [95,98,99,107,111,115,124,126,128,131–133,136,142–144].

The technical limitation of these advanced routes is not only whether they can increase H_2 concentration, but whether they can maintain performance over realistic operating cycles. CaO deactivation, sorbent sintering, oxygen-carrier attrition, ash interaction, catalyst poisoning, carbon deposition, regeneration energy, and impurity tolerance remain major constraints [73,74,107,111,131–133,136,142–144]. Therefore, future technical comparisons should include cyclic stability, regeneration performance, tar removal, impurity tolerance, and continuous operating time rather than maximum H_2 concentration alone.

Operational reliability is affected by coupled rather than isolated limitations. Feedstock variability, tar and particulate formation, ash deposition, slagging, agglomeration, reactor corrosion, catalyst coking, sorbent sintering, oxygen-carrier attrition, pressure control, and gas-cleaning requirements can reduce conversion stability and increase downtime, auxiliary energy consumption, maintenance, and H_2 purification costs [73,74,107,111,131–133,136,142–144]. Start-up and shutdown behavior, dynamic feedstock changes, catalyst regeneration, and impurity accumulation are also insufficiently reported. Future experimental studies should therefore provide continuous operating hours, failure modes, regeneration cycles, impurity tolerance, maintenance requirements, and performance degradation rates rather than reporting only optimized steady-state results.

SCWG and hydrothermal gasification represent a technically different route for wet feedstocks. Sewage sludge, oily sludge, algae, food waste, microalgae, and other high-moisture residues are poorly suited to conventional dry gasification unless drying is economically and energetically justified. SCWG avoids the drying penalty and can convert wet biomass directly into H_2-rich gas, but performance depends on temperature, pressure, residence time, feed concentration, catalyst selection, salt precipitation, and heat recovery [77,86,89,104,151,153–155,157–161]. The main scale-up barriers are corrosion, plugging, salt deposition, catalyst recovery, high-pressure operation, heat integration, and continuous-flow reliability. Therefore, SCWG should be evaluated through H_2 yield, energy efficiency, exergy performance, solids loading, water management, and reactor durability rather than H_2 yield alone.

Integrated hydrogen-production systems for wet feedstocks should be evaluated as complete process chains rather than as isolated SCWG reactors. A representative configuration comprises feedstock preparation, supercritical water gasification, cooling and salt separation, one or more water–gas shift reactors, CO_2 separation, and final H_2 purification by pressure swing adsorption or membranes. The water–gas shift reaction, $CO + H_2O \rightleftharpoons CO_2 + H_2$, converts residual CO and steam into additional hydrogen and CO_2, thereby increasing H_2 recovery and reducing the CO concentration before purification. The integration of SCWG with WGS is particularly relevant because reforming, methanation, and shift reactions already interact within the supercritical medium, while a downstream WGS reactor can provide further control of the final H_2/CO ratio [72,77,81,130,146,153,154,160,161]. Nevertheless, the integrated system increases heat-exchanger duty, pressure-management requirements, corrosion exposure, salt-deposition risk, catalyst-deactivation potential, and downstream separation demand. Therefore, SCWG–WGS systems should be compared using net H_2 yield, CO conversion, final H_2 purity and recovery, heat-recovery efficiency, high-pressure equipment requirements, and continuous operating stability rather than gasifier-outlet composition alone.

Algal and microalgal feedstocks require feedstock-specific analysis. Their high volatile-matter content and carbohydrate and lipid fractions can support rapid thermochemical conversion and H_2-rich syngas production; however, performance is strongly dependent on species, composition, pretreatment, and conversion route rather than being inherently superior to lignocellulosic biomass. Catalytic gasification of algal biomass reached 48.95 mol% H_2, with a reported H_2 yield of 37.8 g H_2/kg biomass, at 851 °C, 16.4 wt% catalyst load-

ing, and a reaction time of 28.8 min [91]. Nevertheless, high moisture, nitrogen, ash, and mineral contents can increase drying demand, NH_3 and HCN formation, gas-cleaning requirements, corrosion, and catalyst deactivation [91,119,149]. Microalgae are therefore better aligned with SCWG and hydrothermal conversion because of their high moisture content, while plasma gasification and carefully integrated steam-gasification systems may require feedstock-specific conditioning before conversion.

Although algae and microalgae represent only 10 of the 111 core studies included in the review, they constitute a distinct and strategically relevant feedstock class because their high moisture content changes the preferred conversion pathway. Conventional dry gasification can require substantial drying and feed-conditioning energy for wet microalgal biomass, whereas supercritical water gasification (SCWG) and related hydrothermal routes can process high-moisture feedstocks in an aqueous reaction environment and thereby reduce or avoid the drying penalty. This makes SCWG particularly relevant for microalgae when the objective is to integrate wet biomass conversion with hydrogen-rich gas production. However, the reviewed evidence also shows that the advantages of wet conversion are accompanied by significant scale-up challenges, including high-pressure operation, corrosion, salt precipitation, catalyst recovery, heat integration, and continuous-flow reliability. Therefore, the limited number of microalgae studies should not be interpreted as evidence of low potential, but rather as an indication that this pathway remains comparatively less mature and requires further pilot-scale validation.

Macroalgae and seaweeds also require separate consideration. Many species have high moisture content and relatively low lignin content, which can favor hydrothermal processing, SCWG, or steam-assisted conversion without energy-intensive drying. An integrated pyrolysis–gasification–WGS study evaluated algal feedstocks including Cladophora glomerata and Gracilaria gracilis and obtained H_2-rich syngas, although the results varied considerably with species and operating conditions [146]. Marine biomass such as Posidonia oceanica also showed that the steam-to-biomass ratio affects both hydrogen-oriented performance and life-cycle impacts [148]. However, high concentrations of salts, ash, alkali and alkaline-earth metals, chlorine, and sulfur may promote corrosion, fouling, slagging, catalyst poisoning, and additional downstream cleaning. Washing or deashing, wet-route conversion, corrosion-resistant materials, and impurity-specific gas-cleaning systems should therefore be considered before scale-up.

Recent techno-economic evidence also indicates that microalgae-based hydrogen systems can reach reported production costs of 2.46–3.87 USD/kg H_2 under integrated steam-gasification, Ca-looping, waste-heat-utilization, and purification configurations, highlighting the importance of complete process integration rather than feedstock conversion alone [149].

Waste-derived and heterogeneous feedstocks require robust conversion and cleaning. Plasma gasification of refractory organic solid waste reported 347.04 g H_2/kg dry waste, H_2 production efficiency of 65.71%, and total energy efficiency of 61.34%, showing strong technical potential for difficult waste but also highlighting electricity and exergy burdens [83]. MSW gasification, RDF gasification, organic fraction of MSW conversion, waste plastic–biomass co-gasification, waste bagasse sorption-enhanced chemical looping, plasma co-gasification of coal and biomass, and biomass-assisted autothermal chemical looping show that waste-to-H_2 systems can increase feedstock flexibility, but their feasibility depends on chlorine, sulfur, nitrogen, heavy metals, ash behavior, tar destruction, gas cleaning, fossil-carbon accounting, and electricity source [43,75,76,79,96,100,101,105,118,121,122,124–129,142,144,165].

Bio-oil, pyrolysis, reforming, and intermediate-liquid routes represent another technical family. These routes convert raw biomass into bio-oil, aqueous fractions, hydrogen-rich gas, or reformable intermediates before H_2 production. They can reduce raw biomass

logistics and enable staged conversion, but bio-oil acidity, oxygen content, viscosity, instability, coke formation, catalyst deactivation, and reformer corrosion remain critical barriers [131,134,145,152,166–168,170–174]. Khongchamnan et al. reported 58.8% H_2 yield, 87.3% conversion, and stable operation over 170 h for two-stage fast pyrolysis and catalytic steam reforming of corn-waste bio-oil [145]. These results show that bio-oil reforming can be technically viable when catalyst stability, coke suppression, and staged conversion are achieved.

Overall, Table 5 confirms that the most technically promising biomass-to-H_2 systems are not necessarily those with the highest isolated H_2 concentration. Rather, they are the systems that integrate stable feedstock conversion, tar reduction, WGS or reforming, CO_2 separation, gas cleaning, H_2 purification, and long-duration operation. Future studies should report feedstock composition, operating conditions, H_2 yield, H_2 concentration, syngas composition, tar concentration, CO conversion, H_2 recovery, final H_2 purity, energy/exergy efficiency, purification method, catalyst/sorbent stability, and continuous operating time.

The technical comparison shows that the highest reported H_2 concentration does not necessarily identify the most deployable system. Greater practical relevance is associated with process chains that combine stable feedstock conversion, tar control, WGS, CO_2 removal, final purification, impurity tolerance, and long-duration operation. Consequently, H_2 yield, syngas-level concentration, final purity, H_2 recovery, energy and exergy efficiency, and continuous operating time should be reported together. This system-level interpretation represents a more reliable basis for technology comparison than isolated maximum H_2 values.

3.4. Techno-Economic Performance of Biomass-Derived Hydrogen

To address the economic and deployment gap identified in Section 3.1, the techno-economic synthesis was designed to move beyond technology-level performance comparisons and examine the conditions that govern cost competitiveness across biomass-to-hydrogen pathways. Accordingly, economic results were interpreted together with plant scale, system boundaries, feedstock logistics, purification requirements, financing assumptions, carbon-management configuration, and technology readiness, rather than as isolated LCOH values.

Techno-economic performance was evaluated through LCOH, CAPEX, OPEX, NPV, IRR, payback period, plant capacity, feedstock price, oxygen demand, electricity consumption, steam demand, purification cost, CCS cost, CO_2 transport and storage cost, carbon-credit assumptions, coproduct credits, and sensitivity analysis. The evidence shows that biomass-derived H_2 cannot be treated as a single economic category because cost values depend strongly on plant scale, pathway, feedstock, system boundary, currency year, capacity factor, purification level, and whether logistics, compression, storage, coproducts, or carbon incentives are included [35,41,43,76–79,86–90,94–101,104,108,112–116,120,121,125–128,134,138,139,142–144,149,151,153,155,157,163,166–168,170–175].

Table 6 was revised to improve the comparability and transparency of the techno-economic evidence. Reported hydrogen-production costs were first harmonized to a common mass-based functional unit (currency/kg H_2) whenever the information provided by the original study allowed direct conversion. For each case, the reported currency and economic reference year, plant scale, process and purification boundaries, and major cost assumptions were extracted explicitly whenever available. When the economic reference year or another essential normalization parameter was not reported, the value was identified as not reported (NR) rather than inferred. Consequently, monetary values expressed in different currencies or based on insufficiently documented reference years were not

treated as directly comparable. Cross-study interpretation therefore considers plant scale, feedstock cost, system boundary, H_2 purification, compression, storage and transportation, CCS/BECCS treatment, CAPEX, OPEX, financing assumptions, coproduct credits, and carbon-credit assumptions together with the reported LCOH. Direct cost comparisons were restricted to cases with sufficiently compatible monetary and methodological bases, whereas within-study scenario comparisons were retained because they preserve a common economic basis.

Table 6. Harmonized techno-economic comparison framework for representative biomass-derived hydrogen pathways.

Configuration	Feedstock	Plant Scale/Scenario	Economic Basis	Reported LCOH or H_2 Cost	System Boundary	Major cost Assumptions/Drivers
Two-stage gasification with/without BECCS	Wood chips/biomass	10 MWth; one no-CCS and two BECCS scenarios	GBP/kg H_2; economic reference year: NR	3.16 GBP/kg H_2 without CCS; 4.17–5.40 GBP/kg H_2 with BECCS; 95% CI: 2.88–4.32 and 3.82–8.06 GBP/kg H_2	Two-stage biomass gasification; comparison of no-CCS and BECCS configurations; downstream storage/transport boundary NR	Biomass feedstock cost, oxygen supply, CCS energy demand and CCS cost are major drivers; BECCS increases LCOH while enabling carbon-negative operation [41].
Biomass–plastic co-gasification with CCS	Woody biomass + polyethylene plastic	Biomass-only and co-gasification cases, with and without CCS; numerical plant scale: NR in current manuscript	USD/kg H_2; economic reference year: NR	Biomass without CCS: 2.34 USD/kg H_2; co-gasification without CCS: 2.18 USD/kg H_2; biomass + CCS: 3.18 USD/kg H_2; co-gasification + CCS: 2.98 USD/kg H_2	Biomass/co-feedstock gasification with optional CCS; storage and transport boundary NR	Feedstock cost, CCS cost and carbon-credit assumptions are decisive; a carbon credit of 70 USD/t CO_2 may reduce CCS cases below 1.8 USD/kg H_2 [43].
Decarbonized biomass gasification	Biomass	CO_2-capture alternatives: MDEA, Selexol, membrane and hybrid configurations; plant scale: NR	EUR/kg H_2; economic reference year: NR	1.81 EUR/kg H_2 without capture; 2.27–2.50 EUR/kg H_2 with capture	Biomass gasification with alternative downstream CO_2-removal configurations; H_2 storage/transport boundary NR	CAPEX approximately 1888–2130 EUR/kW; CO_2-removal cost as low as 24.43 EUR/t for the membrane case; capture increases production cost [120].
Sorption-enhanced waste gasification	RDF/solid waste	100 MWth RDF; H_2 + power co-production	EUR/kg H_2; economic reference year: NR	2.72 EUR/kg H_2	Sorption-enhanced gasification with in situ CO_2 capture and H_2/power co-production	Overall efficiency 50.10%; TRL 3; economic interpretation must account for co-production, carbon capture and low technology readiness [79].
Catalytic SCWG	Soybean straw	56,000 t/y soybean straw; approximately 170 t/day plant	USD/kg H_2; economic reference year: NR	Minimum selling price: 1.94 USD/kg H_2	SCWG-based hydrogen production; storage and transportation excluded	Net rate of return: 37.1%; economics depend on feedstock, catalyst, utilities, labor and other cash-flow assumptions. The reported value should be interpreted as a plant-level rather than delivered-H_2 cost [77].
Olive-pomace pyro-gasification	Olive pomace pellets	Pyro-gasification + reforming + WGS + PSA; H_2 production approximately 512.8 t/y at ER = 0.1	EUR/kg H_2; economic reference year: NR	16.30–24.45 EUR/kg H_2	Conversion, reforming, WGS and final PSA purification included; storage/transport boundary NR	Thermochemical efficiency 47.3% at ER = 0.1; process configuration, reforming and purification contribute strongly to cost; decentralized scale limits economies of scale [78].
Remote-community gasification	Forest biomass; MSW; plastics; tires	14 t/day H_2 remote-community scenario	USD/kg H_2; economic reference year: NR	Forest biomass: 19.09 USD/kg H_2; plastics: 15.80 USD/kg H_2; tire waste: 13.75 USD/kg H_2	Remote-community hydrogen production; deployment context and feedstock logistics are integral cost considerations	Small scale, remote logistics, feedstock availability and infrastructure strongly increase hydrogen cost [76].
Agricultural-residue gasification vs. biogas reforming	Agricultural residues; biogas	Small- vs. large-scale comparison; numerical capacities NR	USD/kg H_2; economic reference year: NR	Biogas reforming: 5.2 USD/kg H_2; small-scale gasification: 4.0 USD/kg H_2; large-scale gasification: 2.8 USD/kg H_2	Comparative hydrogen-production pathways; detailed purification, compression and storage boundaries NR	CAPEX: approximately 2400, 3000 and 2200 USD/kW; OPEX: approximately 0.75, 0.60 and 0.45 USD/kg H_2, respectively. Scale strongly affects reported LCOH [150].

Table 6. *Cont.*

Configuration	Feedstock	Plant Scale/Scenario	Economic Basis	Reported LCOH or H_2 Cost	System Boundary	Major cost Assumptions/Drivers
Integrated co-pyrolysis + gasification + reforming + WGS	Maize husk + rice husk	Integrated lignocellulosic process; numerical plant scale: NR	MUSD; economic reference year: NR	LCOH not reported	Integrated conversion chain through WGS; final purification, compression, storage and transport boundaries NR	CAPEX: 14.7971 MUSD; OPEX: 5.9313 MUSD/y; NPV: 127.58–204.87 MUSD; payback: 5.13–5.94 y; IRR: 36.77–41.55%. Not suitable for direct LCOH comparison because LCOH was not reported [139].
Microalgae steam gasification + Ca-looping	Microalgae	Steam gasification + Ca-looping combustion + waste-heat utilization; numerical plant scale: NR in current manuscript	USD/kg H_2; economic reference year: NR	2.46–3.87 USD/kg H_2	Steam gasification, carbon-management configuration and waste-heat utilization; purification included as an important economic component	H_2 purification significantly affects cost; economic performance depends on integration of heat recovery, capture and purification [149].

