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Review

Available Pilot-Scale Technologies for Gasification of High-Ash-Content Biomass

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Abstract

The transition toward low-carbon energy systems and circular economy frameworks has intensified interest in biomass and waste valorization technologies that deliver reliable energy carriers while mitigating greenhouse gas emissions. Among the thermo-chemical pathways, gasification has emerged as a particularly flexible and robust option for transforming biomass resources into synthesis gas suitable for power generation, hydrogen production, and synthetic fuels. This review critically examines biomass gasification as a feasible alternative for valorizing waste and producing syngas. The manuscript discusses the physicochemical characteristics of biomass, highlights its influence on syngas quality, tar formation, and cold gas efficiency. The fundamental stages of the gasification process and the effects of different operating parameters were systematically reviewed. Special attention was given to the challenges posed by low-quality biomass, such as sewage sludge, digestates, and manures, which are characterized by high-ash content and high moisture levels. Syngas energy content reported across different experiences was usually around 4–5 MJ/m^3 when operating with low-quality biomass, resulting in lower efficiencies than those reported for lignocellulosic biomass (around 30–70%, expressed as cold gas efficiency (CGE)). Current small-scale commercial gasification technologies were also reviewed, with emphasis on operational constraints. This review provides an integrated perspective on the operational challenges associated with low-quality biomass gasification and discusses technological pathways to enhance process efficiency and salability. Although biomass gasification cannot yet be regarded as a fully mature technology across all feedstocks, it nonetheless constitutes a technically significant pathway for strengthening energy system resilience and advancing the production of sustainable fuels within a net zero carbon framework.

Keywords: syngas; waste valorization; energy efficiency; tar reforming

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1. Introduction

Energy is essential for the development and quality of human life. In recent decades, energy consumption and carbon emissions have increased significantly due to population growth and rising income levels. This trend will continue, with the global energy demand expected to rise to 21,546 Mtoe by 2050 and CO_2 emissions to 41.0 Gt by the same year [1,2].

Given the high impact of these emissions on global warming, the focus has been set on accelerating the transition of production cycles to a net zero carbon economy by the efficient use of energy, increasing the share of renewables in the energy production mix, and facilitating access to alternative fuels as well as developing more efficient technologies based either on the use of electricity or alternative biofuels. Therefore, greater investment in research and technology development is crucial to increasing productivity and profitability [3]. While renewables offer potential for power generation, they face limitations due to their inherently intermittent nature. Additionally, their availability can adversely affect the energy market when excess energy is produced during low-demand periods, causing negative electricity prices. An example of the difficulties arising when managing an energy mix based mainly on renewables was the recent Spanish shutdown in April 2025, which set off alarms regarding the energy mix composition and grid reliability [4–7]. Other renewable technologies are not free of controversy. Hydropower relies on the availability of water and tides and their impact on ecosystems. In contrast, geothermal energy and biomass-based systems present challenges related to site limitations, gas leakage, and particulate emissions, requiring advanced control, the establishment of safety standards, and replantation procedures to achieve sustainability [4]. Therefore, energy supply diversification is crucial to improving security and is one of the main challenges for economic growth, especially in emerging economies [8,9].

Gasification is one of the thermochemical conversion processes with great potential for valorizing biomass and waste to produce energy and sustainable materials, generating fewer gas emissions than traditional combustion, and offering a superior life cycle impact compared with conventional hydrogen-production processes [10,11]. There is growing interest in developing efficient biomass-based power systems, as well as in producing liquid fuels and hydrogen from renewable resources, driven by their inherent environmental and societal benefits and by the increasing need to reduce greenhouse gas emissions associated with fossil fuels. Although gasification technologies have been successfully demonstrated for producing energy from fossil fuels, biomass-based gasification is not yet a fully mature commercial process. As reported by Kirkels and Verbong [12], after many years of research and development, the biomass gasification process still requires extensive research, with not enough mature technologies being widely applied at the commercial level.

Biomass represents a viable and sustainable alternative to fossil fuels for energy production, with the potential to achieve, under certain conditions, a neutral or even negative carbon footprint [13,14]. It is an abundant resource that can be easily stored and transported, and estimates suggest that it could supply up to 20% of the global energy demand [15,16]. Furthermore, existing technologies for converting biomass into valuable fuels benefit from extensive industrial experience, which facilitates their deployment. Among the available conversion technologies, thermochemical processes have attracted increasing attention due to their flexibility and availability to process heterogeneous biomass resources. Primary biomass sources include energy crops, forestry residues, agricultural and urban waste, such as municipal solid waste and garden trimmings, as well as algae and microalgae cultures. Energy crops are grown exclusively to produce biomass for biofuel generation [17]. These include wood, grasses, herbaceous plants, starch-rich species, and oilseeds [18]. Biomass from these crops can be used directly for heat and electricity or converted into fuels compatible with existing storage and transport infrastructure and different engine systems. Typical examples, such as whole-crop maize, Miscanthus, short-rotation coppice willow, and poplar, can be processed through combustion, gasification, pyrolysis, or hydrothermal methods to obtain energy and valuable organic compounds. Additionally, pre-treatment steps may prepare biomass for fermentation to produce alcohols or biogas.

Gasification technologies have traditionally been designed for lignocellulosic biomass, including materials such as wood pellets and residues from the wood-processing industry. Increasing attention is now directed toward the valorization of low-quality biomass streams—such as sewage sludge, digestates, and animal manures—as a practical and sustainable strategy for managing the substantial quantities requiring final disposal. However, these feedstocks present significant operational challenges due to their inherently high moisture content and elevated ash levels.

The present manuscript examines biomass valorization through gasification, with particular focus on organic waste, which poses several challenges that must be overcome for this technology to become a key player within the current portfolio of valorization strategies. It outlines key biomass characteristics and transformation processes, highlighting gasification as the most promising option for reliable, dispatchable renewable energy that can complement intermittent sources. The document also reviews the main operating parameters of gasification and finalizes with a review of approaches for converting low-quality biomass.

2. Methods

This review focuses on biomass gasification, with particular emphasis on studies addressing the conversion of high-ash-content biomass, including sewage sludge (biosolids), animal manures, and digestates. A structured literature review was conducted to identify relevant peer-reviewed publications published between 2000 and 2025. The review primarily targeted studies reporting experimental results obtained at pilot scale, as these are considered more representative of industrial performance than laboratory scale investigations.

The literature search was conducted using Google Scholar, Scopus, and PubMed as the primary databases. The initial search using the keyword combination "biomass gasification" returned approximately 286,000 records. From this dataset, review articles and book chapters were excluded, reducing the number of relevant publications to approximately 86,100 research articles. This exclusion was carried out only when searching for experimental studies. However, the present manuscript included review articles and book chapters relevant to the subject to provide background and contextual information. To further refine the dataset, the search considered documents containing in the title the term "pilot scale" in combination with selected feedstock descriptors. This filtering step yielded 44 publications addressing pilot scale biomass gasification in general. When the keyword "sewage sludge" was included, 25 relevant studies were identified, whereas only 7 publications focused on the pilot scale gasification of manure. The search combining "digestate" with "pilot scale gasification" returned a single study, highlighting the limited availability of pilot scale experimental data for this feedstock. The final selection of publications was qualitatively analyzed with respect to feedstock properties, reactor configuration, operating conditions, syngas composition, cold gas efficiency, tar formation, and ash-related operational challenges, reducing the analysis to 288 manuscripts. The gray literature was also searched to gather information regarding commercial technologies.

3. Biomass Characterization

The chemical composition of biomass is critical for assessing and optimizing its energy potential, improving fuel quality, process efficiency, and reducing emissions [19–21]. Although thermochemical processes like gasification resemble coal conversion, biomass generally has lower density, higher volatile matter and alkali content, and reduced sulfur levels, all of which influence particle behavior and gasifier operating conditions [22]. Accurate characterization provides essential data for heat and mass transfer, as well as for the modeling and simulation of thermochemical conversion [23]. Unlike fossil fuels, biomass

exhibits significant variability, making characterization vital for predicting reaction pathways and operational challenges [18]. Key properties such as moisture, ash, alkali content, and particle size directly affect the process efficiency. Proper characterization enables better emission control and minimizes waste management requirements [20,24].

Chemical energy is stored in cellulose, hemicellulose, and lignin in plants, with proportions varying by species [18]. Ultimate analysis determines the elemental composition—carbon, hydrogen, nitrogen, sulfur, and oxygen—providing essential data for estimating higher- and lower-heating values (HHV/LHV), which are critical for modeling thermochemical processes [25]. For example, the hydrogen-to-carbon ratio strongly influences the pyrolysis products. Hemicellulose, cellulose, and lignin decompose at different temperature ranges, and their distinct thermal behaviors affect the overall yield during high-temperature breakdown [26]. Several correlations have been proposed to estimate HHVs from elemental composition, some of which are listed in Table 1.

