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P.T Borges; E.E.S Lora; O.J Venturini; M.R Errera; D.M.Y Maya ...

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Review

A Comprehensive Technical, Environmental, Economic, and Bibliometric Assessment of Hydrogen Production Through Biomass Gasification, Including Global and Brazilian Potentials

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Abstract: It is well known that the widespread utilization of fossil fuels contributes to climate change, so exploring new sustainable energy sources is more important than ever for energy transition pathways. The variability and intermittency of solar and wind sources are of concern. Hydrogen (H_2) utilization as an energy carrier can address this issue. The technology for producing hydrogen from biomass gasification has not yet reached a high level of technological maturity. The main novelty of this work is to evaluate the state of the art of the technologies for producing H_2 from solid biomass, taking into account technological, economic, and environmental indicators and the results of a bibliometric study, and also the calculation of the technical potential for hydrogen production through biomass gasification on a worldwide and Brazilian scale. The most frequently mentioned technology to boost H_2 production efficiency is the addition of catalysts to the gasifier. Primary catalyst utilized in biomass gasification for hydrogen enhancing enhancement, such as olivine, CaO, and CeO_2-Ni-CaO are reviewed in the article. As a result, the syngas had an H_2 content rise of 511%, 659.6%, and 853.4%, respectively. According to the reviewed literature, the levelized cost of hydrogen production can reach an average value of USD3.15/kg of H_2, and the average yield is 0.1 kg-H_2/kg-biomass. The worldwide potential for hydrogen production from solid biomass in an optimal trends scenario for 2050 is estimated to be 45.03 EJ, and Brazil's potential is 6.5 EJ.

Keywords: biomass gasification; hydrogen; catalyst; bibliometric analysis; potential; LCOH

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1. Introduction

Energy transition policies seek to mitigate global warming, climate change, and air pollution. In this sense, renewable energy resources and technology utilization should be amplified, but the intermittency of the primary sources, solar and wind, poses severe challenges to satisfying existing demand curves [1]. Hydrogen production through electrolysis and its role in energy storage could be a solution to renewable energy variability and intermittency [2]. Other complementary solutions include system flexibility enhancement, transport electrification, biomass energy utilization, and electricity accumulation in batteries [3,4]. Hydrogen can substitute fossil fuels as working fluids in engines and turbines [5]. It can also be used as a renewable reagent substitute in metallurgy, fertilizer,

ammonia production, and biofuel hydrogenation and augmentation [6]. It also allows implementation "carbon-negative" technologies through biomass gasification, followed by carbon capture [7]. Today's market is mainly dominated by grey and blue hydrogen (see color classification of hydrogen by the producing pathway), both obtained from natural gas without and with carbon capture, respectively [8]. The hydrogen demand is expected to increase from 52 to 82 Mt by 2050 [9], so new sources should be investigated, especially those that would present better environmental performance.

In this sense, biomass gasification for hydrogen production from syngas has excellent potential due to massive biomass and residue availability at both global and Brazilian levels and its promising low production cost. Hydrogen from biomass allows the implementation of circular economy projects for biomass and waste conversion into fuels and electricity.

While designing biomass to hydrogen systems, some aspects to be considered include [10–13]:

- The gasifier and gasification agent type and the impurities content in the gas;
- The use of in situ catalyzers to increase H_2 generation;
- The sequence of reactors and catalysts to be used in the purification train;
- The economic feasibility and the levelized cost of hydrogen;
- Sustainability issues through Life-Cycle Analysis (LCA).

As a result, the primary goal of this work is to provide a comprehensive review of the leading technical, economic, and sustainable aspects of biomass gasification for H_2, supplemented by a bibliometric analysis of the literature. It is done by thoroughly reviewing the literature on the critical characteristics connected with the production of hydrogen from biomass gasification: gasifier types, yield, life cycle GHG emissions, and costs. This is followed by a comparison of the effect of different primary catalysts on hydrogen yield and, finally, a calculation of the technical potential for hydrogen production in the world and in Brazil, based on our waste potential surveys, as well as recommendations on technological alternatives for industrial hydrogen production from biomass gasification.

Most of the found reviews ([2,3,6,9,14–22]) address individual topics covered in this paper. None of them cover all of the topics, nor make the key connections that are arguably indispensable. This paper contributes with the novelties highlighted below:

- A comprehensive literature evaluation of the main parameters associated with hydrogen production from biomass gasification: types of gasifiers, yield, life cycle GHG emissions, and costs.
- A comparative evaluation of the effect of different primary catalysts on hydrogen yield at the gasifier outlet.
- An analysis of hydrogen purification systems typologies.
- A bibliometric study of the recent literature on biomass production through biomass gasification.
- A novel calculation of the technical potential of hydrogen production in the world and Brazil, based on previous calculations of solid biomass potential.
- Recommendations on technological alternatives for the industrial implementation of hydrogen production from biomass gasification.

2. Main Hydrogen Production Gasification Technology and Gasification Agents

Gasification technologies can be classified according to their operational principle, as shown in Figure 1, or the gasification agent used, as shown in Figure 2. In the first case, it considers the relationship between the input and output paths of raw materials and products.. In the second case according to [14], it is possible to quote five types: hydrothermal gasification, air gasification, steam gasification, two-stage pyrolysis-gasification system, and the least widespread plasma gasification.

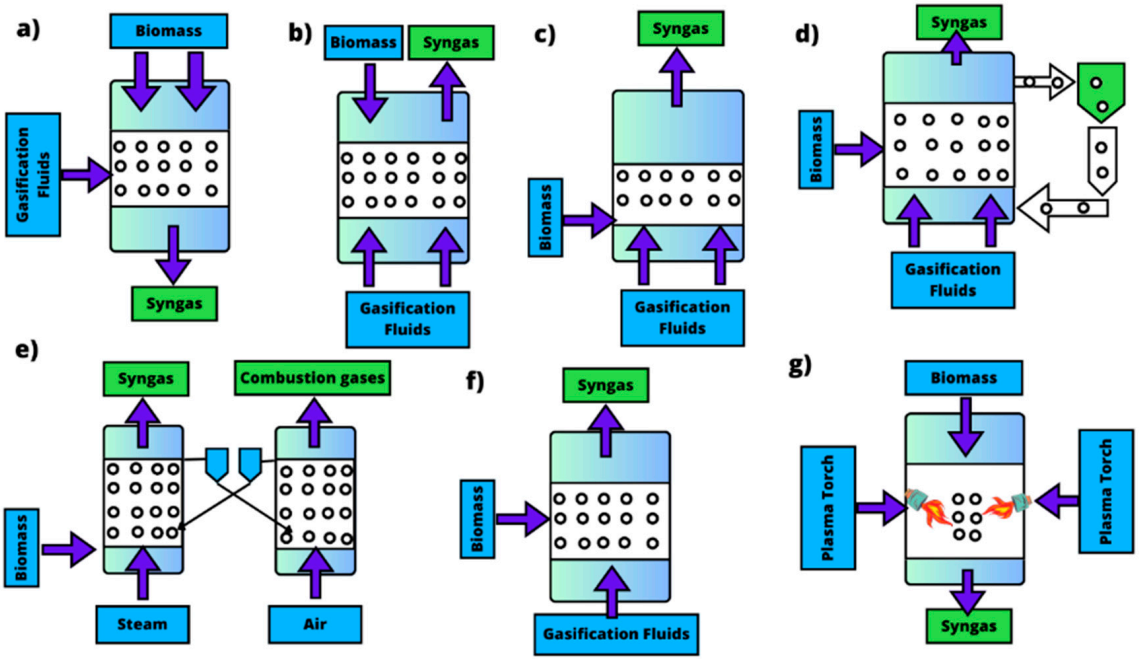


Figure 1. Typology of gasifiers according to configurations: (**a**) fixed bed /downdraft, (**b**) fixed bed /updraft, (**c**) fluidized bed/bubbling, (**d**) fluidized bed/circulating, (**e**) doubled bed reactor, (**f**) entrained flow gasifier, (**g**) plasma torch.