Note: All reported hydrogen-production costs were standardized to a mass-based functional unit of currency/kg H_2 whenever direct conversion was possible. NR indicates information that was not explicitly reported in the current evidence extraction and therefore was not inferred. Economic reference year, plant scale, system boundary, H_2 purification, compression, storage, transportation, CCS/BECCS treatment, feedstock cost, coproduct credits, and carbon-credit assumptions were retained explicitly whenever available. Reported costs expressed in different currencies or based on unspecified economic reference years were not treated as directly comparable. Accordingly, cross-study LCOH ranking was avoided unless the monetary basis and major system-boundary assumptions were sufficiently aligned. Energy-based costs were converted to a mass basis using the lower heating value of hydrogen (33.33 kWh/kg H_2). Note: Hydrogen production costs were harmonized to a mass-based functional unit (currency/kg H_2) whenever direct conversion was possible. Energy-based costs reported in EUR/MWh H_2 were converted using the lower heating value of hydrogen (33.33 kWh/kg H_2). Original currencies and currency years were retained; therefore, monetary values were not converted between currencies or adjusted for inflation.

To complement the tabulated techno-economic evidence and facilitate visual comparison among case studies reported on the same currency basis, Figure 4 summarizes the H_2 production costs of selected USD-denominated scenarios. The values are presented as originally reported and should be interpreted in conjunction with differences in plant scale, system boundaries, purification requirements, feedstock logistics, storage and transportation assumptions, and other study-specific methodological conditions.

Figure 4 reported hydrogen production costs for selected USD-denominated biomass-to-hydrogen case studies included in the techno-economic synthesis. Point estimates represent the values reported by the original studies, whereas horizontal intervals indicate reported cost ranges. The reported costs should be interpreted together with the corresponding plant scale, system boundary, hydrogen-purification requirements, compression, storage and transportation assumptions, CCS/BECCS configuration, and major economic assumptions summarized in Table 6. Because several studies do not provide a sufficiently documented economic reference year for complete inflation normalization, the figure is intended to illustrate the variability of representative USD-denominated case studies rather than establish a universal cross-study cost ranking. The catalytic SCWG value of 1.94 USD/kg H_2 reported in [77] excludes hydrogen storage and transportation. Table 6 and Figure 4 show that the reported cost competitiveness of biomass-to-hydrogen pathways is highly conditional and strongly dependent on case-specific assumptions, scale, process configuration, and system boundaries. Favorable plant-gate values have been reported for optimized SCWG, large-scale gasification, waste-to-H_2, and integrated systems. Okolie et al. reported a minimum selling price of 1.94 USD/kg H_2 for soybean straw SCWG, although storage and transportation were excluded; therefore, this value should be interpreted as a favorable plant-gate estimate rather than a delivered hydrogen cost [77]. Waste-to-H_2 and

power co-production by sorption-enhanced solid-waste gasification reported 2.72 EUR/kg H_2, with high-purity H_2 and in situ CO_2 capture, although low TRL and process integration risk remain important barriers [79]. In contrast, olive-pomace pyro-gasification reported 16.30–24.45 EUR/kg H_2, showing that decentralized systems with extensive reforming, WGS, PSA, and limited economies of scale can remain economically challenging [78].

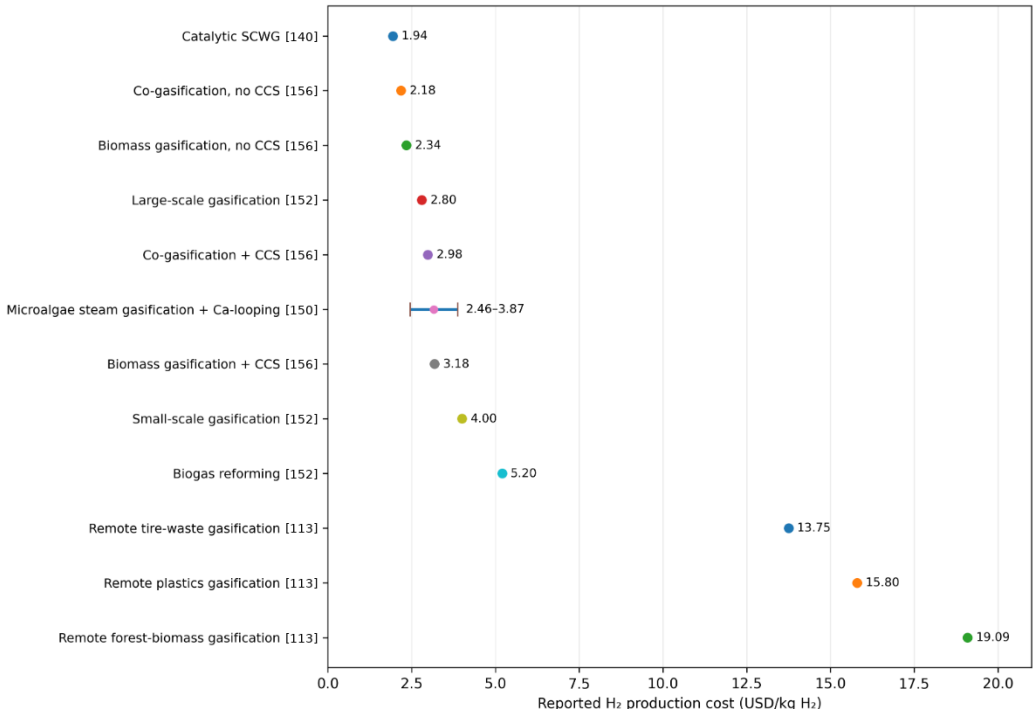


Figure 4. Reported hydrogen production costs for selected USD-denominated biomass-to-hydrogen case studies included in the techno-economic synthesis.

The USD-denominated cases presented in Figure 4 further illustrate the variability of reported hydrogen-production costs across different deployment contexts. Reported values range from approximately 1.94–5.20 USD/kg H_2 in selected plant-gate, integrated, and scale-comparison scenarios, whereas remote-community applications reach approximately 13.75–19.09 USD/kg H_2. These values are presented as representative reported costs rather than as directly harmonized cross-study estimates. Their interpretation therefore requires consideration of plant scale, feedstock, process configuration, purification boundary, logistics, storage and transportation assumptions, and other economic conditions summarized in Table 6. Accordingly, Figure 4 is intended to illustrate the dispersion of reported USD-denominated costs rather than establish a universal cost ranking among biomass-to-hydrogen technologies.

Plant scale remains an important economic driver, particularly when comparisons are made within a common study basis. In the scale-comparison analysis reported in [150], agricultural-residue gasification reached 2.8 USD/kg H_2 at large scale compared with 4.0 USD/kg H_2 at small scale, while biogas reforming was reported at 5.2 USD/kg H_2. Remote-community scenarios evaluated in [76] reported substantially higher costs, including 19.09 USD/kg H_2 for forest biomass, 15.80 USD/kg H_2 for plastics, and 13.75 USD/kg H_2 for tire waste. These results illustrate how scale, logistics, feedstock availability, and deployment context can strongly influence hydrogen-production costs, although values from different studies should not be interpreted as strictly equivalent economic benchmarks.

CCS and BECCS also introduce important economic–environmental trade-offs that are most reliably evaluated through within-study comparisons. In [41], the reported LCOH

increased from 3.16 GBP/kg H_2 without CCS to 4.17–5.40 GBP/kg H_2 in BECCS configurations. Similarly, Karimi et al. reported 2.34 USD/kg H_2 for biomass gasification without CCS and 3.18 USD/kg H_2 with CCS, while biomass–plastic co-gasification increased from 2.18 to 2.98 USD/kg H_2 after CCS integration [43]. Under a carbon-credit assumption of 70 USD/t CO_2, the reported CCS cases could decrease below 1.8 USD/kg H_2. These within-study comparisons demonstrate that the economic impact of carbon capture depends strongly on carbon pricing, CO_2 transport and storage requirements, energy penalties, feedstock characteristics, and the selected system boundary. To enable comparison across studies reported in different currencies, Figure 5 expresses selected scenario differences as relative changes in H_2 production cost rather than as absolute monetary values. This within-study normalization highlights the effect of scale, process configuration, and carbon-capture integration while avoiding direct comparison among USD-, EUR-, and GBP-denominated results.

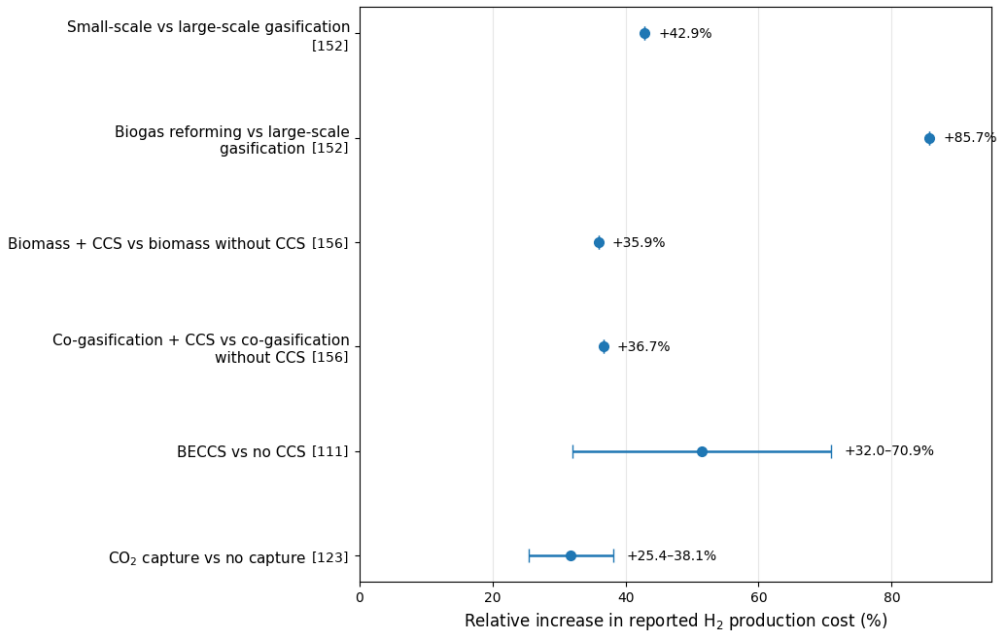


Figure 5. Relative changes in reported H_2 production cost within selected techno-economic scenario comparisons. Relative changes were calculated using the reported values within each original study and are therefore dimensionless. Point estimates represent single relative changes, whereas horizontal intervals represent ranges derived from reported cost ranges. The figure compares scenario changes only within the same study and does not imply direct comparability among different currencies, price years, plant scales, system boundaries, feedstocks, or financing assumptions. For [41], the BECCS range was calculated relative to the reported no-CCS reference case; for [120], the CO_2-capture range was calculated relative to the reported no-capture case.

Figure 5 illustrates that the economic impact of system configuration can be substantial even within individual studies. In [150], small-scale gasification increased the reported H_2 production cost by approximately 42.9% relative to the corresponding large-scale gasification case, while biogas reforming was approximately 85.7% higher than the large-scale reference. Carbon-capture integration also increased reported costs within the evaluated studies: by approximately 35.9–36.7% in the CCS scenarios of [43], by approximately 32.0–70.9% for BECCS in [41], and by approximately 25.4–38.1% for CO_2-capture configurations in [120]. These results reinforce that economic performance is highly sensitive to scale and process-boundary choices and should not be interpreted solely from absolute LCOH values.

Hybrid and polygeneration systems expand the economic boundary beyond standalone gasification. Wind-powered electrolysis integrated with biomass gasification reported strong techno-economic performance in a dual fluidized-bed oxygen–steam configuration, including 46 vol% H_2, NPV of USD 25 million, IRR of 156%, payback of 0.69 years, LCOE of USD 0.13/kWh, and LCOH of USD 4.42/kg [35]. Exergoeconomic integration with geothermal energy, biomass–LNG multigeneration, renewable methanol systems coupled with biomass gasification, solar–biomass chemical looping, solar-assisted biomass chemical looping, glycerol cogeneration with biomass chemical looping, and autothermal MSW chemical looping show that hybridization can improve energy integration but complicates allocation among H_2, electricity, methanol, heat, cooling, LNG services, and coproducts [87,98,115,116,143,144,155].

Several TEA studies report project-level indicators beyond LCOH. Integrated co-pyrolysis and gasification of lignocellulosic biomass reported CAPEX of 14.7971 MUSD, OPEX of 5.9313 MUSD/y, NPV of 127.58–204.87 MUSD, payback of 5.13–5.94 years, and IRR of 36.77–41.55%, but without a directly comparable LCOH [139]. Other studies apply surrogate modeling, multi-objective optimization, AI-based optimization, K-means clustering, machine learning, or regional optimization to biomass gasification and hybrid hydrogen systems, but their comparability is limited when they do not harmonize capacity factor, feedstock cost, H_2 purity, compression, storage, and system boundaries [84,86,87,90,112,125,138,147,175].

Bio-oil reforming and pyrolysis-derived systems show different economic drivers from direct gasification. Comparative TEA of bio-oil gasification and bio-oil reforming, aqueous-phase reforming of pyrolysis bio-oil aqueous fraction, catalytic steam reforming of pyrolysis bio-oil, oriented pyrolysis, methane tri-reforming, and sorption-enhanced steam reforming show that catalyst lifetime, coke suppression, hydrogen purification, coproduct valorization, biochar credits, and liquid-phase intermediate handling strongly affect economic feasibility [166–168,170–174]. These routes should not be merged uncritically with direct solid biomass gasification because their logistics, intermediate upgrading, reactor requirements, and product portfolios differ.

Across the reviewed techno-economic studies, the most recurrent sensitivity drivers were plant scale and capacity factor, feedstock price and transportation distance, capital expenditure, discount rate, oxygen and electricity demand, steam consumption, catalyst or sorbent replacement, hydrogen yield and purity, compression and storage, and the cost of carbon capture, CO_2 transport, and permanent storage. Their relative importance varied according to pathway and system boundary. Large centralized plants were generally more sensitive to capital cost, capacity factor, and financing assumptions, whereas decentralized systems were more strongly affected by feedstock availability, logistics, and equipment utilization. Carbon credits, waste-treatment revenues, and coproduct valorization could partially offset production costs, but their effect depended on policy and market assumptions [43,77,84,86,138,144].

Overall, Table 6 demonstrates that cost competitiveness improves with large scale, low-cost residues, reliable feedstock supply, high capacity factor, heat integration, waste-treatment credits, carbon credits, renewable energy coupling, coproduct valorization, process intensification, and policy incentives [35,41,43,77,79,94–101,112–114,120,125–128,134,139,142–144,149,151,163,166–168,171–174]. Conversely, cost increases with small scale, remote logistics, uncertain biomass supply, high oxygen or electricity demand, tar removal, gas cleaning, PSA/membrane purification, compression, storage, CCS energy penalty, and low TRL. Future TEA studies should report plant capacity, currency year, feedstock cost, CAPEX, OPEX, LCOH, capacity factor, H_2 purity, compression, storage, CO_2 transport, permanent storage, coproduct credits, carbon-credit scenarios, and sensitivity analysis.

The techno-economic evidence demonstrates that the reported cost range is driven as much by methodological assumptions as by the conversion technology itself. Plant scale, capacity factor, currency and reference year, feedstock price, transportation distance, purification boundary, compression, storage, carbon capture, financing conditions, and coproduct or carbon-credit revenues can reverse the apparent ranking of pathways. Therefore, LCOH values should not be compared or averaged without harmonizing these assumptions. The principal economic insight is that no universally lowest-cost route can be identified from the existing literature because the studies do not apply a common system boundary or cost basis.

As a concise external benchmark, renewable-powered water electrolysis shows similarly strong dependence on system configuration and resource conditions. A recent comparative optimization study reported a specific energy consumption of 39.63 kWh/kg H_2 and a total annualized cost of 2.45 MUSD/year for biomass gasification, compared with 68.7 kWh/kg H_2 and 3.72 MUSD/year for water electrolysis under the same study framework [175]. For renewable electrolysis specifically, a PEM-based analysis reported LCOH values of approximately 3.56–5.34 USD/kg H_2 under operating-cost uncertainty [31], whereas an off-grid PV–electrolysis–battery system reported 10.77 USD/kg H_2 under its base-case configuration [30]. These values should be interpreted as contextual benchmarks rather than as a universal ranking because electricity price and availability, capacity factor, plant scale, feedstock logistics, storage requirements, and system boundaries differ substantially among studies. Accordingly, biomass conversion and renewable electrolysis are better viewed as complementary sustainable H_2 pathways whose relative performance depends on local resource and deployment conditions.