Table 1. Correlations reported in the literature for estimating HHVs from elemental and proximate analysis.

HHV Correlations	References
HHV (MJ/kg) = 0.3491 C + 1.1783 H + 0.1005 S − 0.1034 O − 0.0151 N − 0.0211 Ash	[25]
HHV (kJ/kg) = 35,430 − 183.5 VM [1] − 354.3 Ash	[27]
HHV (kJ/kg) = 1.87 C^2 − 144 C − 2820 H + 63.8 C H + 129 N + 20,147 HHV (kJ/kg) = 5.22 C^2 − 319 C − 1647 H + 38.6 C H + 133 N + 21,028 Average model for plant biomass: HHV (kJ/kg) = 3.55 C^2 − 232 C − 2230 H + 51.2 C H + 131 N + 20,600	[28]
HHV (MJ/kg) = 0.3536 FC [2] + 0.1559 VM − 0.0078 Ash	[29]
HHV (MJ/kg) = 19.914 − 0.2324 Ash HHV (MJ/kg) = −1.3675 + 0.3137 C + 0.7009 H + 0.0318 O	[30]

[1] VM: volatile matter. [2] FC: fixed carbon.

3.1. Volatiles

There is an evident relation between gasification performance and biomass properties. Some studies have reported a positive influence of volatile matter and biomass HHV on the carbon monoxide (CO) content of syngas and therefore on the energy density of the combustible gas fraction [31,32]. A high content in volatiles translates into the formation of a large number of gaseous species and light tars produced during the process, which impacts the reactor's design and operating conditions. The application of biomass pretreatments such as drying is necessary in many cases to reduce moisture levels, milling to obtain a predefined particle size, and operations intended to reduce the nitrogen and alkali content of biomass such as fractionation and leaching [33].

The primary components of syngas are CO, carbon dioxide (CO_2), hydrogen (H_2), methane (CH_4), and water. When air is used as the gasifying agent, a significant portion of the syngas consists of nitrogen (N_2), resulting in a substantial decrease in the energetic density. Syngas also contains a small number of volatile organics (short-chain hydrocarbons) with a varying chemical composition, which is particularly dependent on the gasifier heating conditions and the type of biomass used as raw material. The most common compounds include C2–C4 species, acids, aldehydes, phenols, and tars. The proportion of volatiles in the raw material relative to its fixed carbon content provides a preliminary indication of biomass behavior during the heating stage and thus of the fate of subsequent reactions. Feedstocks with a high volatile matter content (e.g., grasses) will be strongly affected by the performance of simultaneous pyrolysis/gasification reactions, leading to syngas with a higher energy density due to their higher CO and methane composition [34,35].

Therefore, proximate analysis is essential for explaining product distribution during the thermochemical process [26].

3.2. Moisture

High moisture levels negatively impact performance by increasing the tendency for heavy tar formation and deposition in the gasifier [36]. However, water content in biomass can enhance H_2 production, with optimal performance heavily reliant on the gasification temperature. To prevent significant declines in syngas quality and gasification efficiency, Dong et al. [37] indicated that a moisture content of 20–25% is ideal for municipal solid waste (MSW) gasification.

Tar is a specific component within volatile matter, composed of organic compounds that condense at low temperatures, therefore generating operating problems due to blockages and the failure of downstream processing pipes and connections. Biomass with high lignin content, such as wood, produces more tars, since lignin phenolic components are a major source for forming heavy, polycyclic aromatic hydrocarbons (PAHs) [38,39]. In addition, the tar composition is not fixed; it evolves under specific temperature and reaction conditions [40], with the gasification configuration and operating parameters being highly relevant to the main components and yield obtained.

While most gasification research emphasizes the chemical composition of feedstock and its impact on gasification efficiency and tar production, the feedstock's physical characteristics and dynamic behavior within the reactor also significantly influence tar formation. Littlejohns et al. [41] reported that the relationship between biomass characteristics and tar formation is unique, and understanding this particular feature can facilitate the development of reliable gasifier systems by adapting process configuration and operation to predefined biomass physical and chemical properties. The development of new analytical procedures for measuring individual tar compounds is important for controlling operational parameters and monitoring emissions in full-scale plants, as several tar components have a strong environmental impact due to their mutagenic and carcinogenic properties [42]. Tar reduction technologies typically use thermal and catalytic cracking, along with cyclones and wet or dry-cleaning systems [43,44].

3.3. Ash

Ash is an inherent component of biomass. Waste biomass, such as agronomic waste, manure, and sewage sludge, typically has a higher ash content, resulting in a lower energy density of the raw material. The ash chemical composition of solid fuels is typically expressed in terms of the following elements: silicon (Si), aluminum (Al), iron (Fe), calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), titanium (Ti), sulfur (S), and phosphorus (P). Wood biomass usually contains relatively low amounts of nitrogen (N), S, and chlorine (Cl), and is characterized by having a low ash content [45,46].

The mineral components of biomass are not eliminated during thermochemical conversion. Instead, they remain as the ash by-product produced in gasification or become part of the char material during pyrolysis. Additionally, biomass may contain salts, organically bound compounds, and other foreign materials such as soil and sand [47]. The high levels of ash in residual biomass pose a major operational problem for gasifiers, leading to fouling, ash sintering, corrosion, reduced process efficiency, and even occasional plant shutdowns. Consequently, a fundamental contradiction emerges between the intended use of gasification for waste valorization and the technological limitations imposed by ash-related complications.

The low melting point of biomass ash is primarily due to the presence of alkali-alkaline metals such as K, Ca, and Mg. Therefore, determining the composition of ash materials

is essential for establishing the trend of eutectic formation along with considering the operating characteristics of a specific gasification system [48]. Additionally, ash deposition on gasifier walls is influenced by the characteristics of the ash itself. Alkali metals can contribute to fouling when they combine with silica and alumina, forming low-melting-point eutectic compounds. The high temperature and flow regime in the gasifier would favor the melting behavior of ash in the first case, and the dissipation of momentum and particle impact with gasifier walls would favor the deposition of particles in the second case [49,50]. The most critical role of characterization is predicting ash behavior and preventing slagging or agglomerations. Nevertheless, the presence of alkali metals does not always bring negative features. Potassium compounds (such as K_2SO_4 and K_2CO_3) have demonstrated to enhance the catalytic reduction of tar [51]. The addition of ash containing alkali metals, Fe, zinc (Zn), and Al has improved catalytic performance during the thermal conversion of waste biomass. This enhancement is crucial for increasing the quality of syngas, especially when the interaction between the gas phase and the catalytic ash-containing bed is optimized [52,53].

3.4. Biomass Physical and Chemical Characteristics

Biomass feedstocks with similar bulk characteristics can behave differently during gasification and produce distinct solid products, as both reactor configuration and operating parameters influence performance. The physical properties and chemical composition of biomass are crucial to the efficient operation of the process. Biomass properties can profoundly affect the design of the feeding mechanism and the reactor geometry and thus its final performance [22]. A complete characterization of biomass enables efficient blending of feedstocks and determines whether pre-processing, such as leaching and torrefaction, is needed to mitigate undesirable outcomes. Biomass properties indicate how feedstock can be modified using these processes to enhance its suitability for gasification. For example, biomass washing reduces levels of K and Cl [54]. Torrefaction improves feedstock properties by reducing its O/C ratio and moisture content, increasing energy density and grindability, and favoring the process by producing a higher-quality syngas and increasing cold gas efficiency (CGE) [55,56]. Torrefaction of biomass enhances its properties, making handling and storage easier. Additionally, reducing biomass volume significantly improves economic efficiency by lowering transport costs. Results from the economic evaluation of various scenarios showed improved overall process performance when torrefaction was included as a pre-treatment stage. This improvement was attributed to the higher energy content of the resulting syngas, enhancements in the logistics chain, and better gasification performance [57]. When assessing the benefits of integrating a torrefaction stage, many advantages are claimed, such as those described in detail by Lu et al. [58], focusing on operating performance and syngas composition, but these claims often overlook the additional energy required for torrefaction as a pretreatment stage. Global energy efficiency is likely to increase only when the torrefaction stage is fully integrated within the gasification plant or when the use of heat recovery units is feasible. In contrast, incorporating an external torrefaction stage generally results in a decline in overall efficiency [59,60].