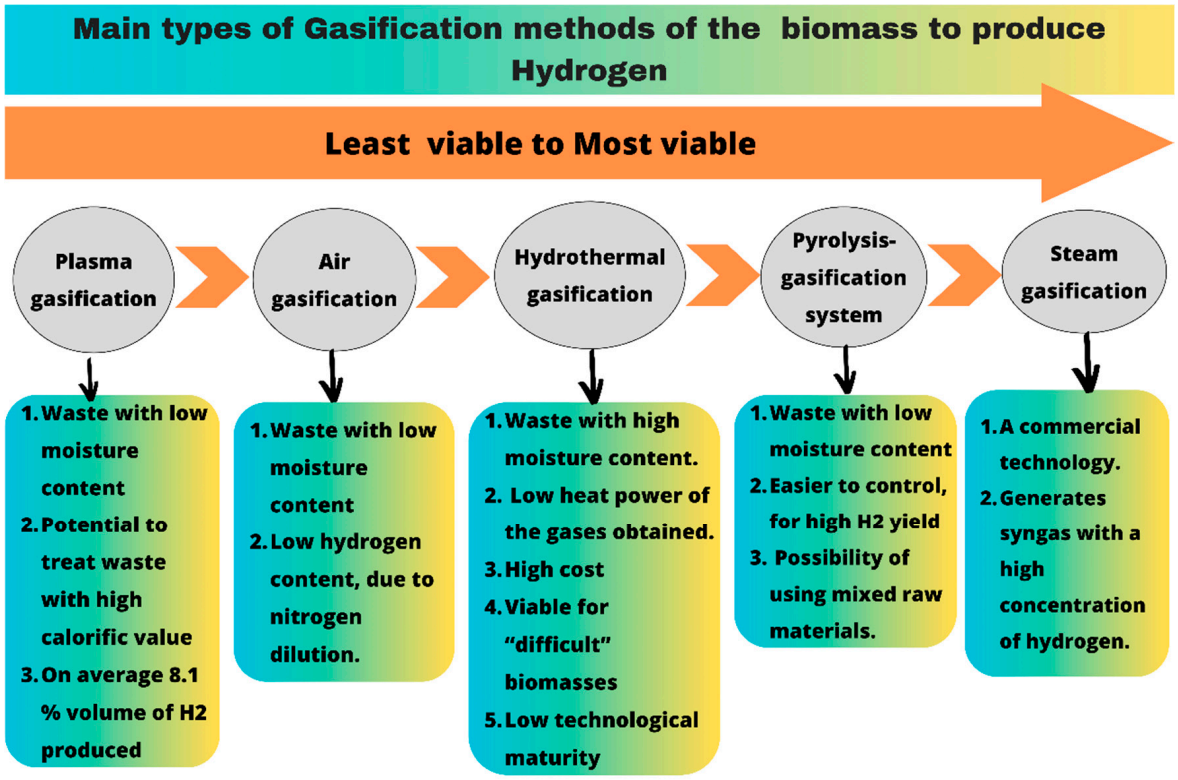


Figure 2. Gasification processes, indicating the most feasible for hydrogen production. Elaborated based on information from: [15,23–27].

Hydrothermal or supercritical gasification is the splitting of organic compounds in supercritical water at high temperatures (200–600 °C) and high pressure (5–50 MPa) [16,17]. When producing hydrogen or methane, conditions include temperature above 374.1 °C and pressure above 22.1 MPa [15]. Air gasification is direct combustion in the presence of an

amount of oxidant much lower than that required for stoichiometric combustion. Generally, some fuel is burned to provide the heat necessary to gasify the remainder [23]. The equivalence ratio ER, the relation between air supplied to the reactor and the stoichiometric one, is the main operational parameter of a gasifier. In air gasification, ER values in the range of 0.2–0.3 are typical. Steam gasification is the process of decomposition of solid carbonaceous material in the presence of steam, air, or O_2, or its mixture, at high temperatures to reform the feedstock to generate product gas of higher heating value with major gaseous components being H_2, CO, CO_2, CH_4, C_2H_6, and trace amounts of other higher series of hydrocarbons [24]. In a gasifier, pyrolysis first occurs, and then gasification is achieved by utilizing catalysts on the gases obtained from the pyrolysis. This system is commonly used to turn plastic waste into hydrogen [25,26]. Plasma gasification has similarities with air and steam gasification, the difference being that torches are used as a heat source. The plasma torch is an independent heat source, which allows temperature control regardless of fluctuations in the quality and quantity of the feed and the supply of less air, O_2, or steam to gasify the feed. A distinct advantage of the process is obtaining two products, the synthetic gas and the vitrified slag, both of which have commercial value [27]. In Figure 2, we have represented existing gasification processes focusing on hydrogen production, from the currently less viable to the more viable one. The viability of each gasification methodology is closely linked to the characteristics of the biomass (size distribution, moisture content, etc.). Additionally, the simplicity of operation of each process, its cost, and, last but not least, the efficiency of converting biomass into hydrogen with or without the addition of catalysts [28]. Considering the necessary scale for hydrogen production, only fluidized bed gasifiers can handle the corresponding biomass flows. Specifically, the double-bed bubbling (DB) and the entrained flow (EF) gasifiers are more suitable for hydrogen production. According to [29], the industrial scale for H_2 production should be in the range of 2 to 10 t/h (66–333 MW), requiring these types of gasifiers.

Table 1 shows the relation between the gasification agent used, the gas calorific value, and composition. Gas temperature and operation costs are also discussed. This table shows that gasifiers using steam and oxygen as the working fluid produce a synthesis gas with approximately 40% hydrogen. The methane content in the synthesis gas during gasification with steam is 8%, which is a consequence of the intensification of various reduction/reforming reactions shown in Figure 3. It is advantageous to start the H_2 purification process from a synthesis gas with a higher hydrogen content, so the preferred gasification agents are steam + oxygen and enriched air with oxygen or carbon dioxide.

Table 1. Relationship between gasification fluid and gas composition.

Parameters	Air Gasification	Oxygen Gasification	Steam Gasification
Heating value of the gas, MJ/Nm^3	Low 4–6	Low 10–15	High 15–20
Products	CO, H_2, Water, CO_2, HC, Tar, N_2	CO, H_2, HC, CO_2	H_2, CO, CO_2, CH_4, light HC, tar
The average composition of the gas	H_2—15%, CO—20%, CH_4—2%, CO_2—15%, N_2—48%, H_2:CO: 0.75	H_2—40%, CO—40%, CO_2—20%, H_2:CO: 1	H_2—40%, CO—25%, CH_4—8%, CO_2—25%, N_2: 2%, H_2:CO: 1
Reactor temperature, °C	900–1100	1000–1400	700–1200
Cost	Low cost	High cost	Average

Source: [29].

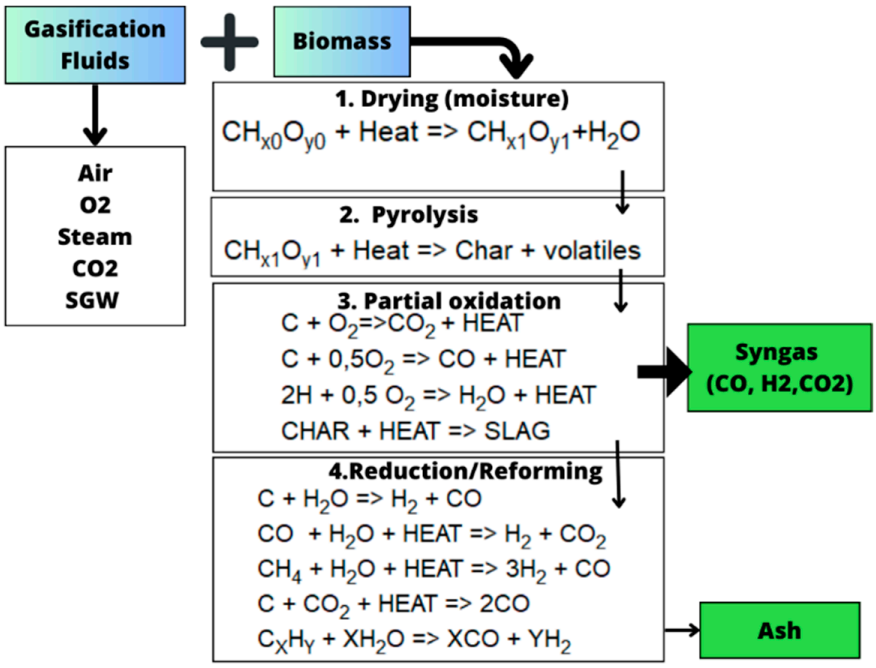


Figure 3. Main reactions occurring during gasification, modified from [30].

The main components of the producer gas, with different concentrations depending on the gasifier type and gasification fluids, are H_2, CO, CH_4, C_xH_y, and impurities, such as tars, particulate, alkali metals, and others; therefore, a purification train should be designed to obtain, from the mixture of gases composing the syngas, high purity hydrogen through the following unit operations:

- Removing impurities affecting the purification train gasifiers catalyzers.
- CO conversion into H_2 and CO_2 by the water gas-shift reaction (WGS).
- Removing CO_2 by monoethanolamine absorption—MEA.
- CH_4 conversion into CO and H_2 by the steam methane reaction (SMR).
- Membrane or Pressure Swing Absorption—PSA for H_2 separation from the resulting mixture of gases.