3.5. Feedstock Suitability, Route Selection, Operational Challenges, and Scale-Up Barriers

Feedstock selection determines route selection, reactor configuration, pretreatment requirements, syngas quality, tar formation, H_2 yield, gas-cleaning burden, catalyst stability, techno-economic feasibility, and life-cycle performance. The PRISMA evidence base covers dry woody biomass, lignocellulosic residues, forestry biomass, agricultural residues, sewage sludge, oily sludge, food waste, biowaste, MSW/RDF, waste plastics, LDPE, tires, biomass–coal blends, biomass–plastic blends, algae, microalgae, oil palm residues, bio-oil, aqueous pyrolysis fractions, and hybrid biomass–renewable systems [35,41–43,70–175].

Table 7 was included to connect feedstock categories with their most suitable conversion routes, technical rationale, and scale-up barriers. This structure is necessary because feedstock frequency alone does not indicate suitability. A feedstock may be widely studied because it is available or easy to process, but its deployment potential depends on moisture, ash, volatile matter, HHV/LHV, mineral content, impurity profile, logistics, pretreatment requirements, and compatibility with gas cleaning and purification.

Table 7. Feedstock suitability, route selection and scale-up barriers for biomass-derived hydrogen.

Feedstock Category	Frequency	Best-Fit Route	Quantitative/Technical Basis	Main Barriers
Lignocellulosic, woody and forestry biomass	75/111	Steam gasification; oxy-steam gasification; dual fluidized bed; BECCS; pyrolysis–reforming	Dominant feedstock category; compatible with gasification, pyrolysis, reforming, and CCS [49,50,60,68,155].	Low bulk density, drying demand, seasonal and regional availability, transportation logistics, particle-size variability, tar formation, competing uses, and sustainable-harvesting constraints.
Agricultural and agro-industrial residues	43/111	Gasification; pyrolysis–gasification; bio-oil reforming; decentralized H_2	Includes straw, rice straw, soybean straw, bagasse, palm residues, olive pomace, citrus peels, and corn waste [69,77,78,145,148].	Ash, alkali metals, slagging, variable moisture, seasonal availability, dispersed collection, transportation requirements, competing uses, sustainable residue-recovery limits, and catalyst stability.

Table 7. *Cont.*

Feedstock Category	Frequency	Best-Fit Route	Quantitative/Technical Basis	Main Barriers
Sewage sludge and wet biomass	17/111	SCWG; hydrothermal gasification; alkaline pyrolysis	High moisture makes drying-intensive gasification less attractive; SCWG uses water as the reaction medium [153,160,162,176].	High pressure, corrosion, salt precipitation, plugging, catalyst recovery, and heat-integration requirements.
MSW, RDF and biowaste	27/111	Waste gasification; plasma gasification; sorption-enhanced gasification; BECCS	Relevant for landfill diversion, methane avoidance, and waste-to-H_2 systems [75,76,79,83].	Feedstock heterogeneity, chlorine, sulfur, nitrogen, contaminants, ash-forming components, variable organic fraction, and syngas-cleaning requirements.
Mixed co-feedstock systems	28/111	Co-gasification; co-pyrolysis; chemical looping; CCS-integrated systems	Biomass–plastic or biomass–RDF blends can improve H_2 yield and energy balance [43,85,129].	Fossil-carbon accounting, impurities, variable composition, feedstock-quality variability, and complex sustainability classification.
Bio-oil and pyrolysis-derived intermediates	20/111	Catalytic steam Reforming; aqueous-phase reforming; bio-oil upgrading	Liquid intermediates may reduce raw-bio mass logistics but require dedicated reforming [63,145,170,171,177].	Bio-oil acidity, high oxygen content, viscosity, instability, coke formation, catalyst deactivation, reformer corrosion, H_2 purification, and coproduct-valorization requirements.
Algae, microalgae, macroalgae, and seaweed	10/111	SCWG; hydrothermal gasification; catalytic steam gasification; integrated pyrolysis–gasification–WGS; plasma gasification for selected conditioned algal feedstocks	High moisture content favors wet conversion; carbohydrate, lipid, and volatile-matter fractions can support H_2-rich gas production; many macroalgae have relatively low lignin content [91,119,146,148,149].	Moisture, ash, nitrogen compounds, NH_3/HCN formation risk, drying cost where required, species variability, and gas-cleaning requirements.
Advanced capture/CaO systems	Cross-cutting	Sorption-enhanced gasification; Ca-looping; CaO-CLG	CaO-CLG achieved 78% H_2, 4.98% CO_2, and tar of 2.48 g/Nm^3 [74]; Ce-modified CaO reached 81.1 vol% H_2 [73].	Sorbent sintering, carbonation/calcination degradation, material stability, and regeneration requirements.
Plasma and difficult waste streams	Specialized	Plasma gasification + WGS + PSA	Optimized plasma gasification reached 347.04 g H_2/kg dry waste, H_2-production efficiency of 65.71%, and total energy efficiency of 61.34% [83].	High electricity demand, exergy destruction, difficult scale-up, and feedstock-conditioning requirements.

Note: Feedstock categories are non-mutually exclusive because individual studies may evaluate more than one feedstock type; therefore, the reported frequencies should not be summed to 111 or interpreted as mutually exclusive proportions of the evidence base. Feedstock suitability was assessed primarily from measurable physicochemical properties, including moisture content, ash and mineral composition, volatile matter, elemental composition, alkali/chlorine content, heating value, and particle-related characteristics, rather than from categorical feedstock labels alone.

Table 7 shows that no single feedstock is universally optimal for biomass-derived hydrogen. Lignocellulosic, woody, and forestry biomass are the most mature feedstock group for gasification-based H_2 production because they are compatible with fixed-bed, fluidized-bed, pressurized, steam, oxy-steam, dual-stage, WGS, PSA, CCS, and BECCS systems [41,70–72,81,82,87–90,92–95,97,102–114,123,134–136,140,141,147]. Their advantages include relatively stable conversion behavior and broad availability, while their limitations include low bulk density, drying demand, particle-size heterogeneity, transport logistics, ash behavior, tar formation, and seasonal variability.

Agricultural and agro-industrial residues are attractive because of low cost, regional availability, and compatibility with circular bioeconomy strategies. Studies involving rice straw, soybean straw, canola straw, olive pomace, citrus peels, bagasse, palm residues, corn waste, maize husk, rice husk, oil palm fiber, and palm rachis show that these materials can support SCWG, pyro-gasification, steam gasification, oxy-steam gasification, bio-oil reforming, co-pyrolysis, chemical looping, TEA, and LCA configurations [77,78,129,138,139,145,148–152]. However, their ash, alkali metals, chlorine, silica, moisture variability, slagging tendency, agglomeration risk, and catalyst-poisoning potential make them more complex than clean woody biomass. For these residues, proximate and ultimate analysis, ash composition, HHV/LHV, mineral content, moisture, and particle size are necessary for selecting reactor type, catalyst, gasifying agent, ash-management strategy, and gas-cleaning system.

Feedstock availability should also be interpreted in terms of sustainably recoverable rather than theoretical biomass potential. Agricultural and forestry residues may already

have competed uses within local bioeconomies, and their diversion to hydrogen production can therefore affect effective feedstock availability and supply cost. In addition, not all generated residue can be sustainably removed from the production system. Harvesting intensity, seasonal supply, collection efficiency, transport distance, storage losses, moisture content, and the need to retain part of the biomass within agricultural or forestry systems can constrain the quantity that can be mobilized for continuous hydrogen production. Consequently, large-scale biomass-to-H_2 deployment should be based on region-specific assessments of recoverable feedstock supply rather than on gross residue-generation estimates alone. Long-term supply strategies should also account for competing material or energy uses, changes in moisture and quality during storage, transport requirements, and the environmental implications of biomass cultivation, harvesting, and logistics.

Wet feedstocks require a different route-selection logic. Sewage sludge, oily sludge, algae, microalgae, food waste, and other high-moisture streams are often unsuitable for conventional dry gasification unless drying is economically justified. SCWG and hydrothermal gasification are particularly appropriate for high-moisture feedstocks because they can reduce or avoid energy-intensive drying. Plasma gasification has also been investigated for algal and waste-derived feedstocks, but its feedstock-conditioning and drying requirements depend on the specific process configuration [72,76,77,79,86,89,91,104,115–123,146,147,149,153–162]. However, these routes face corrosion, plugging, salt precipitation, catalyst recovery, high-pressure operation, heat-recovery challenges, and in some cases high electricity demand.

MSW, RDF, biowaste, waste plastics, refractory organic wastes, tires, sewage sludge, and mixed waste streams broaden biomass-to-H_2 toward circular-economy applications. These feedstocks can reduce landfill disposal, valorize difficult residues, and support waste-to-H_2 configurations, but they introduce feedstock heterogeneity, chlorine, sulfur, nitrogen, heavy metals, ash-forming components, variable organic fractions, fossil carbon, and gas-cleaning complexity [43,75,76,79,83,85,96,100,101,105,118,121,122,124–129,142,144,156,163,165]. Plasma and high-temperature systems can treat difficult wastes, but their electricity demand and exergy losses require careful evaluation.

Mixed co-feedstock systems provide flexibility but complicate sustainability classification. Biomass–plastic, biomass–RDF, biomass–coal, biomass–LDPE, sludge–wood, biomass–methane, and mineral-rich co-feeds can improve H_2 yield, syngas composition, energy balance, or process stability [43,75,85,90,101,105,118,121,122,129]. However, fossil-derived co-feeds weaken renewable-hydrogen claims unless fossil-carbon accounting, CCS performance, and LCA boundaries are explicitly reported. Therefore, these systems should be classified as waste-to-H_2, low-carbon H_2, or potentially carbon-negative H_2 only when carbon accounting supports that interpretation.

Bio-oil, aqueous pyrolysis fractions, and intermediate-liquid routes should be treated separately from direct solid biomass. They may reduce raw biomass transport constraints by converting distributed biomass into liquid or reformable intermediates, but their scale-up depends on bio-oil stabilization, catalytic reforming, coke resistance, corrosion control, H_2 purification, and coproduct valorization [131,134,145,166–168,170–174]. These routes are promising when they integrate staged reforming, stable catalysts, aqueous-phase reforming, sorption-enhanced reforming, biochar valorization, or coproduct credits.

The main scale-up barriers across Table 7 and the broader evidence base are feedstock heterogeneity and logistics, tar formation, gas cleaning, catalyst deactivation, sorbent degradation, oxygen-carrier stability, ash and alkali management, SCWG corrosion and plugging, plasma electricity demand, CCS energy penalty, high CAPEX, uncertain LCOH, inconsistent LCA boundaries, and limited pilot-scale validation [35,41–43,70–175]. These barriers are interconnected: feedstock impurities increase tar and ash problems; tar poi-

sons catalysts; gas cleaning increases cost and energy demand; CCS improves GWP but increases CAPEX and auxiliary energy; and limited pilot validation weakens TEA and LCA assumptions.

Although tar formation was repeatedly identified as a major operational and economic barrier, a pooled quantitative sensitivity analysis linking tar concentration directly to LCOH was not methodologically possible. The reviewed studies did not consistently report tar loading, tar-removal efficiency, gas-cleaning CAPEX and OPEX, catalyst replacement frequency, plant downtime, hydrogen losses, and economic system boundaries using comparable units. The revised manuscript therefore links tar formation only to documented process-level consequences, including catalyst poisoning, fouling, additional reforming and filtration equipment, auxiliary energy demand, maintenance, and reduced plant availability. The lack of harmonized tar-related techno-economic data is identified as a research gap, and future studies should report the effect of tar loading and removal requirements on CAPEX, OPEX, plant availability, and LCOH.

Consequently, Table 7 supports an integrated feedstock–route–barrier framework. Dry woody biomass is best aligned with mature gasification and BECCS; agricultural residues require ash and alkali control; wet feedstocks are generally better aligned with SCWG or hydrothermal routes; MSW/RDF and plastic-rich streams require robust gas cleaning and fossil-carbon accounting; algae and microalgae require wet-route or impurity-aware systems; and bio-oil requires catalyst-stable reforming.

Feedstock flexibility should not be interpreted as feedstock interchangeability. Dry lignocellulosic biomass, agricultural residues, wet sludge, algae, municipal waste, plastic-containing streams, and bio-oil intermediates require different reactors, pretreatment strategies, impurity-control systems, and supply-chain configurations. The feedstock–route–barrier framework developed in this review indicates that deployment should be designed around measured feedstock properties rather than attempting to adapt every resource to conventional dry gasification. This distinction is essential for avoiding technically unsuitable pathway selection and unrealistic cost or environmental assumptions.

3.6. Life-Cycle Emissions, CCS/BECCS and Decarbonization Performance

Life-cycle emissions and decarbonization potential were analyzed separately because biomass-derived hydrogen should not be automatically classified as green or carbon-negative. Environmental performance depends on feedstock origin, system boundary, functional unit, electricity mix, auxiliary energy demand, H_2 purification, gas cleaning, CO_2 capture rate, CO_2 transport, permanent storage, coproduct allocation, and biogenic/fossil carbon accounting [41–43,70,71,80,85,102,106,108,117,122,129,135,137,141,144,148,150,156,163–169].

Direct comparison among the reviewed LCA results is limited by differences in system boundaries. Gate-to-gate assessments generally include only biomass conversion, syngas conditioning, and hydrogen upgrading, whereas cradle-to-gate studies may additionally include biomass cultivation or residue collection, preprocessing, transportation, auxiliary utilities, gas cleaning, and hydrogen purification. Cradle-to-grave assessments may further incorporate hydrogen compression, storage, distribution, final use, and end-of-life processes. Consequently, carbon-intensity values obtained under different system boundaries were not pooled or treated as directly equivalent. The functional unit, allocation method, electricity mix, treatment of biogenic carbon, carbon-capture configuration, CO_2 transport, and permanent-storage assumptions were retained as reported in the original studies.

Table 8 was included to synthesize representative LCA, CCS/BECCS, and decarbonization results. The purpose of this table is not only to report GWP values, but also to show how system configuration changes the environmental classification of biomass-derived H_2. Therefore, the table compares cases without capture, with CCS, with BECCS, with

chemical looping, with fossil-derived co-feeds, with waste-heat recovery, and with different functional units.

Table 8. Life-cycle emissions, CCS/BECCS and decarbonization performance of biomass-derived hydrogen pathways.