The significant variability in the physical and chemical properties of biomass makes it difficult to standardize energy production methods compared to fossil fuels. Table 2 presents the different biomass types and their main characteristics.

Table 2. Biomass proximate and ultimate analysis. Data reported by different authors in scientific literature.

Biomass	Moisture (%)	Proximate Analysis (%)			LHV (MJ/kg)	HHV (MJ/kg)	Ultimate Analysis (%)					Refence
		VM	Ash	FC			C	H	N	O	S	
Salix Taxa	7.48 ± 1.26	74.84 ± 0.94	2.8 ± 0.62	20.31 ± 0.68	17.76 ± 0.44	19.35 ± 0.33	49.97 ± 0.78	5.76 ± 0.32			0.05 ± 0.01	[61]
Black locust		80.94	0.8	18.26		19.71	50.73	5.71	0.57	41.93	0.01	[62]
SRC Willow Chips	2.9	82.5	1.7	12.9	4.4 [1]		45.4	5.7	0.8	48	0.1	[63]
Eucalyptus Urosemente	12.40	59.36	11.28	16.96			53.24	6.36	0.12	40.14	0.14	[64]
Pine Trunk	11.5	83.7	0.8	15.5			47.3	6.4	0.13	45.18	0.99	[23]
Eucalyptus (Bark)	3.4	89.6	4.2	6.2	13.8	15.2	43.10	6.46	0.25	50.18	0.01	[23]
Eucalyptus (Trunk)	2.1	88.9	1.0	10.1	16.0	17.6	47.20	7.03	0.11	45.65	0.01	[23]
Eucalyptus (Branches)	6.7	82.9	3.2	13.9	20.7	22.3	55.90	7.55	1.44	35.10	0.01	[23]
Pine Cone		73.98	2.61	23.41			43.99	3.65	1.67	50.18	0.51	[65]
Poplar		82.21 ± 0.32	1.29 ± 0.04	16.5 ± 0.317	16.94 ± 0.37	18.61 ± 0.55	44.15 ± 1.04	3.92 ± 0.23	0.642 ± 0.3			[66]
Hardwood, Chestnut		74.2	0.7	25.1		18.44	49.74	5.28	0.19	44.45		[67]
Wood Pellet	3.00 ± 0.15	62.50 ± 4.72	1.50 ± 0.37	18.1 ± 0.52		18.31	49.18	6.81	0.19	40.74	0.08	[68]
Western red cedar (WRC)		93.35 ± 0.51	0.45 ± 0.05	6.20 ± 0.32		19.68 ± 0.20	49.35 ± 0.61	6.02 ± 0.05	<0.5%	44.64 ± 0.66	<0.5%	[69]
Forest wood/Gua Zumaumlifolia (Northern Colombia)	7.99	80.92	1.8	17.28	16.82 ± 0.91		49.1 ± 0.7	5.8 ± 0.2	ND	45.1 ± 0.5		[70]
Forest wood Cordia alliodora (Northern Colombia)	7.41	81.75	1.53	16.72	18.16 ± 3.8		49.2 ± 0.2	5.8 ± 0.1	ND	45.1 ± 0.1		[70]
Forest wood Eucalyptus Grandis (Central Colombia)	10.28	81.66	1.17	17.17	17.80 ± 0.9		51.0 ± 0.2	6.1 ± 0.1	ND	42.9 ± 0.3		[70]
Firewood Pinus Patula (Southern Colombia)	8.55	84.11	0.4	15.49	17.64 ± 1.43		47.2 ± 0.6	6.2 ± 0.1	0.3 ± 0.01	46.3 ± 0.4		[70]
Sugarcane Bagasse		81.86 ± 1.01	2.04 ± 0.01	15.98 ± 0.32		16.79 ± 0.04	42.09 ± 0.21	5.42 ± 0.08	0.18 ± 0.04	51.50 ± 0.33	0.12 ± 0.01	[71]
Tobacco	1.9–5.4	61.9–68.0	15.9–18.1	9.9–16.0			35.8–42.5	5.4–6.2	2.6			[72]
Eucalyptus globulus	5.51	77.13	0.51	16.85		19.38	47.76	6.32	0.09	45.77	0.05	[73]
Sawdust	7.0	70.0	2.3	20.7		18.2	46.23	6.14	2.2	45.42	<0.01	[74]
Firewood Sawdust	12.18	74.69	0.42	12.71		17.7	45.51	5.83	0.001	48.66		[75]
dewatered poultry sludge		67.50	25.09	7.41			51.13	7.67	4.24	11.53	0.34	[76]
Chicken Manure		70.35 ± 0.23	21.12 ± 0.47	8.53 ± 0.38		15.55	37.46 ± 1.19	5.22 ± 0.12	8.28 ± 0.23	26.00 ± 2.31	1.92 ± 0.09	[77]
Swine Manure		77.70 ± 0.47	7.13 ± 0.39	15.17 ± 0.67		12.92 ± 0.08	33.52	6.17	2.8	56.69	0.82	[78]
Cattle Manure	18	49	26	7		10.4	33.7	4.91	3.07	58.31	<0.01	[74]
Goat Manure	37.7 ± 0.3	52.8 ± 0.4	10.0 ± 0				43.9 ± 0.3	1.5 ± 0.2	2.8 ± 0.1	51.3 ± 0.2	0.6 ± 0	[79]
Raw Poultry Manure	16.69 ± 0.04	36.34 ± 0.18	51.35 ± 0.38	11.99 ± 0.05			25.56 ± 1.39	3.27 ± 0.79	2.19 ± 0.17	69.35 ± 2.43	0.69 ± 0.17	[80]
Chicken Manure (cage)	70.9	67.5	15.6	16.9	12.744		39.67	4.72	5.49	34.12	0.4	[81]
Chicken Manure (Litter)	18.1	69.9	12	18.1	16.55		42.86	5.57	5.50	33.39	0.68	[81]
Chicken Manure (Free-range)	54.9	50.4	44.4	5.2	8.58		21.85	2.50	1.73	29.24	0.28	[81]
Yak Manure	7.64	51.78	27.27	13.31		13.37	33.24	4.29	1.82	30.90	0.22	[82]
Pig Manure	71.99 ± 9.65	66.12 ± 9.08	24.18 ± 11.14	10.54 ± 3.83			37.74 ± 6.43	5.62 ± 1.00	2.79 ± 0.71	28.90 ± 5.68	0.63 ± 0.30	[83]
Dairy Manure	75.59 ± 9.22	60.60 ± 12.55	28.20 ± 16.2	11.73 ± 4.54			34.42 ± 8.96	4.91 ± 1.39	1.92 ± 0.50	30.44 ± 8.54	0.65 ± 0.41	[83]
Beef Manure	75.66 ± 7.82	64.58 ± 8.14	22.64 ± 11.88	13.73 ± 4.05			37.64 ± 6.16	5.26 ± 1.12	2.16 ± 0.64	31.90 ± 6.81	0.59 ± 0.28	[83]
Layer Manure	72.26 ± 9.95	62.56 ± 7.09	32.44 ± 9.80	6.48 ± 6.51			33.02 ± 6.18	4.81 ± 1.14	3.39 ± 1.25	25.74 ± 6.95	0.81 ± 0.39	[83]
Broiler Manure	63.88 ± 8.79	62.47 ± 11.02	27.76 ± 13.56	10.45 ± 5.90			33.62 ± 8.83	5.06 ± 1.94	3.70 ± 1.26	30.75 ± 7.29	0.89 ± 0.55	[83]

[1] Value reported is much lower than estimated from elemental analysis-based equations.

Grippi et al. [20] indicated that some feedstock characteristics may better accommodate to some specific bioenergy production methods. Direct combustion requires biomass with low moisture (<10–12%) and ash content, but high lignin concentration. In contrast, anaerobic digestion is better suited for feedstock rich in readily biodegradable organics, with high moisture levels and low lignin content. For ethanol production, materials with a high carbohydrate content are preferable. If biological treatment of lignocelluloses is considered, pretreatment is necessary to release fermentable sugars from cellulose and remove lignin. Therefore, materials with low lignin content are preferred. Similarly, gasification and pyrolysis benefit from biomass with moderate lignin levels and low ash content, which facilitates effective syngas production and reduces ash accumulation.

Multiple studies have shown that blending unconventional biomass with conventional fuels—such as wood, coal, or petroleum coke—can improve gasification performance. These mixtures help reduce the drawbacks associated with high-alkali, high-ash biomass and mitigate logistical challenges related to seasonal feedstock availability and long-distance transport in large-scale gasification systems [84–86]. Unlike biomass combustion, where mixing different feedstocks can greatly affect performance due to the differences in burning profiles and ignition temperatures [87], gasification allows for easier control by adjusting parameters such as temperature and the biomass-to-air ratio [88]. As a result, incorporating diverse waste streams throughout the year can enhance operational flexibility, helping the plant adapt to fluctuations in biomass price, availability, and regional supply conditions.