The main factors influencing the obtained hydrogen yield in a gasifier are:

- The type of gasification fluid.
- The reaction temperature, which depends on the ER, increases the H_2 yield due to the enhancement of endothermic reactions (most gasification reactions).
- The biomass moisture: according to [19], in steam gasification, increasing biomass moisture increases H_2 yield, as more steam is available for WGS and SMR reactions. Otherwise, during air gasification, an increase in biomass moisture leads to a reduction in H_2 yield.
- The type of biomass and its composition, according [31], also influence the hydrogen yield and process efficiency. Therefore, higher volatile and carbon content results in higher H_2 yield.

3. Technologies for Purification, as Well as Their Phases and Catalysts

Hydrogen production from biomass gasification has two main stages: the gasification and the purification train, Figure 4.

It is worth noting some important points about the purification train:

- Depending on the methane content in syngas, a steam reformer is necessary at the inlet of the purification train or at the end of the process to convert CH_4 present in tail gas.

- The water–gas shift (WGS) process is usually carried out in two stages: a high temperature (HTS) and a low temperature one (LTS) [32].
- A biodiesel scrubber for tar separation could be necessary before the MEA process that removes CO_2 from the gas.
- As a final stage, a PSA or a membrane separator can be used for high-purity H_2 obtainment. The main criteria selections are the cost and complexity of these systems at different production scales.

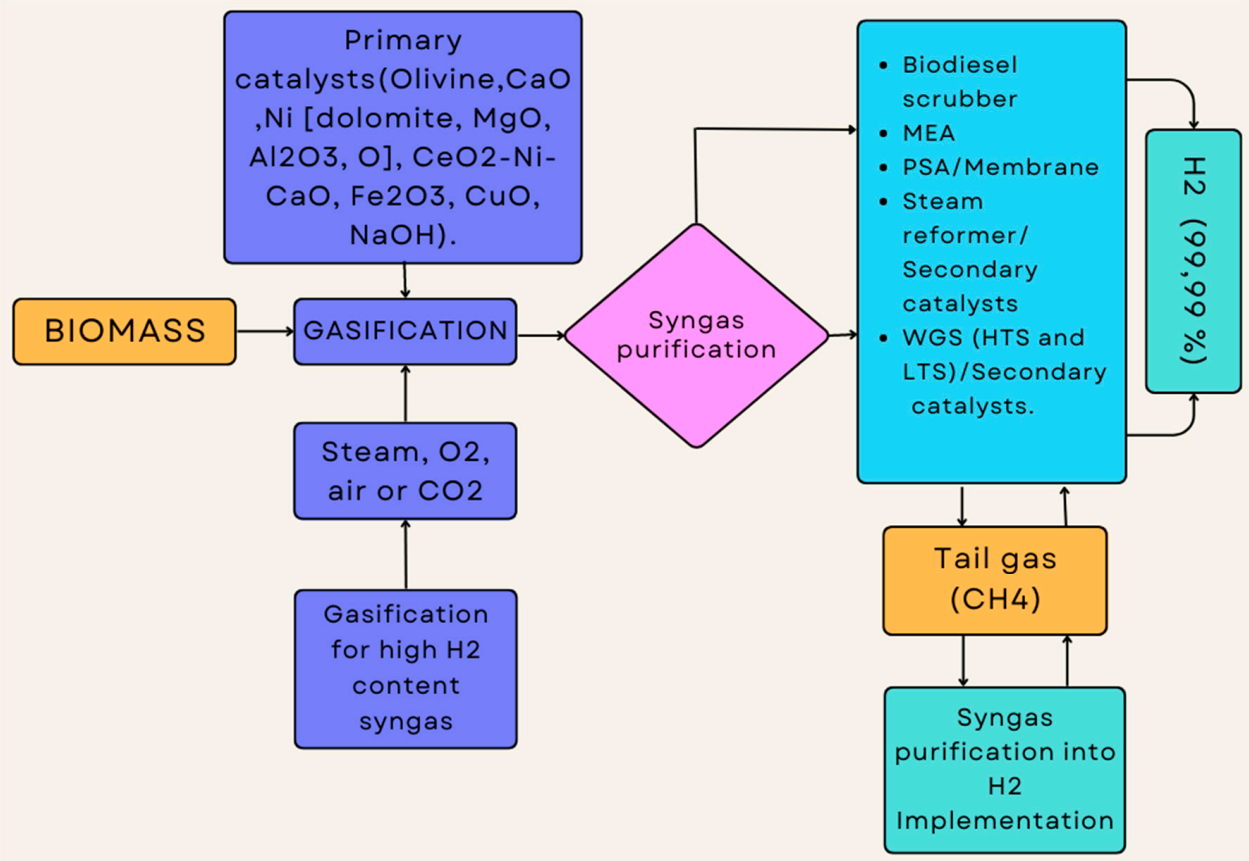


Figure 4. General scheme of H_2 production through biomass gasification.

Topologies of Purification Stages

The sequence of unit operations in the purification of synthesis gas for high-purity hydrogen can use different topologies, as shown in Figure 5, which was elaborated using the information of diverse authors. Figure 5a shows the topology proposed by [33], which developed a model in IPSE PRO considering implementing a steam reforming step immediately after the gas cleaning step using a membrane system as the last step. The WSR reactor has two stages: HTS and LTS high and low temperatures, respectively. Whereas [32], whose topology is shown in Figure 5b, when assessing a 10 MW plant using the COCO simulator and, based on the Gussing plant's experimental results, proposed installing the WGS reactor immediately after the gas cleaning system. The steam reformer treats the tail gas, where methane appears in higher concentration. The author also shows the main parameters (pressure and temperature) at the input and output of each unit operation. The selection of membrane or PSA technology for the last stage of purification must consider the hydrogen flow to be treated and the cost of these systems [32,33].

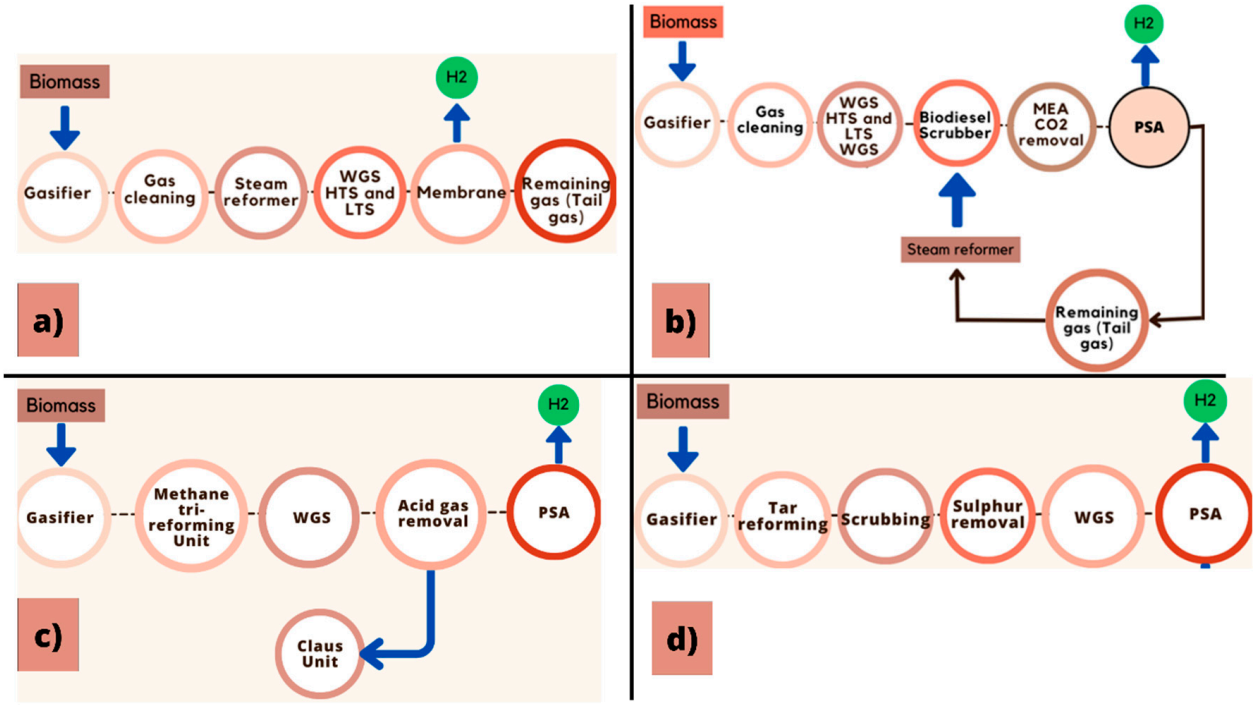


Figure 5. Syngas purification topologies to produce a gas with a high hydrogen concentration: (**a**) [33], (**b**) [32], (**c**) [34], (**d**) [35,36].