Route/Study Focus	Feedstock	System Boundary/Functional Unit	Reported Carbon Intensity/GWP	Carbon-Capture and Storage Assumptions	Critical Interpretation
Two-stage gasification with/without BECCS	Wood chips/biomass	Integrated TEA/LCA; 10 MWth plant. Detailed upstream and downstream boundary elements were not fully specified in the current evidence extraction.	Without CCS: +4.57 kg CO_2/kg H_2; with BECCS: −14.7 to −21.3 kg CO_2/kg H_2	BECCS configuration; gross CO_2 sequestration: 21.65–30.22 kg CO_2/kg H_2. Detailed CO_2 transport and permanent-storage assumptions: NR in current extraction	The negative values are conditional on biogenic-carbon capture and storage and should not be generalized beyond the reported LCA boundary. The same biomass pathway changes from net-positive to net-negative only under the BECCS configuration [41].
Biomass gasification + carbon capture	Forest residues	Functional unit: 1 kg H_2. Detailed life-cycle boundary: NR in current extraction.	No capture: +2.99 kg CO_2-eq/kg H_2; with capture: −18.8, −9.71, and −9.56 kg CO_2-eq/kg H_2	Carbon-capture/BECCS configurations included; detailed CO_2 transport, storage permanence, and allocation assumptions: NR in current extraction	Capture substantially reduces GWP and produces negative reported values under the assessed scenarios; however, the result remains dependent on energy, solvent, chemical, and storage assumptions [80].
Biomass–plastic co-gasification with CCS	Woody biomass + PE plastic	Cradle-to-gate LCA.	Without CCS: +5.8 to +6.5 kg CO_2-eq/kg H_2; with CCS: −12.3 to −14.7 kg CO_2-eq/kg H_2	CCS integrated into the production system. Fossil-derived PE is present; detailed permanent-storage assumptions: NR in current extraction	Negative cradle-to-gate GWP is reported under CCS, but plastic co-feeding introduces fossil carbon and therefore requires explicit fossil/biogenic carbon accounting. The result should not automatically be classified as green H_2 [43].
Agricultural-residue gasification	Agricultural residues	Comparative LCA against biogas reforming; functional unit reported on a per-kg-H_2 basis.	Agricultural-residue gasification: 1.30 kg CO_2-eq/kg H_2; biogas reforming: 5.047 kg CO_2-eq/kg H_2	No full BECCS configuration	Gasification shows lower GWP than the comparator but remains net-positive. Lower GWP therefore does not imply carbon negativity. Water consumption was also higher: 5.37 m^3/kg H_2 vs. 0.041 m^3/kg H_2 [150].
Co-pyrolysis + chemical-looping co-gasification	Rice straw + agricultural plastic waste	Functional units: 1 kg H_2 and 1 MWh electricity.	Best H_2 scenario: 3.87 kg CO_2-eq/kg H_2; electricity scenario: 0.87 t CO_2-eq/MWh	Chemical-looping configuration; no full BECCS claim reported	Results depend strongly on functional unit and coproduct allocation. The positive H_2 carbon intensity does not support a carbon-negative classification [129].
Co-gasification with carbon capture and waste-heat recovery	Switchgrass; switchgrass + LDPE; switchgrass + coal	Environmental/economic assessment using ReCiPe midpoint methodology; exact functional unit/boundary details: NR in current extraction.	Carbon-negative results reported for integrated biomass, biomass–LDPE, and biomass–coal scenarios; directly harmonized numerical value not available in the current synthesis	Carbon capture + waste-heat recovery	Reported negative results are configuration-specific. LDPE and coal co-feeding introduce fossil carbon and weaken any generalized renewable or green-H_2 classification; fossil-carbon allocation must be reported transparently [85].
Indirect biomass gasification with CO_2 capture	Short-rotation poplar	Gasification + WGS + PSA + CO_2 capture; functional unit and full up-stream/downstream boundary: NR in current extraction.	Negative GWP benchmark: approximately −14.63 kg CO_2-eq/kg H_2	CCS-integrated route; detailed transport and permanent-storage assumptions: NR in current extraction	The negative value supports BECCS potential under the reported configuration but is sensitive to cultivation, pretreatment, syngas cleaning, capture, and storage assumptions [42].
Lignocellulosic biomass gasification	Poplar/ lignocellulosic biomass	Environmental and exergetic evaluation; detailed functional unit/boundary: NR in current extraction.	Exergetic efficiency: approximately 48%; no directly harmonized carbon-negative value reported	No automatic carbon-negative classification	Biomass origin alone does not establish low-carbon or carbon-negative H_2. Poplar cultivation, pretreatment, and gas cleaning are important environmental contributors [71].
Steam gasification of residues	Citrus peels; *Posidonia oceanica*	LCA of residue-derived H_2; detailed functional unit/boundary: NR in current extraction.	Increasing steam-to-biomass ratio reduced GWP by 63.5% for citrus peels and 67.6% for *Posidonia*	No full BECCS configuration	Relative GWP reduction demonstrates the influence of operating conditions but does not by itself establish a negative life-cycle carbon intensity [148].
Sorption-enhanced waste gasification with carbon capture	MSW + woody biomass; MSW + mixed plastic waste	Process-level technical and environmental assessment; complete life-cycle boundary not reported in the current synthesis.	No directly harmonized life-cycle carbon-intensity value reported	CO_2 capture approximately 90–92%; final H_2 purity 99.99 mol%	High capture efficiency and H_2 purity do not demonstrate carbon-negative production by themselves. A complete LCA including upstream emissions, fossil-plastic carbon, auxiliary energy, CO_2 transport, and permanent storage would be required [75].

Because carbon-capture efficiency and life-cycle carbon intensity are different indicators, both were retained whenever they were reported. A high capture percentage does not by itself demonstrate carbon-negative hydrogen because upstream emissions, auxiliary energy, fossil-derived co-feeds, CO_2 transport, storage permanence, and system boundaries may change the final life-cycle result. Studies reporting capture performance without a complete life-cycle assessment were therefore not treated as direct evidence of carbon-negative production.

For the purposes of this review, a reported negative carbon intensity was interpreted as evidence of carbon-negative hydrogen only when the original study evaluated net life-cycle greenhouse-gas emissions within an explicitly defined system boundary and accounted for the relevant treatment of biogenic carbon and CO_2 capture and permanent storage. Negative values were not inferred from CO_2 capture efficiency or gross CO_2 sequestration alone. Where the original study did not clearly specify upstream biomass supply, electricity and auxiliary-energy inputs, CO_2 transport and storage, storage permanence, coproduct allocation, displaced-product credits, or fossil-derived co-feed accounting, the reported negative value was retained as study-specific evidence but interpreted as boundary-dependent rather than as a universally transferable carbon-negative result. Accordingly, carbon-capture efficiency, gross CO_2 removal, and net life-cycle carbon intensity were treated as distinct indicators throughout the synthesis.

Table 8 shows that the reviewed biomass-derived hydrogen systems span from net-positive to negative reported life-cycle carbon intensities, depending on the specific process configuration and LCA assumptions. Rabea et al. reported +4.57 kg CO_2/kg H_2 for the configuration without CCS and −14.7 to −21.3 kg CO_2/kg H_2 for the assessed BECCS configurations, together with gross CO_2 sequestration of 21.65–30.22 kg CO_2/kg H_2 [41]. These negative values should be interpreted within the system boundary and carbon-accounting assumptions adopted in the original study. They indicate that the assessed pathway can achieve a negative net life-cycle balance when biogenic CO_2 is captured and stored, but they should not be generalized to biomass-derived hydrogen systems operating under different upstream, energy, transport, or storage conditions.

A similar boundary-dependent behavior was reported for forest-residue and integrated carbon-capture systems. Wu et al. reported +2.99 kg CO_2-eq/kg H_2 without capture and values between −18.8 and −9.56 kg CO_2-eq/kg H_2 for the assessed capture configurations [80]. Patel et al. also reported negative environmental results for selected biomass, biomass–LDPE, and biomass–coal co-gasification scenarios incorporating carbon capture and waste-heat recovery [85]. These results illustrate the potential of CCS, chemical looping, and heat integration to reduce net life-cycle emissions; however, their interpretation depends on the treatment of biogenic and fossil carbon, auxiliary-energy requirements, system boundaries, allocation procedures, and CO_2 transport and storage assumptions.

Biomass–plastic co-gasification further illustrates the importance of carbon-accounting boundaries. The study reported +5.8 to +6.5 kg CO_2-eq/kg H_2 without CCS and −12.3 to −14.7 kg CO_2-eq/kg H_2 with CCS [43]. Although the CCS scenarios achieved negative reported cradle-to-gate GWP values, PE co-feeding introduces fossil-derived carbon and therefore prevents these results from being interpreted automatically as evidence of universally green or carbon-negative hydrogen. Likewise, biomass–coal and plasma co-gasification systems may reduce emissions relative to their respective reference cases, but their environmental classification depends on fossil-carbon allocation, electricity supply, capture configuration, storage assumptions, and functional unit [121,122].

3.7. Integrated Discussion and Future Research Priorities

The integrated synthesis of the 111 core studies shows that thermochemical biomass-to-H_2 pathways cannot be evaluated through a single criterion. High H_2 yield, high H_2 concentration, low LCOH, low GWP, carbon-negative potential, feedstock flexibility, and scale-up readiness do not always occur simultaneously. Each pathway involves trade-offs among feedstock properties, reactor performance, gas cleaning, H_2 purification, cost, carbon capture, and life-cycle impacts [35,41–43,70–175].

Taken together, Tables 4–8 provide a structured interpretation of the evidence base. Table 4 maps the research questions and shows why the discussion must move beyond keyword frequency. Table 5 demonstrates that technical performance depends on the complete conversion and purification chain, not only on the gasifier. Table 6 shows that cost competitiveness is conditional on scale, integration, feedstock logistics, and policy incentives. Table 7 connects feedstock properties with route selection and scale-up barriers. Table 8 demonstrates that decarbonization depends on LCA boundaries, CCS/BECCS integration, and carbon accounting rather than on biomass use alone.

To improve cross-metric readability, terminology and units were standardized throughout the main comparative tables wherever the original data permitted direct conversion. H_2 yield is reported on a mass basis (g H_2/kg feedstock) when possible, final H_2 purity is distinguished from syngas-level H_2 concentration, hydrogen-production costs are expressed on a mass basis (currency/kg H_2), and life-cycle carbon intensity is reported as kg CO_2-eq/kg H_2 when supported by the original study. Because these indicators represent different physical and methodological dimensions, they were not combined into a single normalized index. Instead, Figure 6 provides a four-panel graphical comparison of representative H_2 yield, final H_2 purity, H_2 production cost, and life-cycle carbon-intensity results extracted from Tables 5, 6 and 8.

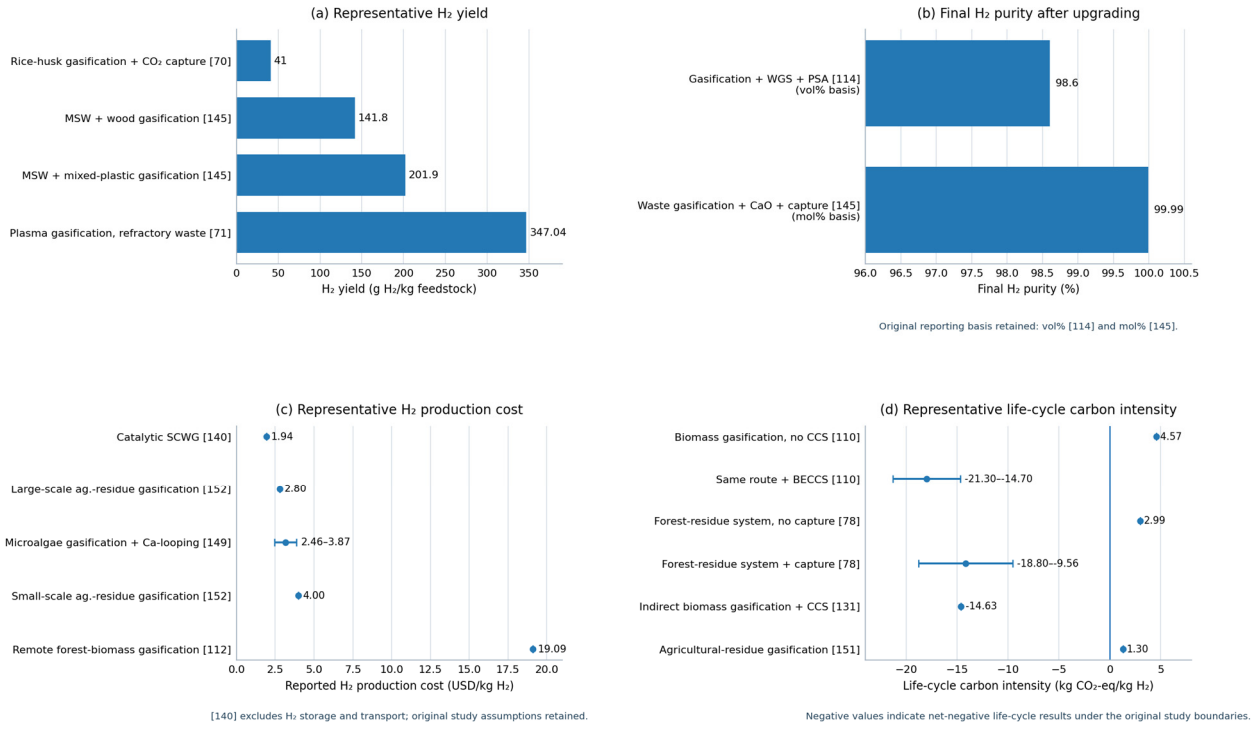


Figure 6. Comparative performance indicators of representative biomass-to-hydrogen pathways.

Figure 6 highlights the substantial variability among biomass-to-hydrogen pathways across technical, economic, and environmental indicators. H_2 yield differs markedly among feedstocks and conversion routes, whereas final H_2 purity above 98% is achieved

only after downstream upgrading and separation. Reported production costs also vary considerably with plant scale, feedstock, process integration, and system boundaries. From an environmental perspective, carbon intensity can shift from positive to negative values when CCS or BECCS is incorporated, although these results remain dependent on the underlying life-cycle assumptions. Therefore, no single pathway simultaneously maximizes H_2 yield and purity while minimizing cost and carbon intensity, reinforcing the need for system-level and case-specific assessment.

An integrated decision framework emerges from the combined technical, feedstock, economic, and environmental evidence. Technology selection should begin with measurable feedstock properties rather than broad categorical labels. Low-moisture lignocellulosic feedstocks are generally compatible with conventional, steam, or oxy-steam gasification, whereas high-moisture streams such as sewage sludge, algae, and other wet residues are better aligned with SCWG and related hydrothermal routes [41,70–75,77–133,136,142–144,146,153,154,160–162]. Waste-derived and heterogeneous feedstocks require additional consideration of ash, chlorine, sulfur, nitrogen, impurities, gas-cleaning requirements, electricity demand, and, when fossil-derived fractions are present, explicit fossil-carbon accounting [43,75,76,79,83,85,96,100,101,105,118,121,122,124–129,142,144,156,163,165]. Bio-oil and pyrolysis-derived intermediates require dedicated reforming, catalyst-stability, coke-control, corrosion-management, and H_2-purification strategies [131,134,145,152,166–168,170–174]. Hybrid and polygeneration configurations can improve heat integration, resource utilization, and coproduct valorization, but they also introduce additional separation requirements, capital investment, process-control complexity, and allocation challenges [35,87,98,115,116,142–144,155]. Overall, the selected conversion route determines the subsequent requirements for gas cleaning, WGS or reforming, CO_2 removal, and final H_2 purification, which in turn influence economic and environmental performance. Technology selection should therefore be based on the complete feedstock-to-purified-H_2 chain and its deployment context rather than on isolated H_2 yield, concentration, cost, or carbon-intensity values. Technology readiness was not reported using a uniform TRL framework across the reviewed studies. Therefore, numerical TRL values were retained only when explicitly provided by the original source, while the remaining pathways were compared qualitatively according to the scale and type of evidence reported, including laboratory testing, cyclic operation, continuous stability tests, pilot-scale validation, techno-economic scale-up scenarios, and identified demonstration needs. This distinction avoids assigning unsupported TRL values while still allowing comparison of the relative scale-up status of the principal thermochemical pathways.

Accordingly, pathway maturity was assessed independently of publication frequency using four evidence dimensions: (i) explicitly reported TRL, where available; (ii) demonstration of operating-scale, distinguishing laboratory, pilot, and larger-scale studies; (iii) evidence of continuous or extended-duration operation; and (iv) demonstration of an integrated process chain capable of producing upgraded or purified hydrogen. Publication frequency was therefore treated only as an indicator of research activity and not as a proxy for technological maturity. Under these criteria, conventional and steam/oxy-steam gasification showed the strongest maturity evidence among the reviewed pathways, particularly because pilot-scale integrated operation including gas cleaning, water–gas shift, and PSA has been demonstrated, producing 98.6 vol% H_2 [72]. However, numerical TRL values were not consistently reported across the literature, and the remaining challenges related to tar control, feedstock variability, long-duration reliability, purification, and CCS/BECCS integration preclude interpreting gasification as universally deployment-ready.

Technology readiness was not reported using a uniform Technology Readiness Level (TRL) framework across the reviewed studies. Therefore, numerical TRL values were retained only when explicitly reported by the original source, whereas the readiness of

the remaining pathways was interpreted from the type and scale of evidence available, including laboratory experiments, cyclic tests, continuous-operation studies, pilot-scale demonstrations, techno-economic scale-up scenarios, and identified demonstration needs. To provide a clearer comparison, Table 9 summarizes the available readiness evidence, reported TRL information, scale-up status, and principal remaining deployment barriers for gasification, supercritical water gasification (SCWG), pyrolysis/reforming, chemical-looping, sorption-enhanced, plasma, and BECCS-integrated pathways. This evidence-based approach avoids assigning unsupported TRL values while enabling a transparent comparison of the relative maturity and scale-up status of the principal thermochemical biomass-to-H_2 technologies.

Table 9. Evidence-based comparison of technology readiness and scale-up status for major biomass-to-hydrogen pathways.