4. Biomass Conversion Following Different Energy Pathways

Biomass can be converted into energy carriers through several biological, physicochemical, and thermochemical pathways. Understanding these conversion routes is crucial to unleashing the energy potential of biomass resources. Figure 1 illustrates the main biomass valorization pathways. Among these alternatives, thermochemical conversion processes have demonstrated great flexibility and the ability to process heterogeneous biomass resources.

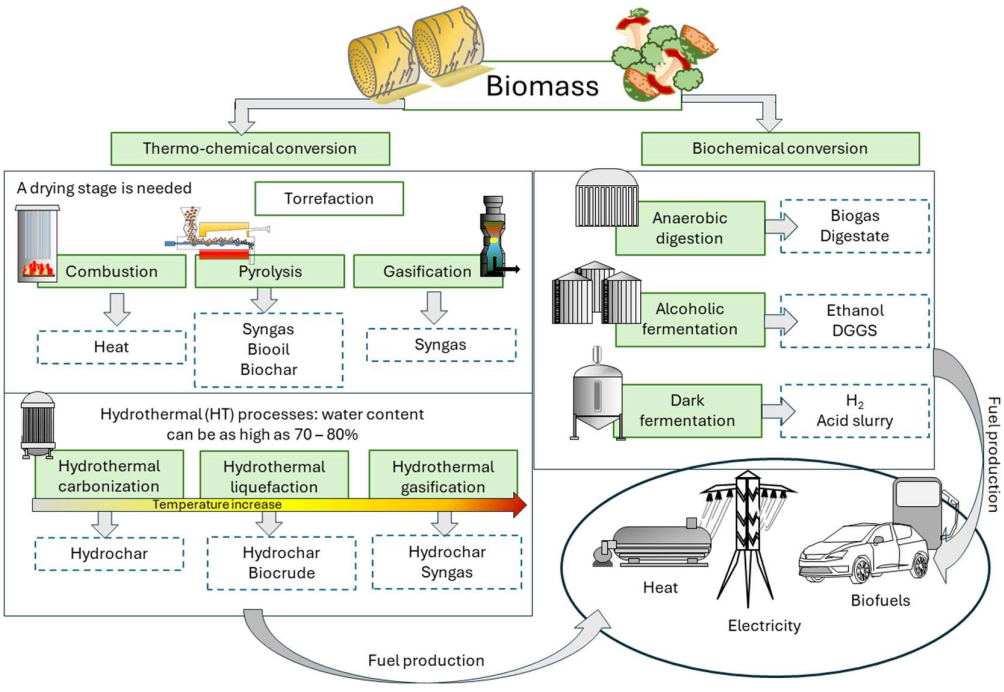


Figure 1. Schematic representation of biomass to energy conversion pathways.

4.1. Main Biological Conversion Pathways for Fuel Production

The main processes in biomass biochemical conversion are anaerobic digestion and alcoholic fermentation. The biomass used as a feedstock in the first case is usually agricultural or crop residues, energy crops and organic waste, such as municipal solid waste, sewage sludge, and animal manure [89,90]. Biogas is obtained as the primary product with a methane content of 50% to 65%, and CO_2 as the second prevalent component, in addition to small quantities of ammonia, water, H_2, hydrogen sulfide (H_2S), and air traces [91]. A digestate slurry is an end-product generated from the anaerobic digestion process. In the context of sewage sludge, this by-product is commonly referred to as biosolids. Due to its high nutrient content, agronomic land application represents an optimal opportunity. The land spreading of biosolids can significantly enhance crop yields and improve soil organic matter, thereby promoting sustainable agricultural practices [92].

Alcoholic fermentation for ethanol production is widely used due to its compatibility with gasoline and the high yields achieved. Butanol production via fermentation is another well-known process that shows high compatibility with petrol fuels, but the microbes' lower tolerance significantly reduces yields [93]. Biomass with a high carbohydrate content, such as sugarcane, beetroot, and cereals, is a common raw material. The yeast *Saccharomyces cerevisiae* is the most widely used organism for industrial ethanol production. However, limitations associated with ethanol tolerance and the accumulation of toxic/inhibitory compounds during lignocellulosic pretreatments, which reduce titers in the fermentation stage, remain a challenge [94]. Enzymatic hydrolysis is an effective way to widen the availability of raw materials suitable for fermentation. Nevertheless, many enzymes are expensive, and some pretreatments, such as thermal, wet oxidation, and alkali treatment, are known to release inhibitors, thus reducing overall process performance [95].

Several companies have attempted to develop industrial processes for fermenting lignocellulosic materials, with research focusing on sugar release and avoiding the formation of inhibitors during pretreatment. This extensive activity has given rise to the biorefinery concept, in which several transformations are coupled in a manner similar to a petroleum refinery, yielding a portfolio of valuable products or building-block components with applications in different industrial processes. Despite huge efforts, the deployment of this technological approach has been slow due to difficulties in achieving economic feasibility. The Borregaard plant (Sparsborg, Norway) is one of the few successful cases. The plant produces ethanol from woody biomass and high-value specialty products, including vanillin, high-quality lignin, and high-purity microfibrillated cellulose [96,97].

4.2. Physical-Chemical Conversion for Biodiesel Production

Biomass resources can also be converted into liquid fuels through physicochemical processes such as transesterification and hydrotreatment. The material is initially submitted to oil extraction procedures and subsequently to a chemical reaction to obtain ester compounds compatible with diesel fuels via transesterification, or to a hydrotreatment process, in which a renewable fuel is obtained that is fully compatible with current diesel and jet engines [98,99]. Lipid-rich vegetable oils, such as canola, sunflower, palm, and soybean, are commonly used for biodiesel production. However, the focus is on non-food crops to avoid distortions in market prices and disruptions in the distribution chain, as in alcoholic fermentation, where lignocellulosic biomass is considered a replacement for traditional rich carbohydrate feedstocks to avoid adverse effects on the food production chain. Algal biomass is a promising candidate to replace some of the current raw materials used in the renewable energy sector. However, high production costs are continuously delaying the expected production of third-generation biofuels [100].

4.3. Thermochemical Conversions for Fuel Production

Thermochemical conversions are more efficient and faster than biochemical processes, with the added advantage of handling a broad range of biomass types and producing various energy products [101,102]. Biomass typically exhibits lower energy density and higher oxygen content than fossil fuels [15]. Therefore, any practical application of this raw material requires an increase in energy density [103]. The end products from thermal processes are categorized into volatile (gases, vapor, and tar) and non-volatile (char and residual ash) [104]. The thermochemical conversion processes are influenced by the biomass feedstock type, elemental composition, and calorific value, as well as by process operating conditions. These conditions are considered determinants of product quality [105]. The different available thermochemical technologies for transforming biomass into energetic products include:

- Combustion: It is an ancient and widely used process that burns biomass in the presence of oxygen to release heat, which can be directly used in domestic and industrial processes, for generating steam to cover heat demand or to produce electricity [106].
- Torrefaction: It is usually classified as a type of pyrolysis process. However, this treatment aims to increase biomass energy density to facilitate transport and handling operations in subsequent processes. During this treatment, moisture content is reduced and grindability is enhanced [107,108].
- Pyrolysis: biomass is converted at high temperatures (300 and 1000 °C) in an oxygen-free environment, producing three main products: syngas, bio-oil, and biochar [109,110]. The heating rate and temperature greatly influence the product yield. Table 3 shows different pyrolysis processes classified by the heating rate and process temperature.

Table 3. Classification of pyrolysis processes based on the heating rate applied.