Figure 5c presents the topology proposed by [37], in which corn straw was selected as the biomass to be gasified. First, corn straw is pretreated and reacted with oxygen from the air separation unit (ASU) in the gasifier to produce raw synthesis gas containing H_2, CH_4, CO, and CO_2. The raw steam synthesis gas, oxygen from the ASU, and CO_2 from the acid gas removal (AGR) are sent to the methane tri-reforming reactor (MTR) to obtain H_2. Through the WGS unit, the unreacted CO in the synthesis gas is converted into H_2, and CO_2 is generated simultaneously. After processing, the raw synthesis gas enters the AGR unit to remove CO_2 and H_2S to obtain clean synthesis gas. The CO_2 is recycled to the MTR unit, and the H_2S is recovered in the Claus Unit. Finally, the cleaned synthesis gas enters the PSA unit to generate H_2 of high purity [37].

Another model was developed by [36] and revalidated by [38], in which different biomass gasification subsystems are proposed to improve hydrogen yield. As shown in Figure 5d, the gasification unit is followed by a tar reforming unit, a syngas cleaning unit, and the water–gas shift and hydrogen purification units. The feedstock is first pretreated by grinding and drying before entering the gasification section. After that, the dried material undergoes so-called gasification and tar reforming. The gasification process used a low-pressure indirect gasifier consisting of two fluidized bed reactors: a gasifier where the biomass reacts with steam at 870 °C and 1.6 bar, producing raw synthesis gas and coal, and a combustor in which the coal fraction is burned to provide the heat needed for the gasification process. The flue gas from the combustor is used to dry the biomass feedstock.

Since the raw synthesis gas contains significant amounts of tar and light hydrocarbons, it undergoes a reforming process to convert them to CO and H_2, thus increasing the yield of the synthesis gas and avoiding fouling problems. The resulting gas stream is sent to the syngas cleaning, water–gas shift, and hydrogen purification section. The synthesis gas stream is cooled and filtered to remove fine particles and condensed alkali compounds. The synthesis gas is then compressed and passes through a sulfur compound removal process. The H_2S contained in the gas is absorbed into an iron solution that acts as a redox catalyst so that the absorbed H_2S is oxidized to elemental sulfur. The reduced iron solution is then regenerated in an oxidation reactor. The cleaned synthesis gas is passed through a water–gas shift (WGS) process, which comprises a high-temperature shift reactor -HTS and a

low-temperature shift reactor (LTS). The HTS and LTS reactors use Fe-Cr and Cu-Zn-based catalysts, respectively. Finally, the hydrogen is separated from other compounds, such as CO_2, CO, CH_4, and other light hydrocarbons, in a pressure swing adsorption (PSA) unit.

Hydrogen yield can be increased by adding catalysts inside the gasifier bed, called primary catalysts. The main ones are Olivine, CaO, Ni (dolomite, MgO, Al_2O_3, O), CeO_2-Ni-CaO, Fe_2O_3 CuO, and NaOH. Adding primary catalysts increases the hydrogen content at the gasifier exit. Figure 6 shows data from different sources illustrating the H_2 content and its increase when catalysts are added.

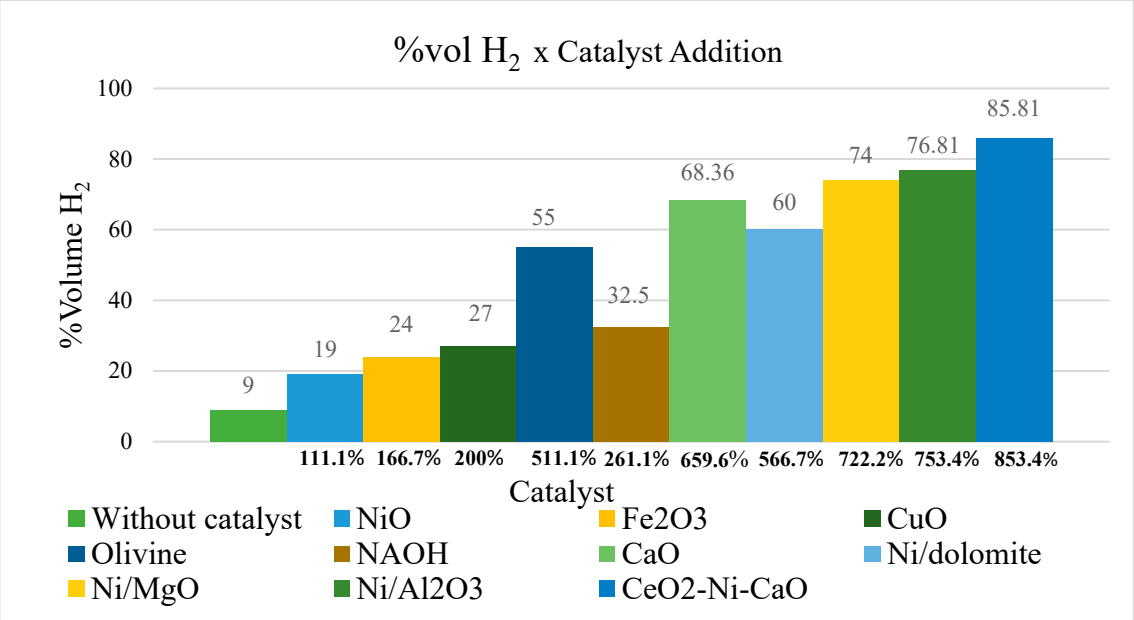


Figure 6. Percentage of H_2 at the gasifier outlet as a function of the type of catalyst applied to the steam gasification analyzed [30,39,40].

The beneficial effects of adding some primary catalysts allow the obtaining of an increase in the H_2 content of the producer gas. This increase can be seen as a function of the volumetric percentage of H_2 obtained in the produced gas. For a gas produced without the addition of any catalyst, the %volume of H_2 is approximately 9%. Whereas when added, for example, the catalyst Olivine, there is an increase to 19% of the H_2 content in the producer gas, representing a twice higher content to the case where no catalysts were added. An interesting fact is that for the case of the catalyst CeO_2-Ni-CaO, there is an increase in the order of 76.81% of the volume of H_2 in the gas, which represents an increase of 853.4% of the volume of H_2 to the gas not added to the catalyst. The values presented in the literature always refer to a specific case, that is, for a given biomass, at given temperatures and with a certain amount of added catalyst [20].

Another interesting catalytic method is the SER (sorption-enhanced reform) [13], where CaO is used to absorb the CO_2 resulting from the methane steam reforming inside the gasifier. $CaCO_3$ is regenerated into CaO in a separate reactor and returned to the gasifier after releasing CO_2. As a result, the hydrogen content in syngas increased up to 60–70%, and at the same time, SER should be considered a carbon-negative technology [41]. The research [37] proposed a two-stage SER that increases production by 39.6% compared to the conventional one-step SER.

4. Previous Theoretical and Experimental Investigations

4.1. Bibliometric Analysis

Based on bibliometric analysis, using the VOS viewer 1.6.19 software and data from the Web of Science database, containing articles, review articles, conference papers, and

book chapters. It is possible to observe the advances and the state of the art regarding research for hydrogen production via biomass gasification. The analysis is carried out from 2010 to 2022, with works on "biomass gasification" and "hydrogen production".

More developed countries such as China, Canada, and the United States of America have shown a high interest in research and publications compared to other countries. The works also show growing research in the catalytic reforming of hydrogen, using various catalysts, intending to increase the percentage of H_2 volume. The method has the limitation that only one database was used, which may or may not represent most other databases. Thus, it is irrefutable that the topics below represent literature searches within the stipulated parameters in the Web of Science.

4.1.1. Correlation Among the Papers by Country

Figure 7 represents the correlations between the central publishing countries on the subject, i.e., the countries that published papers whose central theme is linked to biomass gasification and hydrogen production. The country with the highest number of publications is the People's Republic of China, followed by Canada and the United States of America, with 535, 113, and 105 works, respectively, published from 2010 to 2022. The clusters are positioned according to the degree of co-authorship of published works, like the People's Republic of China, which has a high number of co-authorships concerning other countries, in addition to the most significant number of publications. In the figure, it is also possible to observe the countries with greater co-authorship. Namely, the countries with the highest co-authorship are represented in the cluster of the same color.