Pathway	Readiness Evidence in the Reviewed Studies	TRL/Scale-Up Status	Main Remaining Scale-Up Limitations
Conventional/steam/oxy-steam gasification	Broadest evidence base and most frequently investigated pathway. Pilot-scale gasification integrated with gas cleaning, WGS and PSA produced 98.6 vol% H_2, demonstrating operation of a complete upgrading chain [72].	Strongest maturity evidence among the reviewed pathways; pilot-scale integrated operation demonstrated. Numerical TRL not consistently reported.	Tar formation, gas cleaning, ash management, feedstock variability, long-duration reliability, H2 purification, and integration with CCS/BECCS.
Supercritical water gasification (SCWG)	Strong experimental, modeling, environmental and techno-economic evidence, particularly for wet biomass. Large-scale economic scenarios have been evaluated, but the review still identifies the need for pilot-scale validation [77,151,153,159,161].	Emerging/pre-commercial scale-up stage. Numerical TRL not consistently reported.	High-pressure operation, corrosion, salt precipitation, plugging, catalyst recovery, heat integration, and continuous-flow reliability.
Pyrolysis + bio-oil reforming	Two-stage fast pyrolysis and catalytic steam reforming achieved stable operation for 170 h with 58.8% H_2 yield and 87.3% conversion [145]. Ex ante studies explicitly identify scale-up uncertainty [168].	Experimental-to-pilot-oriented development; intermediate readiness. Numerical TRL not consistently reported.	Bio-oil instability, coke formation, catalyst deactivation, corrosion, intermediate handling, purification, and long-duration catalyst stability.
Chemical-looping gasification/hydrogen production	Experimental studies report high H_2 concentrations and cyclic sorbent/oxygen-carrier performance, including CaO-assisted systems with approximately 78–81.1 vol% H_2 [73,74,132,133].	Laboratory/early scale-up stage. Numerical TRL not consistently reported.	Oxygen-carrier attrition, sorbent degradation, cyclic stability, solids circulation, reactor integration, impurity tolerance, and pilot-scale validation.
Sorption-enhanced gasification/Ca-looping	High-H_2 performance has been demonstrated experimentally, while a 100 MWth RDF-based H_2/power configuration was evaluated at TRL 3 [79].	Low-to-intermediate readiness; TRL 3 explicitly reported for the representative waste-gasification case [79].	Sorbent sintering, carbonation–calcination degradation, regeneration, heat integration, scale-up, and system-integration risk.
Plasma and high-temperature waste gasification	High H_2 yield and energy-efficiency values have been reported for difficult waste streams, but the review identifies plasma gasification among the pathways still requiring pilot-scale demonstration [83].	Emerging/demonstration-limited pathway. Numerical TRL not consistently reported.	High electricity demand, exergy destruction, electrode/reactor durability, feedstock conditioning, gas cleaning, and scale-up cost.
BECCS-integrated biomass gasification	Gasification itself is comparatively mature, whereas BECCS integration introduces additional capture, transport, storage, and process-integration requirements. Several studies evaluate techno-economic and LCA scenarios rather than fully demonstrated commercial systems [41–43].	Maturity depends on integration level; gasification is comparatively mature, but full biomass-to-H_2 + BECCS chains remain less demonstrated. Numerical TRL not consistently reported.	CCS energy penalty, CO_2 transport and permanent storage, capture integration, economics, carbon accounting, infrastructure, and long-duration system validation.

The main future research priorities are sixfold. First, technical studies should report standardized feedstock characterization, operating conditions, H_2 yield, H_2 concentration, syngas composition, tar content, CO conversion, H_2 purity, H_2 recovery, energy efficiency, exergy efficiency, and continuous operation time. Second, process studies should move from isolated gasifiers toward complete chains including pretreatment, conversion, gas cleaning, WGS, CO_2 removal, PSA or membranes, compression, storage, and carbon

capture. Third, catalyst, sorbent, and oxygen-carrier stability must be tested over multiple cycles using real feedstocks containing ash, sulfur, chlorine, nitrogen, alkali metals, and moisture. Fourth, TEA studies should harmonize plant capacity, currency year, feedstock cost, CAPEX, OPEX, LCOH, capacity factor, H_2 purity, compression, storage, CO_2 transport, carbon credits, and sensitivity analysis. Fifth, LCA studies should distinguish renewable, low-carbon, and carbon-negative H_2 using transparent carbon accounting and multi-impact assessment. Sixth, pilot-scale demonstrations are needed for SCWG, chemical looping, sorption-enhanced gasification, plasma gasification, bio-oil reforming, BECCS-integrated systems, and hybrid renewable–biomass configurations.

Taken together, the evidence supports a system-level decision framework in which feedstock properties determine the feasible conversion route, the conversion route defines gas-cleaning and purification requirements, and these downstream requirements influence both economic performance and life-cycle impacts. Technology readiness and deployment context then determine whether the resulting pathway can progress beyond laboratory or conceptual performance. Future research should therefore prioritize complete and continuously operated process chains, standardized technical and economic reporting, transparent life-cycle carbon accounting, and pilot-scale validation rather than further optimization of isolated reactor-level indicators.

4. Conclusions

This review integrated 111 original studies and 26 supporting review articles to critically assess thermochemical biomass conversion for sustainable hydrogen production. Its principal contribution does not lie in providing another technology-by-technology comparison, since the main thermochemical pathways have already been extensively discussed in previous reviews. Instead, the present synthesis integrates reactor-level hydrogen performance with the economic, environmental, and deployment conditions that determine the practical feasibility of biomass-to-hydrogen systems. Particular emphasis was placed on the relationships among plant scale, feedstock logistics, hydrogen purification, CAPEX, OPEX, LCOH, financial assumptions, life-cycle carbon intensity, CCS/BECCS integration, technology readiness, and scale-up requirements. This system-level perspective enables the assessment to move beyond isolated experimental performance and toward identifying the conditions under which specific biomass-to-hydrogen pathways may become technically, economically, and environmentally viable. The integrated evidence indicates that pathway selection should be based on the complete feedstock-to-hydrogen system rather than on the isolated performance of a conversion reactor. Gasification shows the strongest maturity evidence for dry lignocellulosic feedstocks, whereas wet biomass is better aligned with SCWG or related hydrothermal routes, and heterogeneous waste streams require more intensive impurity control and gas cleaning. Regardless of the conversion route, production of fuel-grade H_2 generally requires an integrated chain comprising feedstock conditioning, conversion, gas cleaning, WGS or reforming where applicable, CO_2 management, and final H_2 purification. Feedstock composition, moisture, ash and mineral content, impurity profile, plant scale, and technology readiness therefore determine whether a technically attractive pathway is also operationally viable.

Economic and environmental performance must likewise be interpreted at the system level. LCOH, minimum selling price, and hydrogen production cost are not interchangeable metrics, and should only be compared when their economic basis, plant scale, and system boundaries are sufficiently compatible. Similarly, biomass origin alone does not establish green or carbon-negative hydrogen: life-cycle classification depends on electricity and auxiliary-energy inputs, allocation procedures, biogenic and fossil carbon accounting, capture efficiency, CO_2 transport, permanent storage, and the selected LCA boundary.

Mixed fossil/biomass configurations should therefore be treated as hybrid comparative cases rather than automatically classified as fully biomass-derived hydrogen. Overall, no single thermochemical pathway is universally optimal; deployment decisions should jointly consider feedstock suitability, complete process integration, purified-H_2 performance, economic feasibility, life-cycle impacts, and technology readiness. The main limitation of the available literature is its methodological heterogeneity. Studies differ substantially in feedstock properties, operating conditions, reactor scale, hydrogen purity, economic year, functional unit, system boundary, and carbon-capture assumptions. Many results are based on simulations, equilibrium models, conceptual plants, or short-duration experiments rather than continuous industrial operation. Future research should therefore prioritize standardized reporting, complete process-chain assessment, multi-cycle testing of catalysts and sorbents, long-duration pilot demonstrations, harmonized TEA and LCA assumptions, and explicit reporting of final H_2 purity, recovery, compression, storage, and CO_2 management. The most important future contribution of the field will be to move beyond demonstrating that biomass can produce H_2-rich gas and instead prove that specific integrated systems can deliver purified hydrogen reliably, economically, and with verifiable life-cycle decarbonization at commercially relevant scales.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/pr14213469/s1. Table S1: Study-level evidence matrix of the 111 core studies included in the PRISMA systematic review, including bibliographic information, feedstock and thermochemical-pathway classification, process integration, evidence type, study scale, hydrogen-performance indicators, techno-economic assessment, life-cycle assessment, CCS/BECCS integration, and mapping to the corresponding manuscript sections and main-text tables.

Author Contributions: Conceptualization, C.L.-A., S.N.-D. and J.F.G.-G.; methodology, C.L.-A., S.N.-D. and S.N.-S.; formal analysis, C.L.-A., J.F.G.-G. and J.M.-C.; investigation, C.L.-A., S.N.-D., J.F.G.-G., S.N.-S. and J.M.-C.; resources, C.L.-A., S.N.-D. and J.M.-C.; data curation, C.L.-A., S.N.-S. and J.M.-C.; writing—original draft preparation, C.L.-A., S.N.-D. and S.N.-S.; writing—review and editing, C.L.-A., S.N.-D., J.F.G.-G., S.N.-S. and J.M.-C.; visualization, S.N.-S. and J.M.-C.; supervision, S.N.-D. and J.F.G.-G.; project administration, C.L.-A. and S.N.-D.; funding acquisition, C.L.-A. and S.N.-D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: The authors gratefully acknowledge the Indian Technical and Economic Cooperation (ITEC) Programme for awarding C.L. a scholarship to participate in the International Training Programme on Hydrogen Energy, held in November 2025 and organized by the National Institute of Solar Energy (NISE) in Gurugram, Haryana, India. This academic experience contributed to strengthening the research perspective and technical background related to hydrogen energy systems.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

AI	Artificial Intelligence
AWE	Alkaline Water Electrolysis
BECCS	Bioenergy with Carbon Capture and Storage
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilization, and Storage
CO_2-eq	Carbon Dioxide Equivalent
GHG	Greenhouse Gas

GWP	Global Warming Potential
H_2	Hydrogen
IEEE	Institute of Electrical and Electronics Engineers
IRR	Internal Rate of Return
LCA	Life-Cycle Assessment
LCOH	Levelized Cost of Hydrogen
ML	Machine Learning
MSW	Municipal Solid Waste
NISE	National Institute of Solar Energy
NPV	Net Present Value
OPEX	Operating Expenditure
PEM	Proton Exchange Membrane
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PSA	Pressure Swing Adsorption
PV	Photovoltaic
RDF	Refuse-Derived Fuel
RQ	Research Question
SCWG	Supercritical Water Gasification
SL	Semantic Layer
SLR	Systematic Literature Review
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolysis Cell
TEA	Techno-Economic Analysis
TRL	Technology Readiness Level
WGS	Water–Gas Shift
WoS	Web of Science

References

1. International Energy Agency. *Global Energy Review 2026*; International Energy Agency: Paris, France, 2026.
2. Mar'I, M.; Seraj, M.; Tursoy, T. The Role of Fiscal Policy in G20 Countries in the Context of the Environmental Kuznets Curve Hypothesis. *Energies* **2023**, *16*, 2215. [CrossRef]
3. Wang, J.-L.; Fan, J.-J.; Liu, Y.; Guo, H.-T.; Guo, M.-Y. Geopolitical Turbulence in the Middle East: Reshaping Global Energy Landscape? *Pet. Sci.* **2026**, *23*, 2231–2234. [CrossRef]
4. Ghosh, S.; Mondal, S. Designing a Predictive Framework on Logistical Failures for the Global Oil and Gas Supply Chain. *Results Eng.* **2025**, *28*, 108242. [CrossRef]
5. Desogus, E.; Grosso, D.; Bompard, E.; Lo Russo, S. Modelling the Geopolitical Impact on Risk Assessment of Energy Supply System: The Case of Italian Crude Oil Supply. *Energy* **2023**, *284*, 128578. [CrossRef]
6. Ye, Z.; Elahi, E.; Peng, B.; Wan, A. From Geopolitical Risks to Sustainable Energy Security: A Tripartite Game Approach for Resilient Cross-Border Infrastructure. *J. Clean. Prod.* **2026**, *555*, 148108. [CrossRef]
7. Liu, J.; Guo, F.; Shi, Y.; Ding, R.; Chen, Z. Assessing the Security of Crude Oil Supply Chain: The Case of China. *Energy Strategy Rev.* **2025**, *59*, 101733. [CrossRef]
8. Guo, X.; Hong, Y.; Yao, S.; Hao, Y. Oil Supply and U.S.-China Tensions: A Multinational Perspective. *Int. Rev. Financ. Anal.* **2025**, *104*, 104278. [CrossRef]
9. Vo, D.H.; Ho, C.M.; Lang, N.D. Greener for Greater Security? The Role of Green Finance in Energy Security amid Rising Geopolitical Risks. *Energy Econ.* **2025**, *151*, 108902. [CrossRef]
10. Özdeş, E.O.; Koç, Y.; Yağlı, H.; Köse, Ö.; Koç, A. Thermodynamic Analysis and Step-by-Step Performance and Emission Optimization of a Real Steam Methane Reforming (SMR) Hydrogen Production Plant. *Int. J. Hydrogen Energy* **2025**, *140*, 233–245. [CrossRef]
11. Bae, M.C.; Kim, J.; Lee, S.; Shin, S.; Kim, M.; Son, S.H. Dynamic Modeling and Scheduling Optimization of Sorption-Enhanced Steam Methane Reforming for Purity-Aware Hydrogen Production. *Int. J. Hydrogen Energy* **2026**, *226*, 154532. [CrossRef]
12. Shahid, M.I.; Farhan, M.; Rao, A.; Hussain, M.S.; Salam, H.A.; Chen, T.; Zhang, Z.; Li, X.; Ma, F. Hydrogen Production by Waste Heat Recovery of Hydrogen-Enriched Compressed Natural Gas via Steam Methane Reforming Process. *Int. J. Hydrogen Energy* **2025**, *117*, 374–392. [CrossRef]