Pyrolysis Process	Heating Rate (°C/s)	Temperature Range (°C)	Residence Time		Particle Size (mm)	Reference
			Vapor Residence Time (s)	Solid Residence Time		
Slow	0.1–1.0	300–950	330–550	5.5–9.2 min	5–50	[111,112]
Intermediate	1–10	400–500	10–30	0.7–0.5 min	0.3–0.75	[113,114]
Fast	10–200	Up to 1000	≤5	<0.5–10 s	≤1	[111,112,115]
Flash	13,000–21,000	900–1200		0.5–0.025	0.1	[116,117]

- Gasification: The process converts biomass into syngas through partial oxidation. Syngas is a mixture of CO, H_2, and CH_4 that can be used to generate electricity or as a raw material for subsequent chemical processes to produce liquid fuels [109,118]. Gasification offers a competitive technical alternative to combustion. The combustion of syngas is cleaner than the direct combustion of biomass, reducing the need for excess air and, consequently, heat losses. Besides, it ensures homogeneous combustion, enabling better process control. The volumetric flow rate is lower than that of the effluent gases in direct combustion, providing a cost-effective gas-cleaning process [119]. However, tar formation remains the major bottleneck to the commercialization of technology [120]. For this reason, recent studies are focusing on the addition of catalysts to reduce the operational problems associated with tar [121,122].
- Hydrothermal processes: The technology involves the thermal cracking of biomass in the presence of water and below the critical point. Under high temperature and pressure, hydroxyl ions enable the degradation of organics, similarly to conventional thermal processes, but with the added advantage of avoiding a prior drying stage of the material, thereby reducing the energy demand [123]. The process can be classified by temperature range: hydrothermal carbonization is limited to temperatures below

260–280 °C, while higher temperatures, close to the critical point (374 °C), encompass hydrothermal liquefaction, where the main product of interest is a biocrude. In contrast, at lower temperatures, hydrochar is the main product. At temperatures above the critical point, the process is called hydrothermal gasification, and as its name suggests, syngas is the main product. Hydrothermal processes may also involve an additional category associated with oxidation or organic matter (wet oxidation) under conditions below or around the critical point [124]. The addition of an oxidant (air or oxygen) significantly favors the conversion of organics into small molecules. When the process is carried out at temperatures above the critical point, it is known as supercritical water gasification [125]. Table 4 is a comparison list of the different thermochemical processes for biomass valorization.

Table 4. Comparison of thermochemical technologies for valorizing biomass.

Process	Main Characteristics	Temperature Range (°C)	Applications	Advantages	Disadvantages
Combustion	Oxidation atmosphere based on the presence of O_2.	Commonly between 1000–1500 °C with higher or lower values depending on the air/O_2 ratio.	Industrial and domestic sectors for producing heat and power. Transport sector and power generation. It is the most widely applied technology capable of adapting to gaseous, liquid and solid fuels.	Wide experience in technology development and versatility in applications.	Emission control increases operational costs
Pyrolysis	Thermal degradation takes place under inert atmospheres.	Wide operational range based on the type of process: torrefaction, slow, fast or flash pyrolysis (300–1200 °C).	Slow pyrolysis is at a mature stage, but the other pyrolysis processes still face challenges in by-product treatment and process efficiency.	High flexibility in the conversion of biomass and waste into valuable biofuels and char.	High operational costs and low-quality products, which may not comply with environmental regulations. Costly treatment of by-products
Gasification	Partial oxidation conditions produce the heat needed for thermal degradation.	600–1200 °C. The temperature range depends on the ER applied and constraints associated with feedstock characteristics.	High development in coal and petroleum slurries gasification. Biomass gasification for producing heat and electricity is a mature technology. Other applications including waste valorization and decentralized small-scale biomass gasification are still under research and improvement.	High flexibility in transforming different raw materials. Production of syngas as a valuable fuel or building block for other processes.	High operational costs. Tar formation control and removal are still a bottleneck
Hydrothermal processes	Water-based technology. Oxidation of organics is mainly based on water reactivity (ionic and free radical reactions).	200–600 °C. The temperature range is used to classify processes into hydrothermal carbonization, liquefaction and gasification.	Technology is still under development. Hydrothermal carbonization is closer to commercial scale. More severe treatments still need to face several challenges associated with material corrosion and stress.	Lower thermal demand since the raw material does not require drying. Valuable products are similar to those obtained from pyrolysis.	High installation and operational costs. Treatment of hydrothermal process water is a significant challenge. Biocrude upgrading is still in its infancy.

5. Biomass Gasification: Process Stages

Biomass used as a raw material has a high moisture content, ranging from 30% to 60% in freshly cut wood [126]. However, some materials, such as algae biomass can exceed 90% [127]; thus, a pre-treatment stage is crucial to ensure adequate water levels, especially in cases when producing high-energy-density fuel gases, where the moisture content must be kept below 20% [128]. Biomass moisture levels below 15% are considered optimal for

gasification [103], but in some cases, achieving these low levels may increase the process's overall energy demand. The initial stage of gasification involves drying the remaining water in biomass (Figure 2). To vaporize this water, the minimum energy requirement is about 2242 kJ/kg, which is added to the energy needed to keep gasification running [129]. As the temperature increases to 150 °C, energy is used to heat the biomass and to drive the phase change of the residual water. Although high moisture levels adversely affect the energy balance due to the enthalpy required to generate steam, the steam may favor the process up to a certain point, as its presence increases H_2 production [130]. However, excessive moisture content (above 30–40%) may increase tar formation, thereby reducing process efficiency [131].

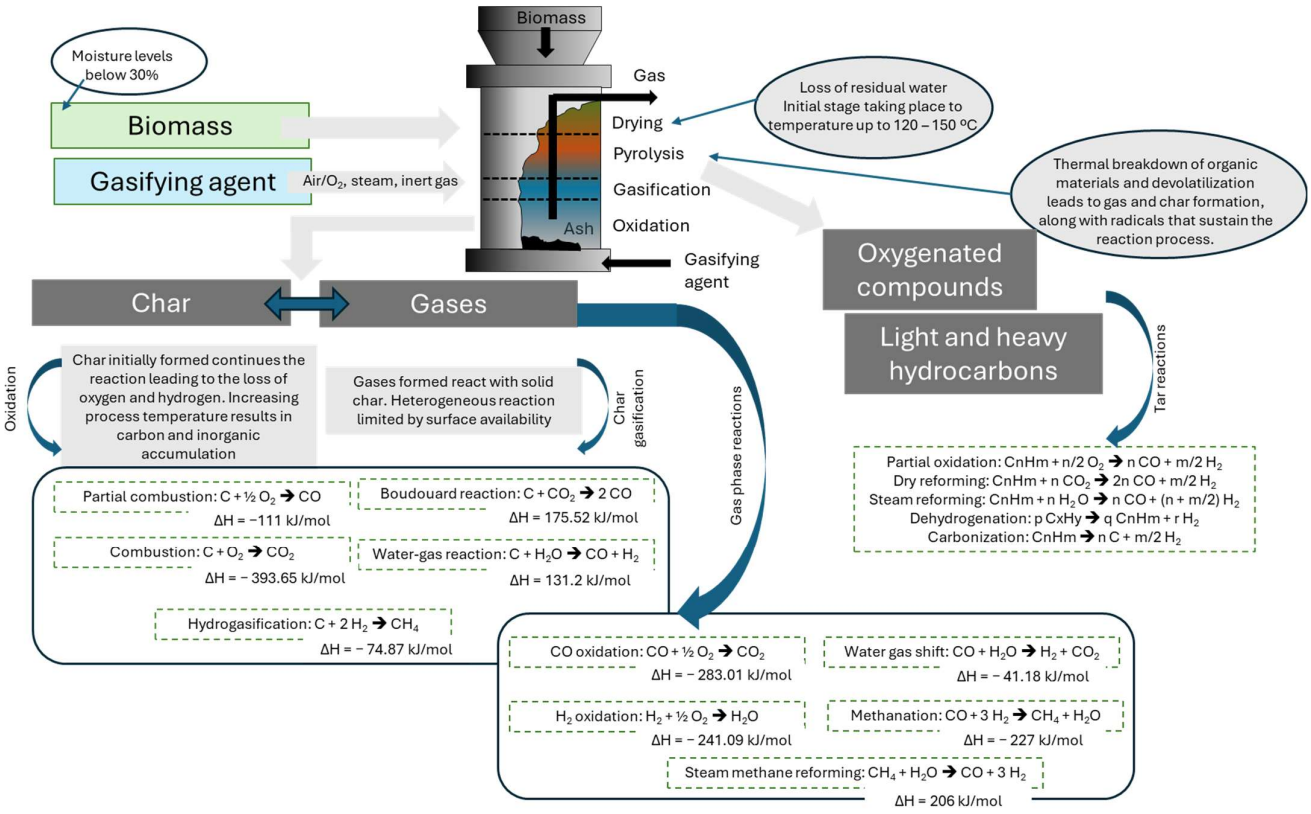


Figure 2. Schematic representation of biomass gasification describing process stages.