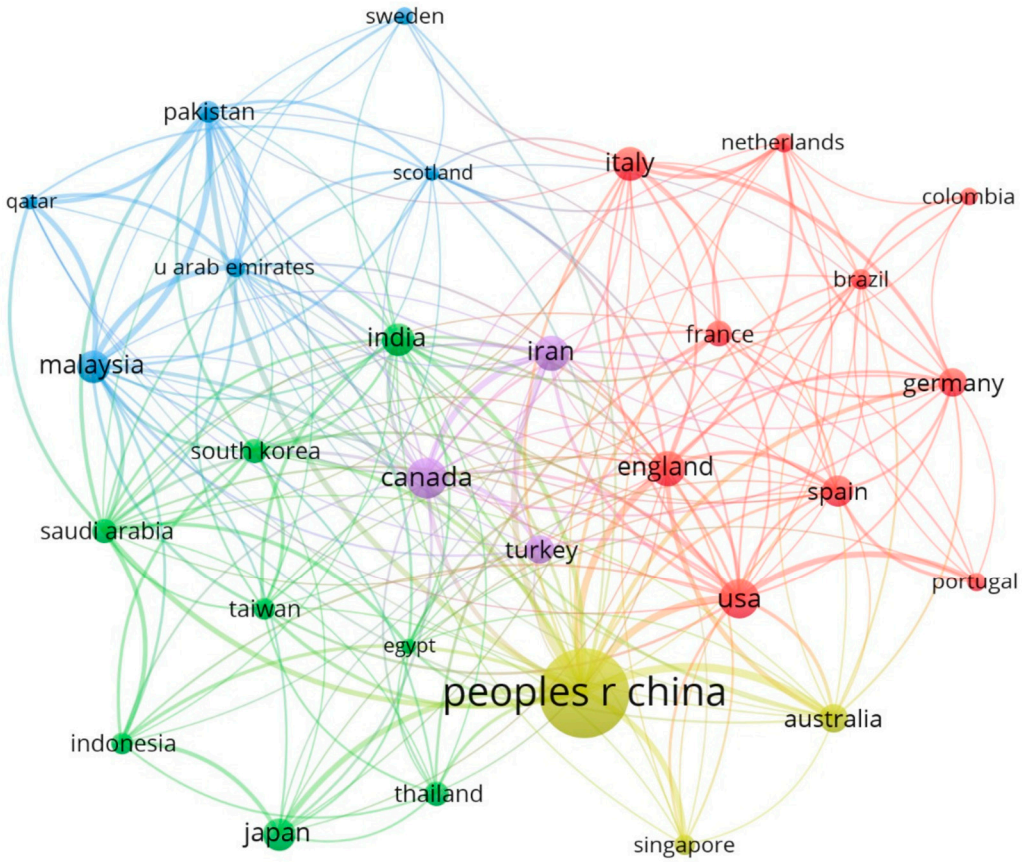


Figure 7. Visualization of the number of publications in the field of hydrogen from biomass and the interactions between authors.

In percentage terms, China, Canada, and the United States of America have approximately 25%, 5.30%, and 4.90% of the published papers, respectively. They also have 22.35%, 8.33%, and 3.7% of the overall citations in the database, respectively.

4.1.2. Research Topics and Co-Authorship

Figure 8a shows which terms related to hydrogen production by biomass gasification are the most cited in the Web of Science database articles. Therefore, they constitute issues being researched more intensively. These are supercritical water gasification, syngas, steam reforming, and fluidized bed, with respectively 130, 111, 61, and 53 occurrences. This is without counting, of course, the main topics, which are biomass, hydrogen, gasification, biomass gasification, and hydrogen production, with 355, 268, 265, 229, and 224 occurrences, respectively. It can also be seen that the densities of the lines between each topic represent the degree of correlation between them. For example, biomass, gasification, and hydrogen have a dense correlation line. That is, it matches the fact that everything researched in the terms proposed in this analysis for hydrogen production via biomass gasification has been observed. At the same time, a line of average density between gasification and hydrogen production is also visible for syngas, fluidized beds, steam reforming, modeling, and process simulations.

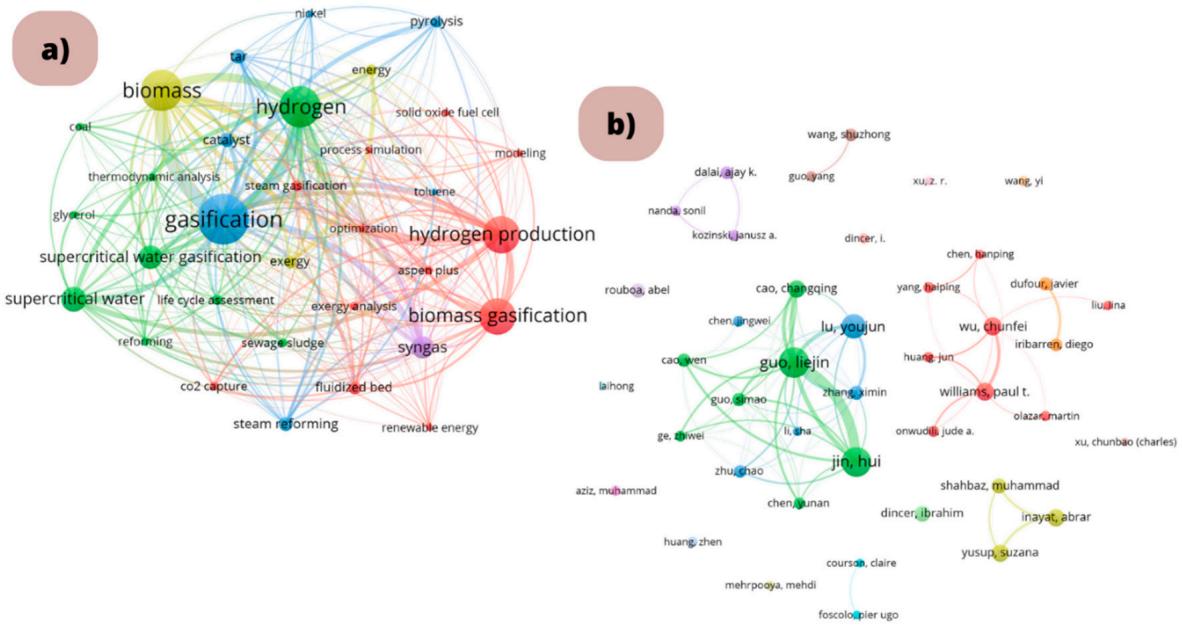


Figure 8. Relationship between: (**a**) co-occurrence among keywords with at least 20 citations, (**b**) co-authorship among authors that have at least 300 citations in their papers.

Similarly, in Figure 8b, it is possible to observe the co-authorships of authors with at least 300 citations in their work. More to the center, a set of authors with high co-authorship-co-authorship can be observed. "Guo, Liejin" is the most influential, followed by "Jin, Hui", with 3117 and 2543 citations each. Next is "Dincer, Ibrahim", with a total of 2356 citations, and the author has no co-authorship with another author with at least 300 citations. However, the central cluster in green has the highest number of citations, with six of its authors being among the ten with the highest number of citations. Another cluster that presents authors with high co-authorship is represented in red, whose author with the highest number of citations is "Williams, Paul T." with a total of 1430 citations, followed by "Wu, Chunfei" with 1299 citations. They are among the ten authors with the highest number of citations. However, the analyses show these authors' interest in observing the process's catalysts and performing the life cycle assessment of the process, thus evaluating the technological readiness of the process.

Some routes for the energy conversion of biomass can be more efficient than biomass gasification. However, in the case of hydrogen production by other routes, even if they are sustainable, the process is expensive, whereas biomass is expected to be cheaper. Therefore, biomass can be an asset in supporting the energy transition of countries that, for example, need to supply their cars with low-cost renewable fuels (H_2), or store H_2 from biomass for later use in fuel cells to compensate the variability of renewable sources.

Conversion efficiency is undoubtedly one of the most critical indicators of the hydrogen production process. However, there is a difference between theoretical values and experimental values, with the last usually lower. Table 2 presents theoretical and experimental data on efficiency and yield values in kgH_2/kg of biomass. Data were obtained from different publications and refer to a given biomass under specific temperature, moisture, and gasification conditions. A previous compilation by ETIP Bioenergy [32] was used as a preliminary reference. As can be seen in Table 2, data theoretical/modeling results are slightly better than the experimental ones. Considering the simple average of the hydrogen values per kg biomass, the theoretical values are 0.0804 kg hydrogen per kg biomass, and the experimental values are 0.07728 kg hydrogen per kg biomass, representing a minimum deviation and illustrating the excellent correlation between theoretical simulations and experiments.