13. Behera, U.S.; Purohit, B.K.; Byun, H.-S. A Comprehensive Review of Fossil-Based Hydrogen Production: Technological Integrations, Environmental Sustainability, and Economic Viability. *Int. J. Hydrogen Energy* **2025**, *140*, 627–652. [CrossRef]
14. Etienne, X.L.; Trujillo-Barrera, A.; Wiggins, S. Price and Volatility Transmissions between Natural Gas, Fertilizer, and Corn Markets. *Agric. Finance Rev.* **2016**, *76*, 151–171. [CrossRef]
15. Yan, F.; Shen, W.; Qi, B.; Mo, L.; Fan, X.; Song, W.; Wang, D. Oxygen-Enhanced Conversion-Based Process Retrofit and Assessment of Natural Gas Steam Reforming for Synthetic Ammonia Production. *Chem. Eng. Res. Des.* **2026**, *226*, 575–588. [CrossRef]
16. Wang, X.; Wang, B.; Wang, S. Policy-Driven Pathways to Decouple China's Hydrogen Expansion from Carbon Lock-In. *Energy* **2026**, *344*, 139924. [CrossRef]
17. Sabra, J.; Maalouf, E.; Zeaiter, J. A Comparative Techno-Economic Analysis and Life-Cycle Assessment of Sustainable Ammonia Production Processes. *Energy Convers. Manag.* **2026**, *350*, 120922. [CrossRef]
18. Wang, Y.; Chen, C.; Wen, Z. A Hybrid Centralized-Distributed Green Ammonia System for Cost-Effective Decarbonization of China's Nitrogen Fertilizer Production. *Appl. Energy* **2026**, *411*, 127584. [CrossRef]
19. Mansour, F.; Al-Hindi, M.; Abou Najm, M.; Yassine, A. Optimizing the Water Energy Food Nexus in Lebanon: A Case Study of the Nexus in a Developing Country Context. *Environ. Dev.* **2026**, *58*, 101438. [CrossRef]
20. Luz, L.; Rosa, L. Decarbonizing Ammonia Production with Renewable Natural Gas in the United States: A Plant-Specific Assessment. *Resour. Conserv. Recycl.* **2026**, *231*, 108929. [CrossRef]
21. Shahid, M.I.; Farhan, M.; Rao, A.; Hussain, M.S.; Zhu, X.; Salam, H.A.; Chen, T.; Li, X.; Ma, F. Analysis of Exhaust Heat Recovery and Hydrogen Production by Steam Methane Reforming under Different Operating Conditions of the HCNG Engine. *Fuel* **2025**, *401*, 135853. [CrossRef]
22. Samris, A.; Naanani, H.; Nachtane, M.; Faik, A. A Physics-Informed Deep Learning Framework for Enhanced Hydrogen Production via Electrified Steam Methane Reforming. *Int. J. Hydrogen Energy* **2025**, *193*, 152376. [CrossRef]
23. Dong, X.; Gong, Q.; Li, Y.; Kong, Z. The Process and Trends of China's Energy Transition and the Strategic Repositioning of Natural Gas. *Nat. Gas Ind. B* **2025**, *12*, 750–765. [CrossRef]
24. Clennar, T.; Du, Y.; Liu, Z. Lab-Scale Green Hydrogen and Fuel Cell Microgrid Digital Twin. *Energy Convers. Manag.* **2026**, *350*, 120928. [CrossRef]
25. Oussmou, B.; Sigue, S.; Abderafi, S. Review of Green Hydrogen Production Technologies, to Choose the Optimal Process of Electrolysis-Renewable Energy. *Renew. Sustain. Energy Rev.* **2026**, *225*, 116205. [CrossRef]
26. Wang, Z.; Wang, S.; Hu, B.; Wang, J.; Qiu, L.; Shi, C.; Zhang, T. Efficient Low-Carbon Hydrogen Production Driven by Solar Energy: Properties, Challenges and Future Perspectives. *Fuel* **2026**, *407*, 137500. [CrossRef]
27. Bozkurt, A.; Genç, M.S.; Seyitoğlu, S.S. A Rankine–Kalina Combined Cycle Hybrid System Integrated with Low-Temperature Geothermal and Solar Energy for Sustainable Hydrogen Production: Comprehensive 9E Analysis. *Case Stud. Therm. Eng.* **2026**, *77*, 107533. [CrossRef]
28. Choi, Y.; Lee, B.; Heo, S. Evaluation of Geographic and Climatic Impacts on Joint Planning of Green Hydrogen and Renewable Electricity Supply Chains. *Int. J. Hydrogen Energy* **2026**, *224*, 154471. [CrossRef]
29. Perdana, G.R.; Bagheri, B.; Kumagai, H.; Sugiyama, M. Techno-Economic Analysis of Integrated Offshore Wind–Solar Energy Systems for Green Hydrogen Production. *Int. J. Hydrogen Energy* **2025**, *180*, 151587. [CrossRef]
30. Shin, H.; Jang, D.; Shin, H.-S.; Park, S.; Kang, S. High-Resolution Dynamic Modeling and Techno-Economic Optimization of off-Grid PV–Electrolysis–BESS Systems for Green Hydrogen Production. *Appl. Energy* **2026**, *409*, 127451. [CrossRef]
31. Kim, H.; Cho, H.-S.; Kim, S.-K.; Jung, H.W.; Park, J. Quantifying the Economic Viability of Green Hydrogen Production via Proton Exchange Membrane Electrolysis under Uncertainties in Renewable Energy Supply and Cost. *J. Power Sources* **2026**, *676*, 239874. [CrossRef]
32. Ling, P.; Wen, C.; Wang, X.; Liu, Q.; Huang, L.; Cao, C.; Tang, C.; Tu, Z. Two-Stage Optimization for Hybrid Renewable Hydrogen Production Systems: Capacity Configuration and Electrolyzer Array Operation Strategy. *Energy* **2026**, *355*, 141127. [CrossRef]
33. Erdiwansyah; Mamat, R.; Ghazali, M.F.; Basrawi, F.; Rosdi, S.M. Green Hydrogen Production and Renewable Energy Storage Integration: A Review of Technologies and System Pathways. *Energy Convers. Manag. X* **2026**, *30*, 101904. [CrossRef]
34. Aguado, R.; Liponi, A.; Owebor, K.; Buzzi, F.; Vera, D.; Baccioli, A. Enhancing Green Hydrogen Production by Integrating PV-Powered Alkaline Water Electrolysis and Oxy-Steam Biomass Gasification. *Energy Convers. Manag.* **2026**, *357*, 121423. [CrossRef]
35. Aminuddin; Hesty, N.W.; Supriatna, N.K.; Putriyana, L.; Yudiartono; Cendrawati, D.G.; Subandriya, A.; Wahid, L.O.M.A.; Suntoro, D.; Nurrohim, A.; et al. Techno-Economic Analysis of Hybrid Green Hydrogen Production: Integrating Wind-Powered Electrolysis and Biomass Gasification on Sumba Island, Indonesia. *Results Eng.* **2026**, *30*, 110703. [CrossRef]
36. Prajapati, A.K.; Ali, S.S.; Kashyap, A.; Ansari, K.B.; Singh, S.; Kumar, A.; Rajnandani; Awasthi, V.; Singh, S.; Shkir, M.; et al. Harnessing Waste for Energy: Feedstock, Technological Advancement, Sustainability, Life Cycle Evaluation, and Future Perspectives. *Fuel* **2026**, *410*, 137965. [CrossRef]

37. Abdullah, M.A.; Nazir, M.S.; Hussein, H.A.; Shah, S.M.U.; Azra, N.; Iftikhar, R.; Iqbal, M.S.; Qamar, Z.; Ahmad, Z.; Afzaal, M.; et al. New Perspectives on Biomass Conversion and Circular Economy Based on Integrated Algal-Oil Palm Biorefinery Framework for Sustainable Energy and Bioproducts Co-Generation. *Ind. Crops Prod.* **2024**, *213*, 118452. [CrossRef]
38. Akhlisah, Z.N.; Ong, H.C.; Lee, H.V.; Tan, Y.H. Environmental Impacts of Biomass Energy: A Life Cycle Assessment Perspective for Circular Economy. *Renew. Sustain. Energy Rev.* **2026**, *226*, 116363. [CrossRef]
39. Laverde-Albaracín, C.; González, J.F.G.; Nogales-Delgado, S.; Román, S.; Ledesma-Cano, B.; Peña-Banegas, D.; Ortiz, Y.; Gunsha-Morales, A. Biomass and Its Role in the Latin American Energy Mix: A Review of Biofuels and Bioelectricity Pathways Toward Sustainable Transitions. *Appl. Sci.* **2026**, *16*, 2246. [CrossRef]
40. Ghodke, P.K.; Sharma, A.K.; Jayaseelan, A.; Gopinath, K.P. Hydrogen-Rich Syngas Production from the Lignocellulosic Biomass by Catalytic Gasification: A State of Art Review on Advance Technologies, Economic Challenges, and Future Prospectus. *Fuel* **2023**, *342*, 127800. [CrossRef]
41. Zhu, J.; Feng, L.; Yu, C.; Wu, L. Renewable Methanol Production from Biomass Gasification Coupled with Green Hydrogen: Process Design and Economic Assessment. *Int. J. Hydrogen Energy* **2025**, *191*, 151693. [CrossRef]
42. Zhao, S.; Li, J.; Chen, C.; Yan, B.; Tao, J.; Chen, G. Interpretable Machine Learning for Predicting and Evaluating Hydrogen Production via Supercritical Water Gasification of Biomass. *J. Clean. Prod.* **2021**, *316*, 128244. [CrossRef]
43. Vargas, G.G.; Flórez-Orrego, D.A.; de Oliveira Junior, S. Comparative Exergy and Environmental Assessment of the Residual Biomass Gasification Routes for Hydrogen and Ammonia Production. *Entropy* **2023**, *25*, 1098. [CrossRef] [PubMed]
44. Razzak, S.A.; Hossain, M.M.; Zakir Hossain, S.M.; Lardhi, M.; Haq, B. Recent Advancement of Catalytic and Non-Catalytic Thermochemical Biomass Conversion Technologies toward Sustainable Hydrogen Production. *Biomass Futures* **2026**, *1*, 100021. [CrossRef]
45. Nosirov, M.; Meyliyeva, A.; Ramazanova, U.; Yusupov, M.; Berdiyorov, G.R.; Rakhimov, K. Hydrogen Adsorption on Nitrogen-Doped Graphene in the Presence of Water: An Atomistic Study. *J. Vac. Sci. Technol. B* **2026**, *44*. [CrossRef]
46. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 Statement: An Updated Guideline for Reporting Systematic Reviews. *BMJ* **2021**, *372*, n71. [CrossRef] [PubMed]
47. Torres-Carrion, P.V.; Gonzalez-Gonzalez, C.S.; Aciar, S.; Rodriguez-Morales, G. Methodology for Systematic Literature Review Applied to Engineering and Education. In *Proceedings of the 2018 IEEE Global Engineering Education Conference (EDUCON), Santa Cruz de Tenerife, Spain, 17–20 April 2018*; IEEE: Piscataway, NJ, USA, 2018; pp. 1364–1373.
48. Maldonado-Correa, J.; Cuenca-Granda, J.; Torres-Cabrera, J.; Cerda Mejía, G.; Bastidas Barragan, W.D.; Guapulema, R.; Paccha-Herrera, E.; Solano, J.C.; Tapia-Peralta, D.; Benavides, J.; et al. Digital Twin Technology in Wind Turbine Condition Monitoring, Predictive Maintenance, and RUL Estimation: A Systematic Literature Review. *Energies* **2026**, *19*, 1477. [CrossRef]
49. Lanjekar, P.R.; Panwar, N.L.; Agrawal, C. A Comprehensive Review on Hydrogen Production through Thermochemical Conversion of Biomass for Energy Security. *Bioresour. Technol. Rep.* **2023**, *21*, 101293. [CrossRef]
50. Bolívar Caballero, J.J.; Zaini, I.N.; Yang, W. Reforming Processes for Syngas Production: A Mini-Review on the Current Status, Challenges, and Prospects for Biomass Conversion to Fuels. *Appl. Energy Combust. Sci.* **2022**, *10*, 100064. [CrossRef]
51. Motta, I.L.; Marchesan, A.N.; Maciel Filho, R.; Maciel, M.R.W. Syngas Cleaning and Conditioning in Biomass Gasification Plants: A Review of Technologies, Bibliometric Trends, and Future Directions. *Int. J. Hydrogen Energy* **2025**, *154*, 150234. [CrossRef]
52. Arregi, A.; Amutio, M.; Lopez, G.; Bilbao, J.; Olazar, M. Evaluation of Thermochemical Routes for Hydrogen Production from Biomass: A Review. *Energy Convers. Manag.* **2018**, *165*, 696–719. [CrossRef]
53. Salam, M.A.; Ahmed, K.; Akter, N.; Hossain, T.; Abdullah, B. A Review of Hydrogen Production via Biomass Gasification and Its Prospect in Bangladesh. *Int. J. Hydrogen Energy* **2018**, *43*, 14944–14973. [CrossRef]
54. Cao, L.; Yu, I.K.M.; Xiong, X.; Tsang, D.C.W.; Zhang, S.; Clark, J.H.; Hu, C.; Ng, Y.H.; Shang, J.; Ok, Y.S. Biorenewable Hydrogen Production through Biomass Gasification: A Review and Future Prospects. *Environ. Res.* **2020**, *186*, 109547. [CrossRef] [PubMed]
55. Dou, B.; Zhang, H.; Song, Y.; Zhao, L.; Jiang, B.; He, M.; Ruan, C.; Chen, H.; Xu, Y. Hydrogen Production from the Thermochemical Conversion of Biomass: Issues and Challenges. *Sustain. Energy Fuels* **2019**, *3*, 314–342. [CrossRef]
56. Alptekin, F.M.; Celiktas, M.S. Review on Catalytic Biomass Gasification for Hydrogen Production as a Sustainable Energy Form and Social, Technological, Economic, Environmental, and Political Analysis of Catalysts. *ACS Omega* **2022**, *7*, 24918–24941. [CrossRef] [PubMed]
57. Wang, Z.; Li, B.; Pipitone, G.; Liu, Q.; Yang, T.; Wang, J.; Li, R. Hydrogen Production from Biomass: A Review Combined with Bibliometric Analysis. *Int. J. Hydrogen Energy* **2025**, *117*, 271–291. [CrossRef]
58. Bartoli, M.; Pirri, C.F.; Bocchini, S. A Comprehensive Review on Hydrogen Production from Biomass Gasification. *Molecules* **2025**, *31*, 99. [CrossRef] [PubMed]
59. Van Minh, N.; Haggam, R.A.; Ben Hamida, M.B.; Abdallah, A.S.H.; Ismoilov, M.; Lionus Leo, G.M.; Jayabal, R. Biomass Gasification for Hydrogen-Rich Syngas Production: Feedstock Engineering, Reactor Design and Sustainability Assessment. *Biomass Bioenergy* **2026**, *213*, 109386. [CrossRef]

60. Goel, A.; Moghaddam, E.M.; Liu, W.; He, C.; Konttinen, J. Biomass Chemical Looping Gasification for High-Quality Syngas: A Critical Review and Technological Outlooks. *Energy Convers. Manag.* **2022**, *268*, 116020. [CrossRef]
61. Huang, S.; Duan, W.; Jin, Z.; Yi, S.; Lv, Q.; Jiang, X. Progress in Carbon Capture and Impurities Removal for High Purity Hydrogen Production from Biomass Thermochemical Conversion. *Carbon Capture Sci. Technol.* **2025**, *14*, 100345. [CrossRef]
62. Setiabudi, H.D.; Aziz, M.A.A.; Abdullah, S.; Teh, L.P.; Jusoh, R. Hydrogen Production from Catalytic Steam Reforming of Biomass Pyrolysis Oil or Bio-Oil Derivatives: A Review. *Int. J. Hydrogen Energy* **2020**, *45*, 18376–18397. [CrossRef]
63. Pandey, B.; Prajapati, Y.K.; Sheth, P.N. Recent Progress in Thermochemical Techniques to Produce Hydrogen Gas from Biomass: A State of the Art Review. *Int. J. Hydrogen Energy* **2019**, *44*, 25384–25415. [CrossRef]
64. Zhang, Y.; Xu, P.; Liang, S.; Liu, B.; Shuai, Y.; Li, B. Exergy Analysis of Hydrogen Production from Steam Gasification of Biomass: A Review. *Int. J. Hydrogen Energy* **2019**, *44*, 14290–14302. [CrossRef]
65. Zhang, Y.; Li, L.; Xu, P.; Liu, B.; Shuai, Y.; Li, B. Hydrogen Production through Biomass Gasification in Supercritical Water: A Review from Exergy Aspect. *Int. J. Hydrogen Energy* **2019**, *44*, 15727–15736. [CrossRef]
66. Vuppaladadiyam, A.K.; Vuppaladadiyam, S.S.V.; Awasthi, A.; Sahoo, A.; Rehman, S.; Pant, K.K.; Murugavelh, S.; Huang, Q.; Anthony, E.; Fennel, P.; et al. Biomass Pyrolysis: A Review on Recent Advancements and Green Hydrogen Production. *Bioresour. Technol.* **2022**, *364*, 128087. [CrossRef] [PubMed]
67. Valizadeh, S.; Hakimian, H.; Farooq, A.; Jeon, B.H.; Chen, W.H.; Hoon Lee, S.; Jung, S.C.; Won Seo, M.; Park, Y.K. Valorization of Biomass through Gasification for Green Hydrogen Generation: A Comprehensive Review. *Bioresour. Technol.* **2022**, *365*, 128143. [CrossRef] [PubMed]
68. Singh, R.; Kumar, R.; Sarangi, P.K.; Kovalev, A.A.; Vivekanand, V. Effect of Physical and Thermal Pretreatment of Lignocellulosic Biomass on Biohydrogen Production by Thermochemical Route: A Critical Review. *Bioresour. Technol.* **2023**, *369*, 128458. [CrossRef] [PubMed]
69. He, C.; Chen, C.L.; Giannis, A.; Yang, Y.; Wang, J.Y. Hydrothermal Gasification of Sewage Sludge and Model Compounds for Renewable Hydrogen Production: A Review. *Renew. Sustain. Energy Rev.* **2014**, *39*, 1127–1142. [CrossRef]
70. Rodgers, S.; Bowler, A.; Wells, L.; Lee, C.S.; Hayes, M.; Poulston, S.; Lester, E.; Meng, F.; McKechnie, J.; Conradie, A. A Surrogate Model for the Economic Evaluation of Renewable Hydrogen Production from Biomass Feedstocks via Supercritical Water Gasification. *Int. J. Hydrogen Energy* **2024**, *49*, 277–294. [CrossRef]
71. Salkuyeh, Y.K.; Saville, B.A.; MacLean, H.L. Techno-Economic Analysis and Life Cycle Assessment of Hydrogen Production from Different Biomass Gasification Processes. *Int. J. Hydrogen Energy* **2018**, *43*, 9514–9528. [CrossRef]
72. Öztürk, M.U.; Ayol, A. Hydrogen-Rich Syngas for Cold Chain Logistics: A Life Cycle Assessment of Biomass Gasification Integration. *Int. J. Hydrogen Energy* **2026**, *231*, 154878. [CrossRef]
73. Scicchitano, C.; Licastro, P.; Freda, C.; Muraca, E.; Catizzone, E.; Macri', D.; Migliori, M. Pyro-Gasification of Olive Pomace Pellets for Renewable Hydrogen Production: Experimental Data-Driven Techno-Economic Analysis. *J. Clean. Prod.* **2026**, *561*, 148415. [CrossRef]
74. Guo, L.J.; Lu, Y.J.; Zhang, X.M.; Ji, C.M.; Guan, Y.; Pei, A.X. Hydrogen Production by Biomass Gasification in Supercritical Water: A Systematic Experimental and Analytical Study. *Catal. Today* **2007**, *129*, 275–286. [CrossRef]
75. Ravindran, J.K.; Fagg, D.P.; Coelho, M.C. Assessing the Environmental Performance of Organic Fraction of MSW Derived Fischer–Tropsch Fuels: Influence of Gasification Route and H2/CO Adjustment Strategy. *Biomass Bioenergy* **2026**, *207*, 108715. [CrossRef]
76. Sangsefidi, D.; Mojaver, P. Eucalyptus Gasification-Driven Energy System for Sustainable Hydrogen-Rich Synthesis Gas and Energy Production: Modeling, Analysis, and AI-Based Multi-Objective Optimization. *Int. J. Hydrogen Energy* **2026**, *216*, 153939. [CrossRef]
77. Gasafi, E.; Reinecke, M.Y.; Kruse, A.; Schebek, L. Economic Analysis of Sewage Sludge Gasification in Supercritical Water for Hydrogen Production. *Biomass Bioenergy* **2008**, *32*, 1085–1096. [CrossRef]
78. Slimene, M.B.; Basem, A.; Hasan, M.A.; Le, L.T.; Khlifi, M.A.; Islam, S.; Atamuratova, Z.; Sabirov, S.; Mukhitdinov, O.; Mahariq, I. Exergoeconomic Analysis and Optimization of a Thermal–Thermochemical System Integrating Biomass Gasification and Geothermal Energy for Power, Methanol, and Liquefied Hydrogen. *Appl. Therm. Eng.* **2026**, *287*, 129438. [CrossRef]
79. Ma, S.; Zhan, J.; Liu, T.; Li, Z.; Sui, J.; Liu, Q. Cogenerating Hydrogen and Electricity from Solar-Biomass Chemical Looping with Integrated Oxygen-Carrier Thermochemical Energy Storage: A Thermodynamic Analysis. *Int. J. Hydrogen Energy* **2026**, *241*, 155415. [CrossRef]
80. Yan, X.; Li, Y.; Ma, X.; Bian, Z.; Zhao, J.; Wang, Z. CeO2-Modified CaO/Ca12Al14O33 Bi-Functional Material for CO2 Capture and H2 Production in Sorption-Enhanced Steam Gasification of Biomass. *Energy* **2020**, *192*, 116664. [CrossRef]
81. Ochieng, R.; Sarker, S. Energy and Techno-Economic Analysis of Integrated Supercritical Water Gasification of Sewage Sludge and Fast Pyrolysis of Wood for Power, Heat, and Hydrogen Production. *Chem. Eng. Sci.* **2025**, *306*, 121236. [CrossRef]
82. Nan, Y.; Liu, Q.; Zhong, W.; Dong, W. Optimization and Energy Efficiency Analysis of Hydrogen Production from Refractory Organic Solid Waste by Plasma Gasification. *Fuel* **2026**, *407*, 137357. [CrossRef]