The second stage involves the thermal decomposition of biomass, called pyrolysis. During this stage, biomass undergoes thermal cracking in the absence of oxygen, leading to devolatilization and the formation of char. Devolatilization starts around 300 °C, and char formation is favored around 400 °C and 500 °C. Huang et al. [132] demonstrated that biomass containing hemicellulose may undergo early pyrolysis at temperatures between 150 and 250 °C. This material decomposes at a slow kinetic rate, producing light hydrocarbons. At higher temperatures, thermal degradation continues at much higher rates, and biomass is rapidly pyrolyzed, producing mainly char and gaseous components (CO, CO_2, H_2, and light hydrocarbons) [133,134]. Partial oxidation reactions play a key role in providing the heat required to sustain the gasification process. The conversion of carbon into carbon monoxide ($\Delta H = -268$ MJ/kg) and into carbon dioxide ($\Delta H = -406$ MJ/kg) releases heat, which is used for thermal cracking of long-chain molecules and for sustaining reactions involving water [33]. In the third stage, gas-solid reactions are the main feature. Char reacts slowly with surrounding gases, such as oxygen, water vapor, and carbon dioxide, via the Boudouard and water–gas shift reactions. Water-gas reactions produce hydrogen [34], thereby increasing syngas energy content and explaining the ongoing research

interest in adding steam as part of the gasification agent. In this final stage, volatile gases, tar, and other products are further refined, thus defining the final gas composition.

An additional stage of tar reforming should be included in the process description, as its commercialization would not be feasible without accounting for syngas cleaning and tar reduction. The subsequent valorization of syngas requires the removal of tar which is usually performed by physical removal, thermal or catalytic cracking, but these processes require an additional stage for treating residual streams from the cleaning process or adversely affect the energy efficiency and operational costs either due to the extra fuel needed for affording high temperatures or due to the costs associated with catalytic reactions [135]. Tar formation depends on operating conditions, gasifier design and biomass composition. Yu et al. [136] studied the formation of tar based on main biomass components: cellulose, hemicellulose and lignin, describing a sequence of reactions based on phenol, phenol derivatives, the formation of compounds known as BTEX (Benzene, toluene, ethylbenzene and xylene isomers), and miscellaneous hydrocarbons ending up forming polycyclic aromatic hydrocarbons (PAHs). Due to its specific molecular composition, lignin is considered the main precursor in tar formation [39]. The increase in water content alters operating temperature, decreasing phenol concentration and increasing toluene and indene, leading to heavy tar formation [36].

6. Factors Influencing Biomass Gasification

Several factors affect the efficiency of the gasification process and the quality of syngas, including feedstock characteristics, reactor configuration, operating conditions, and the gasifying agent [137,138]. Grasping the intricate relationships among these parameters and their impact on syngas quality and overall process performance is essential to developing a profitable operation. This operation must possess a high degree of flexibility, allowing it to adjust to varying scales that depend on the availability of raw materials and the geographical constraints that may arise. By understanding these dynamics, new systems can be developed that not only optimize efficiency but also may be easily adapted to the specific conditions of each unique environment.

6.1. Feedstock Characteristics

One important factor influencing syngas production is the ratio of holocellulose (cellulose and hemicellulose) to lignin [131]. A high cellulose content increases syngas production but also has a detrimental effect because it tends to produce light tars at high heating rates [139]. The lignin content in biomass increases the energetic density of the material due to its HHV compared to cellulose/hemicellulose components (around 25–27 MJ/kg for lignin against 17 MJ/kg for holocellulosic components (cellulose and hemicellulose)). However, it enhances the kinetics of heavy-tar formation [140]. A positive correlation exists between biomass volatile matter, carbon content, calorific value, and the energy yield derived from the process, resulting in better performance when torrefied biomass is used directly as an input material [34].

Physical characteristics are also important, as they determine the design of the feeding equipment, the best configuration of the gasifier, and the retention time needed to complete the reaction. Low-bulk-density biomass (<200 kg/m^3) formed by small particles is not suitable for a fixed-bed system, where channeling of syngas flow and bed bridging may occur, leading to uneven flow and contact between the solid and gas phases [41]. The lack of bed homogeneity reduces CGE and increases tar concentration in syngas. On the contrary, the use of biomass in the form of pellets is more suitable for a fixed bed system since it reduces bed agglomeration. In bubbling fluidized bed gasifiers, pellets are preferred since they are a homogeneous high-density material, which allows for keeping appropriate

control of bed distribution based on the difference in bulk pellet and hot bed density; thus, the control of the residence time of biomass and air flow is achieved by modifying superficial fluid velocity [141].

6.1.1. Particle Size

Particle size can significantly influence the efficiency of biomass gasification and the quality of syngas [142]. According to Siddiqui et al. [143], smaller particles have a larger surface area per unit volume, leading to better heat transfer and more efficient reactions. The composition of syngas is also affected by particle size. Smaller particles enhance the production of higher levels of H_2 and CO, obtaining better conversion efficiencies [144]. Shorter residence times are required when using a feed with small particles, as in entrained-flow gasifiers, where reactions must be completed in a few seconds. The quality of the produced syngas is affected by this phenomenon, as smaller particles require shorter chemical times, reducing tar formation and allowing full conversion of organics [145]. In contrast, larger particles tend to produce syngas with higher CH_4 concentrations, but at short residence times, this can lead to incomplete reactions [142,143]. Therefore, reactor type and operation mode influence the suitable particle size of the feed, with entrained reactors operating with smaller particles (smaller than 0.5–0.1 mm) [146], whereas fixed and bubbling bed reactors require a higher particle size [147,148].

6.1.2. Moisture Content

Moisture has an adverse impact on energy efficiency because it reduces global performance, as it requires extra energy addition for the water phase change, thus lowering the gasification temperature, affecting reaction kinetics, syngas quality, and also causing incomplete reactions leading to higher tar formation, unless extra energy is supplied to increase process temperature to desired values [35,103]. High moisture levels in raw biomass can disrupt the overall gasification process and complicate particle size reduction, potentially requiring more energy to achieve a set size [149]. In addition, slagging and fouling can appear in the reactor, associated with high water content in the raw material, which may increase operational costs [137]. However, the water content of biomass may increase hydrogen and CO levels in syngas [150], which may benefit the energy balance up to a certain point [130]. There is a compromise between the equivalence ratio (ER) needed to increase the role of oxidation reactions and therefore the heat release required to maintain optimal gasification temperature (at a given moisture content), and the quality of syngas, since a higher air injection will increase the CO_2 and nitrogen levels in syngas. Plis and Wilk [151] tested different biomasses in a fixed-bed gasifier with varying moisture content. CO levels reported were higher for drier biomass, benefiting CGE. Increasing biomass moisture content in their experiments led to higher CO_2 evolution, resulting also in a significant decrease in CGE. Most gasification processes can tolerate moisture levels up to 30% without significantly impacting the energy balance [152]. However, some gasifiers, such as updraft, bubbling, and fluidized bed gasifiers, can tolerate water contents of 55–60% [153].

6.1.3. Inorganic Content

Ash particles in the raw material may partially melt and fuse together at high temperatures, forming larger agglomerates or clumps (sintering), depending on the ash composition [154]. Additionally, the presence of ash may have environmental impacts by releasing certain inorganic compounds, producing metal emissions that must be controlled to comply with environmental regulations [155]. Reactor design also plays an important role in controlling tar formation and is closely linked to the type of raw material treated [156].

Inorganic elements such as K, Ca, and Na can act as catalysts during gasification, thereby improving reaction rates and overall efficiency [157]. However, they may also cause

corrosion and fouling issues when operating at high temperatures. The presence of these metals favors H_2 production (particularly in the case of K) and influences the reactions of tar reforming and cracking [158,159], but these metals may also be released with syngas, forming part of the benzene, xylene, furfural, and naphthalene-based components [160]. K has a more pronounced effect on gasification than Ca, as K can volatilize and become a mobile species during char formation, thereby increasing gasification reactivity in solid–gas phase reactions [161]. Ma and coworkers [162,163] studied ash accumulation and agglomerate formation in a pressurized entrained-flow gasifier using bark-derived residues and peat. These authors reported that slag produced during the process contained quartz and feldspars in a silicate melt with layers of alkaline-earth metal silicates. Fly ash, on the other hand, was enriched in K.

Biomass pretreatment methods such as washing, leaching, and torrefaction can reduce or eliminate some inorganic content before gasification [157]. The use of hydrothermal carbonization (HTC) for removing chlorine from biomass has also been proposed, reporting a 90.5% removal [164]. However, the energetic efficiency of the process needs to be carefully evaluated, since the introduction of an HTC stage increases the capital investment costs and energy demand due to the heating of the entire biomass–water mixture, which can have a water content up to 70%, yet a drying stage is still needed to remove excess moisture from the hydrochar.