Table 2. Theoretical and experimental values of hydrogen yield and efficiency of the biomass to hydrogen gasification processes.

Number	Theoretical	Experimental	Hydrogen Yield (Kg H_2/kg Biomass)	Efficiency	References
1	X		0.107	0.696	[42]
2	X		0.1	0.67	[43]
3	X		0.061	0.41–0.45	[32]
4		X	0.058	0.4	[44]
5		X	0.165	0.654	[45]
6		X	0.102	0.654	[44]
7	X		0.091	0.654	[46]
8	X		0.08 * 0.083 **	0.53 * 0.6 **	[47]
9	X		0.082	0.61	[33]
10	X		0.074	0.47	[48]
11		X	0.046	0.65	[49]
12	X		0.0584	0.389	[50]
13			0.119 ***	-	[51]
14		X	0.0154	0.4759	[52]
15	X			0.47–0.54	[53]

* Entrained flow gasifiers. ** Double fluidized bed. *** Tubular.

The efficiency of the gasification process is around 60%, and the simple average efficiencies of the theoretical and experimental values are 0.5549 and 0.56678, respectively. Some processes have relatively low efficiencies of around 0.4, and others are somewhat high, around 0.69. This is a high standard deviation depending solely on the process since experimental and theoretical processes vary between these values with minor discrepancies.

5. Technological Readiness Level (TRL), Economic Viability, and Sustainability Studies

The TRL can be understood as an indicator of the technical readiness of a given technology. It considers the following development stages of a technology: basic research, feasibility tests, technology development, demonstration at the pilot level, and finally, the commercial operation phase, with values that go from 1 to 9 [29].

According to [50], the TRL of hydrogen production from biomass is 7. Otherwise, a report published by [21] first considers the process technologies TRL separately and then the TRL of the complete gasification hydrogen production system. Technologies such as

the PSA, WGS, and steam reforming have a TRL of 9, and the DFB gasifier has a TRL of 8. This equipment has already reached its commercial stage and is available from various suppliers. However, when the complete system is analyzed using the DFB gasifier, the TRL of the system is rated as 5, indicating that the complete system has only been tested at the laboratory/pilot scale. That allows one to establish that the individual components can work together. However, the whole process chain has yet to be tested on an industrial scale and has yet to reach its commercial stage. Otherwise, supercritical gasification has a long way to go until its commercial stage, as its TRL, according to [9], is 4.

Only a few laboratory and pilot projects on hydrogen production through biomass gasification have been commissioned worldwide. One example is the pilot plant of the European Gasification Center in Gussing—Austria, which was designed and commissioned by the company Bioenergy2020+ and the University TU Wien.

The pilot plant installed in Gussing has a DBF system that produces a high calorific gas. The system has a gas cooler, a bag filter to remove dust particles, a WGS stage, and an organic solvent scrubber to remove water and tar from the gaseous product. The gas purification stages correspond to the schematic shown in Figure 5b. With this plant configuration, chemical efficiencies of over 60% (based on net calorific values) and total efficiencies of up to 80% through waste heat utilization can be reached [54].

The work of [55] analyzed how impurities influence the degradation of the purification train of catalyzers and the role of the gas cleaning step. Evaluated impurities were: sulphur compounds, mainly (H_2S), ammonia, and BTX (benzene, toluene, and xylene). The authors conclude that an iron/chromium catalyst can achieve 77% CO conversion in a sulfur-rich environment. Although in the stage of biodiesel scrubbing, all these compounds can be removed down to the allowed concentration.

Some crucial remarks on the Gussing Plant purification train design and operation are summarized by [54], these being:

- **WGS:** iron/chromium catalyst is used at atmospheric pressure and temperature 250–450 °C.
- **Biodiesel scrubber:** two stated, gas to biodiesel ratio 0.1 m^3/L, benzene removal of 70%.
- **MEA:** use monoethanolamine in a water solution (30–70%) and 9.1 mol of MEA per mole of CO_2.
- **PSA**: with Pressures between 23/10 bars. Hydrogen recovery is 90%, with a purity of 99.9%.
- **Tail gas reforming:** platinum-based catalyst, temperature 850 °C, methane conversion 99%, steam to carbon ratio 3/1.

A few industrial projects are planned; among them are the ones announced by B&W Brighloop and NRG Korea, B&W, and Kiewit Industrial. The Brighloop technology is an oxidation and reduction novel looping process with CO_2 capture, producing two streams of almost pure hydrogen and CO_2. According to B&W [56], two projects are being planned for the near future: an industrial commercial of 1.5–15 tons per day of hydrogen and a commercial utility of 60–320 tons of hydrogen per day, respectively.

Economic viability studies on hydrogen production through gasification show that the production costs could be much lower than the present costs of producing green hydrogen through electrolysis. Hydrogen costs are highly dependent on biomass costs, which, according to [57], represent 36 to 62% of the final hydrogen cost (LCOH). Table 3 shows a resume of the primary studies about LCOH. Table 3 presents the literature data on the costs required to produce 1 kg of H_2 by biomass gasification calculated using the levelized/average cost LCOH.

Table 3. LCOH values as a function of biomass, its cost, and the production technology used.

No	Type of Biomass	Cost of Biomass USD/kg	Gasifier Technology	LCOH USD/kgH_2	Reference
1	Wood chips	0.1057	DFB	5.37	[57]
2	Wood biomass	-	FB	1.77–2.77	[22]
3	Lignocellulosic residues	0.006–0.025	DFB	1.99–5.6	[42]
4	Canadian pinewood	0.1	FB	3.7	[58]
5	Forest residues	-	DFB	1.52–2.92	[59]
6	Biomass	0.0424	-	3.59	[36]
7	Biomass	0.075–0.1	-	3.1–3.5	[32]
8	Wheat straw	0.044	-	0.98	[47]

DFB = Double fluidized bed. FB = Fluidized bed.

Compared with Table 3, LCOH data using natural gas are much lower and reported as 1.1 and 2.17 by [32,35], respectively. Sustainability studies have been carried out on hydrogen production through biomass gasification. To overcome the difficulties in comparing different life cycle assessment studies (LCA), reference [60] conducted the harmonization of hydrogen energy systems.

The following LCA indicators were calculated and shown in Table 4:

- Global Warming Potential—GWP values obtained in different life cycle studies of the process of H_2 and its comparison with the values from the natural gas reforming process are shown in Table 4. The researchers [37] compared the life cycle of the production of hydrogen production through biomass staged gasification (BSGH) with conventional natural gas steam reforming (NGSH).
- Cumulative Energy Demand—CED considers the energy content of all different energy sources, both renewable and non-renewable, in the whole life cycle [61].
- LCSA—life cycle sustainability analysis and CExC—Circular Economy Assessment. The combination of economic, environmental, and social aspects in the life cycle using the LCSA shows a higher sustainability of biogas gasification hydrogen when compared with natural gas ones [38].
- Hydrogen can also be produced with net negative carbon emissions by applying the H_2 BECC concept that combines biohydrogen production with carbon dioxide capture and storage, representing a significant difference from carbon-neutral hydrogen production through electrolysis. This compensates GHG emissions in agriculture and waste management [62].

Table 4. Main indicators of life cycle studies of hydrogen production from biomass gasification and natural gas reforming.

LCA Results	Hydrogen from Biomass Gasification	NG Reforming	Reference
GWP $kgCO_2e/kgH_2$	8.0	12.0–14.0	[61]
	0.18	11.43	[35]
	5.37	11.98	[37]
	−0.5	11.0	[32]
	3.54	11.98	[22]
CED MJ/kgH_2	30.0	180–200	[61]
	25.36	200.9	[38]
LCSA, Kg H_2/Euros kg CO_2	1.54	0.004	[35]

GWP—global warming potential. CED—cumulative energy demand. LCSA—life cycle sustainability analysis.

Analyzing data from Table 4, it is possible to conclude that the combination of economic and environmental aspects in the life cycle using the LCSA indicator shows the best performance of biogas gasification hydrogen when compared with the natural gas one [38].

By normalizing the analyses, it is possible to represent in boxplot form the LCA ratios from Table 4, the biomass cost and the LCOH from Table 3, and lastly, the process efficiency as a function of hydrogen addition from Table 2. Regarding the LCOH from solid biomass Figure 9c, 50% of the costs in USD/kgH_2 are between 3.50–375 USD, and the other 50% are between 3.50–2.15 USD approximately.