83. Jaiyen, P.; Kamolram, K.; Arpornwichanop, A.; Wongchaisuwat, P.; Limleamthong, P. Machine Learning-Aided Multi-Stage Optimization of Low-Carbon Hydrogen via Biomass Gasification: Emission-Aware Design and Cost-Efficient Feedstock Blending. *Fuel* **2026**, *412*, 138047. [CrossRef]
84. Peng, Z.; Tian, J.; Shi, L.; Yi, L.; Wang, L.; Lu, L.; Xu, J.; Jin, H.; Chen, B. Data-Driven Study on the Hydrogen Production Performance of Oily Sludge via Supercritical Water Gasification: Experimental Analysis and Machine Learning. *Fuel* **2026**, *419*, 138814. [CrossRef]
85. Valente, A.; Iribarren, D.; Dufour, J. Life Cycle Sustainability Assessment of Hydrogen from Biomass Gasification: A Comparison with Conventional Hydrogen. *Int. J. Hydrogen Energy* **2019**, *44*, 21193–21203. [CrossRef]
86. Wu, D.; Gao, Z.; Wu, S.; Xiao, R. Negative Net Global Warming Potential Hydrogen Production through Biomass Gasification Combined with Chemical Looping: Environmental and Economic Assessments. *Int. J. Hydrogen Energy* **2024**, *66*, 24–32. [CrossRef]
87. Sara, H.R.; Enrico, B.; Mauro, V.; Andrea, D.C.; Vincenzo, N. Techno-Economic Analysis of Hydrogen Production Using Biomass Gasification -A Small Scale Power Plant Study. In *Proceedings of the Energy Procedia*; Elsevier Ltd.: Amsterdam, The Netherlands, 2016; Volume 101, pp. 806–813.
88. Kang, K.; Azargohar, R.; Dalai, A.K.; Wang, H. Hydrogen Production from Lignin, Cellulose and Waste Biomass via Supercritical Water Gasification: Catalyst Activity and Process Optimization Study. *Energy Convers. Manag.* **2016**, *117*, 528–537. [CrossRef]
89. Nakyai, T.; Authayanun, S.; Patcharavorachot, Y.; Arpornwichanop, A.; Assabumrungrat, S.; Saebea, D. Exergoeconomics of Hydrogen Production from Biomass Air-Steam Gasification with Methane Co-Feeding. *Energy Convers. Manag.* **2017**, *140*, 228–239. [CrossRef]
90. Raheem, A.; Ji, G.; Memon, A.; Sivasangar, S.; Wang, W.; Zhao, M.; Taufiq-Yap, Y.H. Catalytic Gasification of Algal Biomass for Hydrogen-Rich Gas Production: Parametric Optimization via Central Composite Design. *Energy Convers. Manag.* **2018**, *158*, 235–245. [CrossRef]
91. Detchusananard, T.; Im-orb, K.; Ponpesh, P.; Arpornwichanop, A. Biomass Gasification Integrated with CO2 Capture Processes for High-Purity Hydrogen Production: Process Performance and Energy Analysis. *Energy Convers. Manag.* **2018**, *171*, 1560–1572. [CrossRef]
92. Li, J.; Xu, K.; Yao, X.; Chen, S. Prediction and Optimization of Syngas Production from Steam Gasification: Numerical Study of Operating Conditions and Biomass Composition. *Energy Convers. Manag.* **2021**, *236*, 114077. [CrossRef]
93. Arnaiz del Pozo, C.; Cloete, S.; Jiménez Álvaro, Á. Carbon-Negative Hydrogen: Exploring the Techno-Economic Potential of Biomass Co-Gasification with CO2 Capture. *Energy Convers. Manag.* **2021**, *247*, 114712. [CrossRef]
94. Helf, A.; Cloete, S.; Keller, F.; Hendrik Cloete, J.; Zaabout, A. Carbon-Negative Hydrogen from Biomass Using Gas Switching Integrated Gasification: Techno-Economic Assessment. *Energy Convers. Manag.* **2022**, *270*, 116248. [CrossRef]
95. Ren, R.; Wang, H.; Feng, X.; You, C. Techno-Economic Analysis of Auto-Thermal Gasification of Municipal Solid Waste with Ash Direct Melting for Hydrogen Production. *Energy Convers. Manag.* **2023**, *292*, 117401. [CrossRef]
96. Rabea, K.; Michailos, S.; Hughes, K.J.; Ingham, D.; Pourkashanian, M. Comprehensive Process Simulation of a Biomass-Based Hydrogen Production System through Gasification within the BECCS Concept in a Commercial Two-Stage Fixed Bed Gasifier. *Energy Convers. Manag.* **2023**, *298*, 117812. [CrossRef]
97. Liu, K.; Liu, T.; Fang, Y.; Zhan, J.; Han, Z.; Li, P.; Liu, Q. A Hybrid Solar-Biomass Hydrogen Production System Using Chemical Looping with Negative Carbon Emissions and Comprehensive Performance Evaluation. *Energy Convers. Manag.* **2024**, *322*, 119161. [CrossRef]
98. Zhang, A.; Li, D.; Zhu, X.; Kim, G.-M.; Zeng, Y.; Jeon, C.H.; Wang, H.; Zhu, T.; Bao, G. A Molten Salt-Mediated Biomass Gasification Process for High-Yield Hydrogen Production with in Situ Carbon Capture: Experiments, Simulation and ANN Prediction. *Energy Convers. Manag.* **2025**, *332*, 119735. [CrossRef]
99. de Souza Santos, D.J.; Vitoriano Julio, A.A.; Castillo Santiago, Y.; Venturini, O.J.; Escobar Palacio, J.C. Techno-Economic Assessment of Hydrogen Production from Biomass and RDF Gasification with Integrated Carbon Capture: A Brazilian Perspective. *Energy Convers. Manag.* **2026**, *353*, 121185. [CrossRef]
100. Jang, M.; Ryu, J. Clean Hydrogen Production via Waste Plastic-Biomass Co-Gasification with Carbon Capture and Sequestration: Techno-Economic and Environmental Assessment under Policy Frameworks. *Energy Convers. Manag.* **2026**, *356*, 121346. [CrossRef]
101. Koroneos, C.; Dompros, A.; Roumbas, G. Hydrogen Production via Biomass Gasification-A Life Cycle Assessment Approach. *Chem. Eng. Process. Process Intensif.* **2008**, *47*, 1261–1268. [CrossRef]
102. Han, L.; Wang, Q.; Luo, Z.; Rong, N.; Deng, G. H2 Rich Gas Production via Pressurized Fluidized Bed Gasification of Sawdust with in Situ CO2 Capture. *Appl. Energy* **2013**, *109*, 36–43. [CrossRef]
103. Lu, Y.; Zhao, L.; Guo, L. Technical and Economic Evaluation of Solar Hydrogen Production by Supercritical Water Gasification of Biomass in China. *Int. J. Hydrogen Energy* **2011**, *36*, 14349–14359. [CrossRef]
104. Cormos, C.C. Hydrogen and Power Co-Generation Based on Coal and Biomass/Solid Wastes Co-Gasification with Carbon Capture and Storage. *Int. J. Hydrogen Energy* **2012**, *37*, 5637–5648. [CrossRef]

105. Kalinci, Y.; Hepbasli, A.; Dincer, I. Life Cycle Assessment of Hydrogen Production from Biomass Gasification Systems. *Int. J. Hydrogen Energy* **2012**, *37*, 14026–14039. [CrossRef]
106. Udomsirichakorn, J.; Basu, P.; Salam, P.A.; Acharya, B. Effect of CaO on Tar Reforming to Hydrogen-Enriched Gas with in-Process CO2 Capture in a Bubbling Fluidized Bed Biomass Steam Gasifier. *Int. J. Hydrogen Energy* **2013**, *38*, 14495–14504. [CrossRef]
107. Iribarren, D.; Susmozas, A.; Petrakopoulou, F.; Dufour, J. Environmental and Exergetic Evaluation of Hydrogen Production via Lignocellulosic Biomass Gasification. *J. Clean. Prod.* **2014**, *69*, 165–175. [CrossRef]
108. Ozbas, E.E.; Aksu, D.; Ongen, A.; Aydin, M.A.; Ozcan, H.K. Hydrogen Production via Biomass Gasification, and Modeling by Supervised Machine Learning Algorithms. *Int. J. Hydrogen Energy* **2019**, *44*, 17260–17268. [CrossRef]
109. Samimi, F.; Marzoughi, T.; Rahimpour, M.R. Energy and Exergy Analysis and Optimization of Biomass Gasification Process for Hydrogen Production (Based on Air, Steam and Air/Steam Gasifying Agents). *Int. J. Hydrogen Energy* **2020**, *45*, 33185–33197. [CrossRef]
110. Marcantonio, V.; De Falco, M.; Capocelli, M.; Amado-Fierro, Á.; Centeno, T.A.; Bocci, E. Modelling and Assessment of a Sorption Enhanced Gasification System Coupled with Hydrothermal Carbonization, Hot Gas Cleaning, and Plasma to Produce Pure H2 from Biomass. *Int. J. Hydrogen Energy* **2023**, *48*, 32672–32685. [CrossRef]
111. Cook, B.; Hagen, C. Techno-Economic Analysis of Biomass Gasification for Hydrogen Production in Three US-Based Case Studies. *Int. J. Hydrogen Energy* **2024**, *49*, 202–218. [CrossRef]
112. Cormos, C.C. Decarbonized Green Hydrogen Production by Sorption-Enhanced Biomass Gasification: An Integrated Techno-Economic and Environmental Evaluation. *Int. J. Hydrogen Energy* **2024**, *95*, 592–603. [CrossRef]
113. de Rezende, T.T.G.; Venturini, O.J.; Escobar Palacio, J.C.; de Oliveira, D.C.; de Souza Santos, D.J.; Lora, E.E.S.; Dovichi Filho, F.B. Technical and Economic Potential for Hydrogen Production from Biomass Residue Gasification in the State of Minas Gerais in Brazil. *Int. J. Hydrogen Energy* **2025**, *101*, 358–378. [CrossRef]
114. Rabea, K.; Michailos, S.; Hughes, K.J.; Ingham, D.; Pourkashanian, M. A New Hydrogen Production Route through Biomass Gasification in a Two-Stage Fixed Bed Reactor within the BECCS Concept: A Techno-Economic and Life Cycle Assessment Study. *Int. J. Hydrogen Energy* **2025**, *124*, 140–152. [CrossRef]
115. Taheri, M.H.; Mosaffa, A.H.; Farshi, L.G. Energy, Exergy and Economic Assessments of a Novel Integrated Biomass Based Multigeneration Energy System with Hydrogen Production and LNG Regasification Cycle. *Energy* **2017**, *125*, 162–177. [CrossRef]
116. Li, Q.; Song, G.; Xiao, J.; Hao, J.; Li, H.; Yuan, Y. Exergetic Life Cycle Assessment of Hydrogen Production from Biomass Staged-Gasification. *Energy* **2020**, *190*, 116416. [CrossRef]
117. Lümmen, N.; Røstbø, E.V. Biowaste to Hydrogen or Fischer-Tropsch Fuels by Gasification—A Gibbs Energy Minimisation Study for Finding Carbon Capture Potential and Fossil Carbon Displacement on the Road. *Energy* **2020**, *211*, 118996. [CrossRef]
118. Kuo, P.C.; Illathukandy, B.; Wu, W.; Chang, J.S. Energy, Exergy, and Environmental Analyses of Renewable Hydrogen Production through Plasma Gasification of Microalgal Biomass. *Energy* **2021**, *223*, 120025. [CrossRef]
119. Cormos, C.C. Green Hydrogen Production from Decarbonized Biomass Gasification: An Integrated Techno-Economic and Environmental Analysis. *Energy* **2023**, *270*, 126926. [CrossRef]
120. Hu, D.; Huang, Y.; Liu, D.; Su, L.; Shen, A.; Chen, Y.; Guo, L. Techno-Economic Analysis of Sewage Sludge Supercritical Water Gasification for Hydrogen and Electricity Co-Generation System. *Energy* **2024**, *313*, 134061. [CrossRef]
121. Zhang, R.; Yin, K.; Wei, R.; Ruan, J.; Yang, J.; Wang, S.; Wang, Y. Comprehensive Analysis of Life Cycle Energy Consumption and Environmental Impact of Hydrogen Production Process via Plasma Co-Gasification of Coal and Biomass. *Energy* **2025**, *324*, 135976. [CrossRef]
122. Cao, H.; Xiang, X.; Wang, H.; Lu, G.; Feng, J.; Bian, J.; Xia, L.; Shi, S.; He, C.; Xiang, Y.; et al. Study on the Exergy Efficiency and Hydrogen Production Rate in Biomass Gasification Process Based on Pilot-Scale. *Energy* **2026**, *348*, 140606. [CrossRef]
123. Udomsirichakorn, J.; Basu, P.; Abdul Salam, P.; Acharya, B. CaO-Based Chemical Looping Gasification of Biomass for Hydrogen-Enriched Gas Production with in Situ CO2 Capture and Tar Reduction. *Fuel Process. Technol.* **2014**, *127*, 7–12. [CrossRef]
124. Tavakoli, N.; Khoshkenar, P.; Pourfayaz, F. A Combined Approach-Based Techno-Economic-Environmental Multi-Optimization of a Hydrogen Generation System through Waste Biomass Air-Steam Gasification. *Renew. Energy* **2024**, *225*, 120259. [CrossRef]
125. Xu, B.; Li, G.; Liu, F.; Ma, S.; Zhang, Y. Life Cycle Assessment and Techno-Economic Analysis of Maleic Anhydride Hydrogenation to 1,4-Butanediol through Biomass Gasification Coupling with Chemical Looping Hydrogen Production. *Renew. Energy* **2024**, *237*, 121623. [CrossRef]
126. Piazzi, S.; Menin, L.; Ress, J.; Antolini, D.; Baratieri, M. Oxy-Steam Gasification in Biomass-to -Biomethane and -Hydrogen Processes: A Thermo-Economic Assessment. *Renew. Energy* **2026**, *260*, 125145. [CrossRef]
127. Motsoeneng, L.G.; Oboirien, B.; Lanzini, A.; Borhani, T.N. Technoeconomic Analysis and Life Cycle Assessment of the Sorption-Enhanced Chemical Looping Gasification of Waste Bagasse Biomass to Produce Hydrogen and Transportation Fuels. *Renew. Energy* **2026**, *263*, 125486. [CrossRef]