The selection of bed material may also improve the gasification performance and syngas composition. The use of dolomite in bubbling bed gasifiers has shown greater reactivity than olivine, thus producing 40% less tar [165]. This approach has been studied by Chiang et al. [166] using rice straw as the biomass, a material characterized by high ash and chlorine content. Their experiments using dolomite as a catalyst and a hot-gas cleaning system based on a packed tower containing zeolite, calcinated dolomite, and activated carbon resulted in almost total tar removal and high H_2S removal efficiency, but lower HCl removal (58.6%). However, olivine as a bed material offers the added advantage of interacting with the ash components, forming a coating layer that positively influences gasification reactions and prevents the accumulation of tar thanks to early steam reforming on the olivine particle surface [167,168].

6.1.4. Activation Energy

Activation energy (Ea) refers to the energy required for a reaction to take place. Ea is important for understanding process kinetics and rates [169]. A lower Ea value is associated with easier reaction initiation (lower temperature), leading to higher conversions under some established conditions [170]. Lower activation energies lead to the earlier thermal breakdown of biomass, triggering degradation and pyrolysis reactions in the initial section of the gasifier following the drying process. In contrast, higher Ea creates a greater temperature barrier to reaction initiation. When this occurs, and the reactor operates at lower temperatures, the slow reaction rate can result in decreased syngas yields. Therefore, biomass with a higher activation energy generally requires higher temperatures to start pyrolysis and effectively sustain subsequent oxidation and reforming reactions. If optimal conditions are not properly controlled, lowering the gasification temperature can prolong the reaction time and decrease the overall conversion efficiency [171]. The parameters that determine process efficiency are not only associated with syngas yield but also with the tendency toward tar formation and the effective breakdown of these complex compounds in the reactor, which consequently leads to higher maintenance costs [172].

The activation energy varies across components within the same biomass type, depending on their structure. For example, cellulose, hemicellulose, and lignin have different values of Ea, which affect their thermal behavior during gasification. Under the same

conditions, the gasification performance of the three main biomass components is entirely different, with cellulose showing the highest carbon conversion and lignin the lowest due to its high phenolic content, which favors tar evolution [136,173]. The kinetics of the pyrolysis of cellulose, hemicellulose, and lignin were studied by Zhu and Zhong [174]. Hemicellulose and lignin showed an early initiation of devolatilization, as evidenced by their lower Ea values; therefore, thermal degradation reactions initiate at an early stage, leading to the formation of volatiles in the case of cellulose and thermal cracking in the case of lignin. In contrast, cellulose showed a clear degradation peak between 240–350 °C and played a dominant role in the thermal performance of the biomass. Biomass with a higher cellulose fraction exhibits faster pyrolysis kinetics, thereby promoting greater volatile release [139].

6.2. Gasification Operating Conditions

6.2.1. Temperature

The temperature influences the process by increasing the reaction rate, improving the conversion efficiency, but it also affects the overall efficiency due to the higher energy demand. Excessive temperatures may cause stress on reactor structural components, leading to the cracking of gasifier internals, bulging, and stress rupture of the vessel shell [175]. Increasing air addition increases the amount of oxygen available for oxidation reactions, releasing more heat, but reduces the energetic content of syngas by raising the CO_2 levels and causing N_2 dilution. However, applying higher temperatures provides sufficient energy to overcome the reaction's Ea barrier, which results in faster biomass conversion [176], facilitating steam tar reforming reactions. Temperature affects the composition of syngas, including its quality and calorific value. Higher temperatures lead to the increased production of H_2 and CO [177,178]. However, this rise in temperature also lowers the energetic density of syngas because the reduction in CH_4 and other gaseous hydrocarbon species results in a decreased energy content per unit volume. Higher temperatures enhance tar cracking, thereby producing cleaner syngas [179,180]. Nevertheless, the gasification temperature is constrained by the biomass ash composition, leading to melting when alkaline metals are the main inorganics; this, in turn, results in slagging, clogging, and equipment damage [177].

6.2.2. Pressure

In general, increasing the pressure enhances the overall gas yield and biomass conversion efficiency [181]. Pressure can influence various aspects of the gasification process, including syngas composition, gas yield, reaction rates, and tar formation. Pressure affects the balance between CO and CO_2. Higher pressures can enhance the water–gas shift reaction, converting CO and H_2O into H_2 and CO_2 [182]. It also favors methanation by reducing gas volume, thereby promoting CH_4 formation. Therefore, a syngas with a higher calorific value and a lower H_2/CO ratio is obtained, making it less suitable for subsequent catalytic synthesis processes [176]. Syngas yields reported by different authors when operating under atmospheric conditions are usually in the range of 1.0–1.8 m^3/kg biomass [183–185]. Adding steam as part of the gasification agent increases this value to 2.5–3 m^3/kg biomass, thanks to the higher proportion of H_2 produced [144,186]. Increasing the operating pressure also affects the H_2 content of syngas, thereby increasing the volumetric yield [187].

When considering the operation of gasification-integrated systems, such as the gasification combined cycle (IGCC) and synthetic fuel production, the need for subsequent gas compression is reduced when the gasifier already operates at high pressure. This configuration also facilitates syngas cleaning and CO_2 separation, thereby enhancing overall process performance. Although the equipment installation costs increase [178], operating at

higher pressures provides an added benefit: a reduction in tar production [187]. Therefore, optimizing the gasification pressure is essential for maximizing process efficiency.

6.2.3. Equivalence Ratio

The equivalence ratio (ER) is one of the most influential parameters, directly affecting the process efficiency [188]. The ER is defined as the ratio of the air supplied per unit mass of biomass to the stoichiometric air required for complete combustion. When the ER increases, more air is introduced, resulting in increased oxidation and CO_2 formation [189]. The ER thus influences the operating temperature, the chemical reactions, and syngas quality. Low ER values (<0.2) result in incomplete biomass conversion and reduced gas yield, with increased tar formation [190,191]. The optimal ER ranges from 0.25 to 0.4 for most downdraft gasifiers, maximizing CO and H_2 yields and minimizing tar and char formation [192]. Other gasifier types have a similar operating range, with 0.3 being the most common value [193,194].

The ER also influences downstream applications. Increasing the ER within the optimal range enhances the cold gas efficiency. It stabilizes the syngas composition by increasing the H_2 and CO proportions relative to CH_4 and CO_2, which is crucial for applications such as Fischer–Tropsch synthesis or for applications that focus on favoring hydrogen production [192,195]. Consequently, ER optimization is necessary to achieve high process efficiency while producing syngas with a composition suitable for its intended end-use.

6.2.4. Residence Time

The residence time is the mean time a fluid volume spends in the reactor; therefore, this value depends on the reactor volume, the fluid circulation regime, and the incoming volumetric flow rate. The residence time is an important parameter because it sets the time that biomass particles are exposed to high temperatures. A successful gasification process thus depends on the interaction between the time required for an organic particle of a given size to complete the reaction and the time this particle spends in the reactor under the operating conditions established. According to Glushkov et al. [137], optimizing both the residence time and particle size can significantly affect the gasification efficiency and syngas quality. Other researchers have reported similar findings. For instance, Rupesh et al. [196] found that residence time is a determining factor for the final syngas composition in the CaO-enhanced air-steam gasification of biomass. The smaller particles of biomass have a higher surface area to volume ratio, causing faster heating up and devolatilization, thus leading to a higher gasification rate and complete conversion in a shorter time [192]. Similarly, residence time interacts with other parameters, such as temperature. Higher temperatures boost the reaction kinetics, leading to increased rates of devolatilization, tar cracking, and gas-phase reactions, and consequently, a shorter time is required for complete conversion [190]. Latifi et al. [197] showed that increasing the bed temperature from 600 to 700 °C and the residence time from 8 to 27 s resulted in increased bio-oil conversion, and thereby, syngas production. Specifically, at 700 °C, these authors observed that the H_2/CO ratio increased from 0.29 to 0.60, concomitant with an increase in residence time. Hernández et al. [198] reported a similar trend when testing gasification temperatures between 750 and 1050 °C.