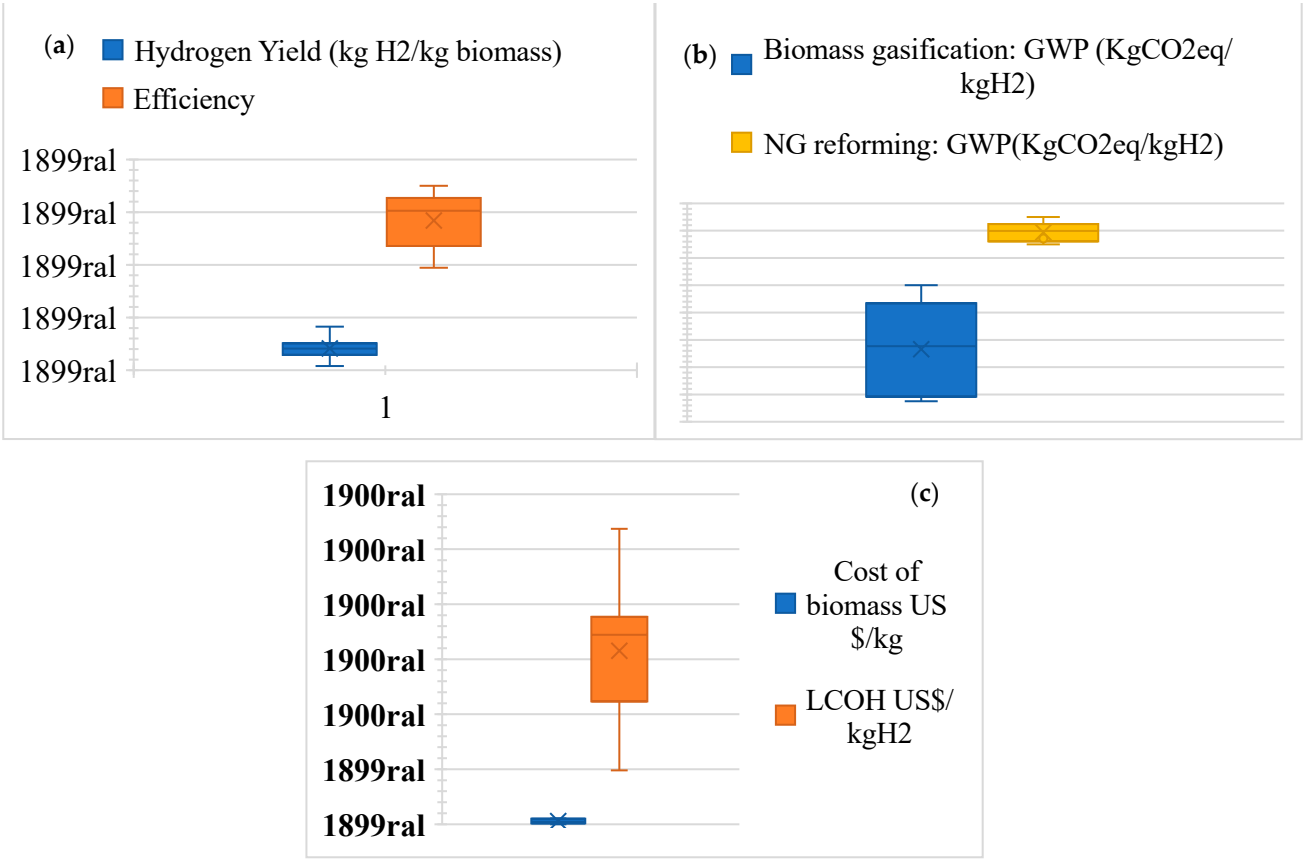


Figure 9. Boxplot representing maximum, average, and minimum values of GWP of the LCA of conventional and biomass gasification hydrogen: (**a**), the efficiency and hydrogen yield: (**b**), the biomass cost and LCOH: (**c**).

The boxplot represents the interquartile range, which is the range between the first quartile and the third quartile. Quartile 1 is the value below which 25% of the data are, and quartile 3 is the value below which 75% of the data are. The height of the box is proportional to the interquartile range. Applying this analysis to the GWP of biomass gasification to produce H_2, it can be seen that 25% of the GWP values are close to zero, while 75% of the GWP values are close to 6 KgCO_2eq. Unlike the H_2 produced via natural gas, for which 25% of the GWP values are above 11 KgCO_2eq and 75% of the GWP values are close to 13 KgCO_2eq.

Similarly, the efficiency is approximately 0.56 in 75% of the data analyzed, with a decrease to 0.38 in the rest, which corresponds to a probability of 25%. While the hydrogen yield is mostly 0.102 in 75% of the data and 0.0875 in the other 25%.

6. Global Green Hydrogen Potential from Solid Biomass Sources for 2050

After the conversion and performance considerations in the previous sections, the last key issue is to determine the hydrogen production potential for the time horizon of 2050. Then, we present projections for the potential role of green hydrogen for 2050 from the production through biomass gasification derived from solid biomass residues availabilities and the average values of hydrogen yield for the world and Brazil.

The method for the world potential in 2050 followed the procedure introduced by [63]. Briefly, it consists of taking current theoretical bioenergy production from nine different sources and making adjustments for 30 years in the future, considering key indicators of yields, technology, land availability, and people's overall dietary and biomaterials demands in three different scenarios. Those scenarios were set based on the type and efficacy of policies designed to boost the production and use of bioenergy, namely business-as-usual (BUS) in optimal trends (OPT), and then in full (climate agenda) adaptation response (FAR). Further details on the scenarios are omitted for the sake of conciseness.

The biomass sources covered in [63], which will be considered for hydrogen production in their totality, are firewood, forest residues, agricultural wastes from crops, wood industry residues, and recovered wood since they can be used in gasifiers (Table 2) after some preparation. The energy conversion efficiency is the arithmetic mean of the energy efficiencies listed in Table 2, and the mathematical formula used to compute the projections is described in the footnotes of Table 5.

Table 5. Global green hydrogen bioenergy potential from solid biomass sources, $TBH2_{2050,k,s}$ (firewood, forest residues, agricultural wastes (crops), wood industry residues, and recovered wood) for 2050 (EJ) on a year basis.

	2020 [a]	**BUS** [b]	**OPT** [b]	**FAR** [b]
Bioenergy Source [d]	**Theoretical Biomass Bioenergy, $BS_{2020,k,s}$ (EJ)**	**Hydrogen Bioenergy (EJ)** [c]	**Hydrogen Bioenergy (EJ)** [c]	**Hydrogen Bioenergy (EJ)** [c]
TOTAL	**46.19**	**28.25**	**45.03**	**51.91**
Firewood	37.29	19.02	31.27	34.40
Forest Residues	0.56	0.28	0.93	1.80
Agricultural Wastes (Crops)	2.23	2.08	2.93	2.92
Wood Industry Residues	2.78	3.12	4.50	5.81
Recovered Wood	3.34	3.75	5.40	6.98

(a) From Table 3 of [63] with no conversion to hydrogen; (b) as described in Table 2 by [63]; (c) theoretical green hydrogen bioenergy potential given by: $TBH2_{2050,k,s} = \eta_{2050} \times BS_{2050,k,s}$; where the conversion efficiency is the arithmetic mean of the energy efficiencies listed in Table 2, $\eta_{2050} = 0.56$; (d) energy crops could be used for hydrogen production as well. However, it is more likely to be assigned to biofuels for internal combustion engines in the form of methanol, ethanol, or biodiesel. Therefore, it was left out of the hydrogen production.

The world's potential is 235.51 MtH_2 (Table 6) in a 2050 "bussines as usual" scenario (BUS). Brazil has a potential for hydrogen production using solid biomass corresponding to 23% (54.1 MtH_2, from Table 7). This result is a consequence of the great availability of agricultural residues. Therefore, Brazil's case deserves further consideration.

The projections for theoretical bioenergy for the selected solid biomass sources for 2050 are indicated in the columns labeled "BUS", "OPT", and "FAR" for the respective scenarios as described by [63]. If no significant policies and incentives are implemented, the potential to produce bioenergy in the form of hydrogen would be 28.25 EJ, from which 2/3 would be from all the firewood produced in 2050. If successful policies and incentives are in place (OPT), there is a potential of 45.03 EJ (H_2). In the most comprehensible scenario (FAR), there is a potential of 51.91 EJ of bioenergy in the form of hydrogen with almost the same proportions as in the business-as-usual scenario.

The projections from Table 5 are compared to global energy indices from the literature in Table 6. The potential shares of bioenergy in the form of hydrogen from solid biomass sources to meet the total energy demand in 2050 are 3%, 5%, and 6% for the respective scenarios considered. From the expected production of hydrogen for 2050, the projections for those three scenarios are 235.51 MtH_2, 375.40 MtH_2, and 432.71 MtH_2, or 94%, 150%, and 172% of the share of global hydrogen expected production of 251 MtH_2 [64]. In the business-as-usual scenario (BUS), if all the solid projected to be produced and directed to bioenergy is converted to hydrogen, solid biomass could supply almost all the IEA expectations from all sources in 2050.