128. Zhao, L.; Dong, P.; Guo, B.; Liang, H.; Dai, Y.; Chen, J. Co-Pyrolysis and Chemical Looping Co-Gasification of Rice Straw and Agricultural Plastics for Hydrogen and Power Generation: Experimental Study and Life Cycle Assessment. *Renew. Energy* **2026**, *266*, 125648. [CrossRef]
129. Okolie, J.A.; Nanda, S.; Dalai, A.K.; Kozinski, J.A. Techno-Economic Evaluation and Sensitivity Analysis of a Conceptual Design for Supercritical Water Gasification of Soybean Straw to Produce Hydrogen. *Bioresour. Technol.* **2021**, *331*, 125005. [CrossRef] [PubMed]
130. Zhang, Y.; Brown, T.R.; Hu, G.; Brown, R.C. Comparative Techno-Economic Analysis of Biohydrogen Production via Bio-Oil Gasification and Bio-Oil Reforming. *Biomass Bioenergy* **2013**, *51*, 99–108. [CrossRef]
131. Kuo, P.C.; Chen, J.R.; Wu, W.; Chang, J.S. Hydrogen Production from Biomass Using Iron-Based Chemical Looping Technology: Validation, Optimization, and Efficiency. *Chem. Eng. J.* **2018**, *337*, 405–415. [CrossRef]
132. Al Lagtah, N.M.A.; Nizar, A. Techno-Economic Evaluation of the Effects of Decarbonisation and Waste Heat Utilisation on Green Hydrogen Produced from Microalgae Steam Gasification. *J. Environ. Chem. Eng.* **2026**, *14*, 121243. [CrossRef]
133. Abawalo, M.; Pikoń, K.; Landrat, M. Comparative Life Cycle Assessment of Hydrogen Production via Biogas Reforming and Agricultural Residue Gasification. *Appl. Sci.* **2025**, *15*, 5029. [CrossRef]
134. Antonini, C.; Treyer, K.; Moioli, E.; Bauer, C.; Schildhauer, T.J.; Mazzotti, M. Hydrogen from Wood Gasification with CCS-a Techno-Environmental Analysis of Production and Use as Transport Fuel. *Sustain. Energy Fuels* **2021**, *5*, 2602–2621. [CrossRef]
135. Inayat, A.; Ahmad, M.M.; Yusup, S.; Mutalib, M.I.A. Biomass Steam Gasification with In-Situ CO2 Capture for Enriched Hydrogen Gas Production: A Reaction Kinetics Modelling Approach. *Energies* **2010**, *3*, 1472–1484. [CrossRef]
136. Karimi, M.; Simsek, H. Techno-Economic and Life Cycle Assessment of Hydrogen Production from Biomass–Plastic Co-Gasification with Carbon Capture and Storage. *Energies* **2026**, *19*, 929. [CrossRef]
137. Padilla-Esquivel, C.A.; Posadas-Paredes, T.; Alcocer-García, H.; Ramírez-Márquez, C.; Ponce-Ortega, J.M. Multi-Objective Optimization and K-Means Clustering Analysis of Green Hydrogen Production Routes via Biomass Gasification and Water Electrolysis. *Processes* **2026**, *14*, 946. [CrossRef]
138. Kichonge, B.; Monge, E.; Kaborogo, F. Techno-Economic Analysis of Biohydrogen Production from Lignocelluloses Biomass via Co-Pyrolysis and Gasification Process. *Biomass Convers. Biorefin.* **2026**, *16*, 163. [CrossRef]
139. Abuadala, A.; Dincer, I.; Naterer, G.F. Exergy Analysis of Hydrogen Production from Biomass Gasification. *Int. J. Hydrogen Energy* **2010**, *35*, 4981–4990. [CrossRef]
140. Moreno, J.; Dufour, J. Life Cycle Assessment of Hydrogen Production from Biomass Gasification. Evaluation of Different Spanish Feedstocks. *Int. J. Hydrogen Energy* **2013**, *38*, 7616–7622. [CrossRef]
141. Khandelwal, K.; German, C.S.; Dalai, A.K. Technoeconomic Analysis of Supercritical Water Gasification of Canola Straw for Hydrogen Production. *Int. J. Hydrogen Energy* **2024**, *96*, 1067–1078. [CrossRef]
142. Li, G.; Li, K.; Ma, S.; Zhang, Y. Techno-Economic Analysis of a Glycerol to Methanol, Ethylene Glycol and 1,2-Propanediol Cogeneration Process Integrated with Biomass Chemical Looping Hydrogen Generation. *J. Clean. Prod.* **2023**, *416*, 137988. [CrossRef]
143. Chen, X.; Sun, Z.; Kuo, P.C.; Aziz, M. Synergistic Solar Energy Integration for Enhanced Biomass Chemical Looping Hydrogen Production: Thermodynamics and Techno-Economic Analyses. *Chem. Eng. J.* **2024**, *485*, 149734. [CrossRef]
144. Bąk, K.; Ziółkowski, P.; Frost, J.; Drosińska-Komor, M. Comparative Study of a Combined Heat and Power Plant Retrofitted by CO2 Capture during the Combustion of Syngas from Sewage Sludge Gasification versus Zero-Emission Combustion of Hydrogen Produced Using Renewables. *Int. J. Hydrogen Energy* **2023**, *48*, 39625–39640. [CrossRef]
145. Fan, W.; Li, Y.; Fu, R.; Althbiti, A.; Alsairy, N.; Bayhan, Z. Leveraging XGBoost Machine Learning with GWO-PSO-MVO Optimization Algorithms in an Advanced Biomass-Assisted Steam Methane Reforming for Blue H2 Production with CO2 Capture: 4E Analysis and Life Cycle Assessment. *Renew. Energy* **2026**, *270*, 125951. [CrossRef]
146. Patel, P.; Dimitriou, I.; Mondal, P.; Singh, O.; Gupta, S. Process Optimisation and Enviro-Economic Assessment of Carbon-Negative Hydrogen Production from Biomass Co-Gasification. *Energy Convers. Manag.* **2025**, *323*, 119211. [CrossRef]
147. Salam, M.A.; Steinberger-Wilckens, R.; Hacker, V. Hydrogen Production Performances of Biomass Gasifier Integrated Smart Hydrogen Production Pilot Plant of BCSIR: A Step towards Sustainable Green Fuel. *Int. J. Hydrogen Energy* **2026**, *230*, 154800. [CrossRef]
148. Quan, C.; Feng, S.; Miskolczi, N.; Gao, N. Biomass Gasification Reforming for Hydrogen Production by Ce-K Co-Catalysis Coupled with CO2 Capture. *Biomass Bioenergy* **2026**, *209*, 108998. [CrossRef]
149. Nasir, R.B.; Kang, T.J.; Rudra, S. Comparative Assessment of Chemical Looping Assisted Biomass Gasification for H2 Production: A Thermochemical, Exergy, and Environmental Perspective. *Case Stud. Chem. Environ. Eng.* **2026**, *13*, 101336. [CrossRef]
150. Gubin, V.; Benedikt, F.; Thelen, F.; Hammerschmid, M.; Popov, T.; Hofbauer, H.; Müller, S. Hydrogen Production from Woody Biomass Gasification: A Techno-Economic Analysis. *Biofuels Bioprod. Biorefining* **2024**, *18*, 818–836. [CrossRef]

151. Heras, F.; Justicia, J.; Baeza, J.A.; Gilarranz, M.A.; Ferro, V.R. Energy and Economic Analysis of Alternatives for the Valorization of Hydrogen Rich Stream Produced in the Aqueous Phase Reforming of Pyrolysis Bio-Oil Aqueous Fraction. *Bioresour. Technol.* **2024**, *399*, 130572. [CrossRef] [PubMed]
152. Zhao, M.; Wang, F.; Fan, Y.; Raheem, A.; Zhou, H. Low-Temperature Alkaline Pyrolysis of Sewage Sludge for Enhanced H2 Production with in-Situ Carbon Capture. *Int. J. Hydrogen Energy* **2019**, *44*, 8020–8027. [CrossRef]
153. Doranehgard, M.H.; Samadyar, H.; Mesbah, M.; Haratipour, P.; Samiezade, S. High-Purity Hydrogen Production with in Situ CO2 Capture Based on Biomass Gasification. *Fuel* **2017**, *202*, 29–35. [CrossRef]
154. Zoghi, M.; Dilmaghani, A.; Saidi, M. Theoretical Investigation of Hydrogen Production from Algal Biomass via an Integrated Pyrolysis-Gasification System Intensified with Water Gas Shift Reaction. *Fuel* **2026**, *421*, 139088. [CrossRef]
155. Nokobi, B.; Kumar, R.S.; Nhuchhen, D.; Hill, J.M. Techno-Economic and Environmental Analysis of Gasification of Waste or Forest Biomass into Hydrogen in Remote Communities Using the Northwest Territories as a Case Study. *Int. J. Hydrogen Energy* **2026**, *203*, 153211. [CrossRef]
156. Cormos, A.M.; Prodan, M.; Petrescu, L.; Cormos, C.C. Waste-to-Hydrogen and Power Co-Production by Sorption-Enhanced Solid Waste Gasification with in-Situ CO2 Capture: An Integrated Techno-Economic and Environmental Impact Evaluation. *Int. J. Hydrogen Energy* **2026**, *238*, 155385. [CrossRef]
157. Wei, R.; Yin, K.; Zhang, R.; Xu, W.; Zhu, Z.; Wang, Y.; Cui, P. Techno-Economic and Thermodynamic Analysis of Hydrogen Production Process via Plasma Co-Gasification of Coal and Biomass. *Energy* **2025**, *314*, 134241. [CrossRef]
158. Wu, N.; Lan, K.; Yao, Y. An Integrated Techno-Economic and Environmental Assessment for Carbon Capture in Hydrogen Production by Biomass Gasification. *Resour. Conserv. Recycl.* **2023**, *188*, 106693. [CrossRef]
159. Khosravi, S.; Neshat, E.; Saray, R.K. Thermodynamic Analysis of a Sorption-Enhanced Gasification Process of Municipal Solid Waste, Integrated with Concentrated Solar Power and Thermal Energy Storage Systems for Co-Generation of Power and Hydrogen. *Renew. Energy* **2023**, *214*, 140–153. [CrossRef]
160. Haryanto, A.; Fernando, S.D.; Pordesimo, L.O.; Adhikari, S. Upgrading of Syngas Derived from Biomass Gasification: A Thermodynamic Analysis. *Biomass Bioenergy* **2009**, *33*, 882–889. [CrossRef]
161. Bagde, A.V.; Paul, M.C. Waste to Hydrogen: Steam Gasification of Municipal Solid Wastes with Carbon Capture for Enhanced Hydrogen Production. *Biomass Bioenergy* **2025**, *198*, 107855. [CrossRef]
162. Farajollahi, H.; Hossainpour, S. Biomass-Assisted Autothermal Chemical Looping Hydrogen Production from Municipal Solid Waste with Integrated Power Cycles and CO2 Purification: Techno-Economic Assessment. *Energy Convers. Manag. X* **2026**, *30*, 101688. [CrossRef]
163. Uregen Guler, N.; Yumurtaci, Z. Environmental Life Cycle Assessment, Uncertainty, and Sensitivity Analysis of Hydrogen Production from Biomass Gasification with Various Agents. *Process Saf. Environ. Prot.* **2025**, *204*, 108143. [CrossRef]
164. Susmozas, A.; Iribarren, D.; Zapp, P.; Linßen, J.; Dufour, J. Life-Cycle Performance of Hydrogen Production via Indirect Biomass Gasification with CO2 Capture. *Int. J. Hydrogen Energy* **2016**, *41*, 19484–19491. [CrossRef]
165. Perez-Rosas, C.; Mero-Benavides, M.; Maisano, S.; Chiodo, V.; Urbani, F.; Sanchez-Silva, L. Life Cycle Assessment of Hydrogen Production from Biomass Residues via Steam Gasification: Comparative Analysis of Citrus Peels and Posidonia Oceanica. *Biomass Bioenergy* **2026**, *208*, 108845. [CrossRef]
166. Crispim, A.M.d.C.; Barros, R.M.; Tiago Filho, G.L.; dos Santos, I.F.S. An Economic Study of Hydrogen and Ammonia Generation from the Reforming of Biogas from Co-Digestion of Municipal Solid Waste and Wastewater Sludge in a Brazilian State. *Int. J. Hydrogen Energy* **2024**, *67*, 312–326. [CrossRef]
167. Comendador, P.; Martínez-Ramón, N.; Olazar, M.; Lopez, G.; Iribarren, D. Ex-Ante Life-Cycle Assessment of Biomass-Derived Hydrogen via Fast Pyrolysis and Sorption Enhanced Steam Reforming: Addressing Scale-up Uncertainties. *Fuel Process. Technol.* **2025**, *278*, 108334. [CrossRef]
168. Khongchamnan, P.; Laobuthee, A.; Veranitisagul, C.; Chomchatwarl, T.; Laosiripojana, N.; Weerasai, K.; Daorattanachai, P.; Chakthranont, P.; Laurenti, D.; Wanmolee, W. Two-Stage Fast Pyrolysis and Catalytic Steam Reforming of Corn Waste Bio-Oil for Hydrogen Production: Screening and Optimization of Ni-Fe Catalysts Supported on Porous Clay Heterostructures. *Fuel Process. Technol.* **2026**, *283*, 108411. [CrossRef]
169. Arafat Hossain, M.; Ganesan, P.; Jewaratnam, J.; Chinna, K. Optimization of Process Parameters for Microwave Pyrolysis of Oil Palm Fiber (OPF) for Hydrogen and Biochar Production. *Energy Convers. Manag.* **2017**, *133*, 349–362. [CrossRef]
170. Liu, F.; Wu, L.; Qiu, Y.; Liu, Z.; Chen, Y.; Chen, J.; Chen, X.; Yi, L.; Chen, B. Thermodynamic and Environmental Analysis of Two-Stage Series Supercritical Water Gasification of Biomass for Hydrogen Production. *Biomass Bioenergy* **2024**, *190*, 107415. [CrossRef]
171. Zhuo, M.; Byres, S.; Liang, Y. Environmental and Economic Benefits of Biomass-to-Hydrogen Systems through Integrated Catalytic Steam Reforming of Pyrolysis Bio-Oil and Co-Product Valorization. *Energy Convers. Manag.* **2026**, *356*, 121314. [CrossRef]
172. Xie, H.; Yu, Q.; Wei, M.; Duan, W.; Yao, X.; Qin, Q.; Zuo, Z. Hydrogen Production from Steam Reforming of Simulated Bio-Oil over Ce-Ni/Co Catalyst with in Continuous CO2 Capture. *Int. J. Hydrogen Energy* **2015**, *40*, 1420–1428. [CrossRef]

173. Li, X.; Chen, Z.; Liu, P.; Wang, Z.; Sun, T.; Wu, S.; Wu, Y.; Lei, T. Oriented Pyrolysis of Biomass for Hydrogen-Rich Gas and Biochar Production: An Energy, Environment, and Economic Assessment Based on Life Cycle Assessment Method. *Int. J. Hydrogen Energy* **2024**, *62*, 979–993. [CrossRef]
174. Li, G.; Wang, S.; Zhao, J.; Qi, H.; Ma, Z.; Cui, P.; Zhu, Z.; Gao, J.; Wang, Y. Life Cycle Assessment and Techno-Economic Analysis of Biomass-to-Hydrogen Production with Methane Tri-Reforming. *Energy* **2020**, *199*, 117488. [CrossRef]
175. Acevedo Pabón, P.A.; Herrera-Rodríguez, T.C.; González-Delgado, Á.D. Sustainable Hydrogen from Palm Oil Rachis: A Techno-Environmental-Economic Assessment for Palm Rachis Gasification in Colombian Post-Conflict Rural Territories. *Sustainability* **2026**, *18*, 1661. [CrossRef]
176. Kumar, R.; Strezov, V. Thermochemical Production of Bio-Oil: A Review of Downstream Processing Technologies for Bio-Oil Upgrading, Production of Hydrogen and High Value-Added Products. *Renew. Sustain. Energy Rev.* **2021**, *135*, 110152. [CrossRef]
177. Akash, M.A.H.; Hossain, M.S.; Sony, S.Y. Integrated Modeling of Biomass Gasification and Staged Water-Gas Shift for Optimized Hydrogen-Rich Syngas Production. *Bioresour. Technol. Rep.* **2026**, *34*, 102659. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.