Table 6. Comparisons of indices about global energy consumption and expected hydrogen production in 2050 with bioenergy in the form of hydrogen and its production from solid biomass sources (firewood, forest residues, agricultural wastes (crops), wood industry residues, and recovered wood) for each one of the scenarios, BUS, OPT, and FAR after Table 5 in year basis.

Indices	Projections of Hydrogen and Energy in Different Scenarios				
	2020	2050			
	CS	BUS	OPT	FAR	IEA (Total)
Global primary energy consumption (EJ)	634 [a]	935 [a]	935 [a]	935 [a]	935 [a]
Global hydrogen production from solid biomass (EJ)	0 [b]	28.25 [c]	45.03 [c]	51.91 [c]	30.11 [b]
Share of global Energy demand supplied as hydrogen from solid biomass	0 [d]	3% [d]	5% [d]	6% [d]	-
Total global hydrogen production (e) or from solid biomass (f) (MtH_2)	72.2 [e]	235.51 [f]	375.40 [f]	432.71 [f]	251 [e]
Share of global hydrogen production supplied by solid biomass	0 [g]	94% [g]	150% [g]	172% [g]	-

(a) Source: U.S. EIA, 2021, Figure 10 from [65]: 2020: 601.5, 2050: 886.3 in quadrillions of BTU; (b) hydrogen bioenergy based on the total hydrogen produced for 2020 and projected to be produced in 2050 in MtH_2 from item (d) below converted to energy based on the hydrogen low heating value LHV_{H2} = 119.96 MJ/kg; (c) From Table 5; (d) projected potential share of bioenergy from hydrogen from the world energy demand; (e) projected global hydrogen production from all sources [64]; (f) production of hydrogen from biomass estimated based on the hydrogen low heating value LHV_{H2} = 119.96 MJ/kg; (g) projected potential share of hydrogen production from solid biomass based on the U.S. EIA projection of 251 MtH_2/year [65].

Now, we explore the hydrogen production potential from solid residues biomass gasification in Brazil for the year 2050 is computed considering the most promising crops for energy conversion pointed out in [66], namely, sugarcane, soybean, eucalyptus, corn, cassava, rice, and cotton (Table 7). In 2020, there was an estimated potential of 26.5 MtH_2, which could almost double in 2050 with a total potential of 54.1 MtH_2 (22% of the IEA projected global production from hydrogen, Table 6). Energy-wise, there was a potential of 3.2 EJ from hydrogen in 2020, and there is a potential of 6.5 EJ in the year 2050 (a quarter of what IEA projection for global energy supply from hydrogen 30.11 EJ, Table 6) with the residues from sugarcane contributing by almost half of the potential.

Table 7. Green hydrogen bioenergy potential from residual biomass sources for Brazil by gasification, $TBH_2Br_{2050,k,s}$ (sugarcane, soybean, eucalyptus, corn, cassava, rice, cotton) for 2050 (in MtH_2 and EJ) on a year basis.

Brazil	Hydrogen Production from Solid Biomass Gasification Potential, $TBH2Br_{y,k}$ (MtH_2) [b]		Energy Potential of Hydrogen from Solid Biomass Gasification $TEBH2Br_{y,k}$ (EJ) [c]	
Biomass Residue Source	**2020** [a]	**2050** [b]	**2020** [a]	**2050** [b]
	26.5 [d]	**54.1** [d]	**3.2** [d]	**6.5** [d]
Sugarcane	8.22	22.85	0.99	2.74
Soybean	8.23	13. 64	0.99	1.64
Eucalyptus	2.81	5.15	0.34	0.62
Corn	5.42	9.65	0.65	1.16
Cassava	0.54	0.93	0.06	0.11
Rice	0.75	1.15	0.09	0.14
Cotton	0.49	0.71	0.06	0.09

(a) The selected biomass from Table 2 of [66], with $MBSBr_{2020,k,s}$ = 633,261.90, 119,281.70, 140,426.13, 80,709.50, 20,606.04, 12,064.20, and 5012.90 (10^3 t/yr) and $MBSBr_{2050,k,s}$ = 1,760,667, 197,686.79, 257,633, 143,538.93, 35,867.50, 18,547.14, and 7236.51 (10^3 t /yr), respectively, for the biosources listed in the first column. Available biomass residues for gasification $BSBr_{y,k,s} = MBSBr_{y,k,s} \times RPR_k \times AA_k$, considering the residue-to-product ratio (RPR_k) of 0.22, 2.30, 0.25, 1.68, 0.65, 1.55, and 2.45, respectively, and the annual availability factor to those residues (AA_k) of 59%, 30%, 80%, 40%, 40%, 40%, and 40%, all from Table 1 of [66]; (b) hydrogen production from solid biomass gasification potential, $TBH2Br_{y,k,s} = \eta_{m,2050} \times BSBr_{y,k,s}$ (MtH_2), where $\eta_{m,2050} = 0.1$ as an average of the mass yield (kgH_2/kg biomass) from Table 2; (c,d) energy potential of hydrogen from solid biomass gasification; (d) $TEBH2Br_{y,k,s} = LHV_{H2} \times TBH2Br_{y,k,s}$ (EJ).

7. Conclusions

- Hydrogen production from fossil-based fuels has potential threats to sustainable economies.
- Fluidized bed gasifiers, using steam as the working fluid, are the most viable for hydrogen production, given their greater biomass processing capacity and hydrogen content in the synthesis gas.
- Among the primary catalysts, CeO_2-Ni-CaO proved to have the highest efficiency in increasing the Hydrogen volume fraction, on the order of 85.81% (volume). Using CaO, NiO, Olivina, Ni/dolomite, and Ni/Al_2O_3, the most frequently evaluated as primary catalysts increases H_2 content in syngas from 46.0 to 59.6%.
- Efforts are being made, through primary catalyst utilization, to produce, already at the gasifier outlet, a gas with the highest possible hydrogen content to allow a more straightforward purification train and considerably reduce the cost of the hydrogen obtained by biomass gasification.
- Hydrogen yield values from biomass gasification are in the range of 0.0154–0.165 kg H_2/kg biomass, an average value of 0.082.
- LCOH values for biomass gasification to hydrogen process are in the range of 0.98 to 5.37 USD/kgH_2. This comprehensive range results from uncertainties related to biomass price, plant CAPEX, and size, as there are no industrial plants for hydrogen production from biomass gasification in operation. The average LCOH value is 3.15 USD/kgH_2.
- GWP values in LCA studies of hydrogen from biomass gasification are in the range of −0.5 to 8.0 in kg CO_2/kgH_2 and 11 to 14 in kg CO_2/kgH_2 for NG reforming, with average values of 3.31 kg CO_2/kgH_2 and 11.88 kg CO_2/kgH_2 respectively.
- Catalyst deactivation due to ammonia, sulphur compounds, and BTX in gas and the need for regeneration is an issue that deserves further studies.
- More experimental research at a pilot plant level is needed to improve the unit's integration and to advance to higher TRL values of the whole process.
- Increasing the efficiency of the primary catalyzers, which increases the hydrogen content at the gasifier outlet, simplifies the hydrogen purification train and reduces its costs.
- There was an estimated solid biomass potential in Brazil of 26.5 MtH_2, which could almost double in 2050 with a total potential of 54.1 MtH_2, corresponding to 3.2 EJ and 6.5 EJ, respectively.
- The global solid biomass potential is around zero EJ in 2020, with projections of 28.25, 45.03, and 51.91 EJ considering the BUS, OPT, and FAR scenarios, respectively. The IEA's projection for 2050 is 30.11 EJ, a difference of 0.72 EJ with the projected value in BUS scenario.
- The bibliometric analysis showed that China, the USA, and Canada have most of the publications on hydrogen production from biomass. Core terms: gasification and hydrogen production are connected with others such as syngas, fluidized bed, steam gasification, steam reforming, supercritical water, catalysts, as well as process simulations. The most cited authors are Guo. L. Jin. H., Dincer. I., Williams. P.T, and Chunfei. W.
- From the bibliometric analysis it can be inferred that obtaining hydrogen by gasifying biomass is a current topic, which includes important issues such as the use of catalysts, steam as a gasification agent, process simulation, life cycle analysis, CO_2 capture, the steam reforming process, gasification in supercritical water, pyrolysis. The concentration of research on the subject in just a few countries makes it necessary to encourage the implementation of international projects on the subject.

In summary, we have addressed the issues over hydrogen production through biomass gasification, which, arguably, are inextricably connected considering the premises and goals of the current energy transition.

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