6.2.5. Gasifying Agents

The use of different gasifying agents (air, oxygen, steam, or CO_2) affects the syngas composition. The gasifying agent determines the heat requirements: increasing the oxygen flow allows oxidation reactions to play a more prominent role, thereby increasing the process temperature, but in turn reduces the syngas quality by diluting it with nitrogen and increasing the syngas CO_2 levels. Air is commonly used in small-scale applications

due to the lower operating costs. However, the high nitrogen content in air significantly reduces process efficiency due to the large volume of gases that must be handled and heated (increased power consumption), affecting the reactor design and syngas cleaning operations [199]. In contrast, the addition of steam favors H_2 production by enhancing the water–gas shift reaction and methane reforming reactions [34,200]. The addition of steam also increases tar reforming, resulting in a lower tar content in syngas compared to standard air gasification [201]. However, as a disadvantage, higher heat demand is required for steam production [202]. The energy efficiency of the steam-oxygen gasification process was assessed by Sandeep and Dasappa [203]. These authors reported a decrease in efficiency when the steam-to-biomass ratio (SBR) exceeded 0.75, setting this value as the limit for achieving energetic advantages in the global process. The energy required to produce steam at 0.75 SBR was estimated at 2.2 MJ/kg biomass. Although a significant increase in syngas H_2 content was achieved, the energy efficiency was similar for air gasification and steam-oxygen gasification.

6.2.6. The Use of CO_2 as a Gasifying Agent Brings Additional Benefits

CO_2 can act as a gasification agent, increasing CO formation by the Boudouard reaction and thereby lowering the H_2/CO ratio. It also increases the carbon utilization efficiency (CE) by improving the char conversion in a CO_2-rich atmosphere [204,205]. Prabowo et al. [206] studied the gasification of rice straw (high-ash-containing biomass) using air and CO_2 as gasifying agents. These authors indicated that the use of CO_2 results in a more efficient process when compared to conventional N_2 atmosphere pyrolysis, whereas in the case of gasification, the use of a mixture of air/CO_2 (optimum mixture: 60% CO_2, 8.3% O_2 and 31.7% N_2) results in better performance thanks to the heat release from oxidation reactions, thus avoiding the need to supply extra energy for keeping the process operating at a specific gasification temperature. Sadhwani et al. [207] also studied the use of CO_2 in gasification. Although these authors did not report significant effects of CO_2/C ratio on process performance, they indicated that using CO_2 affected the process chemistry, now dominated by the Boudouard reaction, char reforming reaction, and radical combination reactions.

The additional advantage of using CO_2 as a gasification agent is the removal of the diluting agent. Increasing the syngas quality involves removing non-energetic gases. Removing N_2 from syngas would require complex physical separation processes due to N_2's inert nature, thereby increasing the energy demand. In contrast, CO_2 removal, a chemically active molecule, can be achieved by membrane separation or by absorption into amine-based liquids or Selexol solvents. Energy estimates indicate that about 3.2 MJ/kg CO_2 removed would be needed when using amine-type scrubbers [208], and the technology is simpler than removing N_2 from syngas. On the contrary, using pure oxygen would require installing an air separation unit, which has an estimated energy demand of 0.7 MJ/kg O_2 with a much higher installation cost [209,210]. The main penalty is the high electricity demand. In contrast, for CO_2 capture, the energy required is in the form of heat, which can be supplied by heat recovery units.

Another interesting strategy is the direct adsorption of CO_2 during gasification using CaO in the presence of air/steam as the gasifying agent. Wei et al. [211] reported that an appropriate S/B ratio is 0.38–0.59, although the recommended adsorbent-to-biomass ratio was high (20) at an operating temperature of 700–800 °C. In a recent study, Shang et al. [212] performed gasification at a small scale using a quartz tube and applying repetitive cycles. These authors reported that although loss of bed stability and structural degradation were observed, hydrogen production was maintained after twenty cycles. However, the use of a low-ash biomass (corn stalks with 3.5% ash content) probably contributed to the

good performance over many cycles. Biomass ash often coats catalyst particles, causing deactivation, especially at high temperatures [131]. For this reason, biomass gasification along with CaO absorption is often performed at temperatures below 800 °C [213,214]. Chen et al. [215] used an Al- and Ti-metal-modified Ca-based catalyst (CaO was used as the carrier). CaAlO obtained the best performance, but the H_2 yield was reduced from 347.7 mL/g to 154.4 mL/g, after only five cycles (at an operating temperature of 800 °C). The study by Cao et al. [216] found that a CaO/biomass ratio of 1.5 was sufficient to enhance H_2 production when combined with steam addition, as higher ratios did not yield a significant improvement in overall performance. In the same study, which focused on modeling gasification reactions, the authors noted that temperatures below 800 °C promoted CO_2 adsorption. However, higher temperatures would be necessary to improve tar reforming but could lead to catalyst deactivation and ash sintering. Table 5 summarizes the gasification agents and their effects on process performance.

Table 5. Common gasifying agents and their main characteristics in process performance.

Gasifying Agent	Main Characteristics	Advantages	Disadvantages	Reference
Air	The most common agent used. ER ratios are in the range of 0.3–0.4. Increasing air flow increases gasification temperature.	Low operational costs. Easy control. Air is an ideal gasification agent for small-scale applications.	The presence of nitrogen dilutes syngas, reducing its energy density. Fixed O_2 proportion.	[192–194]
Air/steam	The addition of steam increases H_2 production. H_2/CO ratio can be modulated.	The addition of steam increases syngas yield and aids in tar reforming. Nitrogen dilution is avoided, or at least partially, by using air/steam or steam as a single agent.	Extra energy demand due to steam production. Higher operational costs are associated with auxiliary systems for steam production.	[185,186,217]
Air/steam/O_2 enriched	Temperature control based on O2 enrichment. H2/CO ratio can be modulated. O_2 enrichment is typically used in large-scale coal gasification plants.	Avoid or reduce nitrogen dilution. This approach offers new integration possibilities with other processes, such as H_2 electrolyzers.	High operational costs when considering the use of air separation units. Steam addition increases energy demand.	[218–220]
O_2	Applied at a large scale for coal gasification. Large-scale demonstration plants of integrated gasification combined cycle (IGCC).	Lower electricity demand due to the lower gas volume handled. High-density energy syngas.	High installation and operational costs. Air separation units have a high electricity demand.	[221,222]
CO_2	Acts as a gasifying agent but also affects Boudouard reaction kinetics, favoring CO formation.	The presence of CO_2 enhances char conversion and carbon conversion efficiency. CO_2 capture allows producing syngas with higher energy density.	When using CO_2 as a single agent, an auxiliary thermal source is needed. A two-stage configuration is needed to separate CO_2 from syngas.	[96,206,211]

6.2.7. Superficial Fluid Velocity

This parameter is particularly relevant in fluidized bed and bubbling fluidized bed gasifiers, where a mixing pattern and specific fluidized bed conditions need to be achieved. Fluidification depends on the characteristics of the feedstock, such as density and particle-size distribution, as well as the input load to the reactor. The study by Emiola-Sadiq et al. [223] evaluated bed hydrodynamics by considering the operating parameters of superficial velocity, varying the air flow injection and biomass loading

(feeding rate). These authors reported that achieving higher carbon conversion was possible by adjusting the fluidization velocity to the biomass loading to improve mixing and avoid undesirable segregation. However, depending on the reactor configuration (with or without particle recirculation), the fluidization velocity may be linked to the reactor residence time. Therefore, increasing this velocity may enhance gas–solid phase reactions and improve mixing and heat transfer [224], but may also reduce the reactor residence time, which adversely affects performance by reducing conversion and increasing the tar concentration in syngas [225].

7. Biomass Gasification Technologies

Gasifiers are usually categorized into fixed bed, moving bed, fluidized bed, entrained flow, and plasma gasifiers. Each type has unique operating characteristics and reactor designs optimized for performance by various manufacturers. Several excellent reviews covering this subject have been published in the literature [35,129,226,227]. The review by Allesina et al. [228] explicitly describes current small-scale gasification technologies. Most of these gasifiers are fixed-bed types, and as the scale increases, the most common technology is the fluidized bed, with some of them including a circulating flow to improve reactor performance. Table 6. lists some of the different types of gasification studies performed using biomass as the raw material. A complete list is included in Supplementary Material, Table S1: List of pilot scale experimental studies on biomass gasification.

Table 6. List of some pilot scale experimental studies on biomass gasification.

Types of Gasifiers	Biomass	Experimental Characteristics	Reference
Downdraft fixed bed	Wood chips	50 kWth gasifier coupled with a pilot-scale gas cleaning unit (water gas shift and pressure swing adsorption unit). High H_2 purity (>99.977% vol.). H_2 yield of 55.1–58.9 g H_2/kg biomass (dry basis).	[229]
	Pomegranate wood chips, walnut shell	Assessed process performance under different electrical power loads. Carbon conversion efficiency increased with increasing electrical power load. Higher ERs were applied when increasing the electrical power load, resulting in lower syngas energy density.	[230,231]
Updraft high temperature agent (HTAG)	Black pellets (based on 75% soft wood and 25% hard wood pretreated with steam explosion) and gray pellets (woody based roadside scrub cuts, no pre-treatment applied)	Use of preheated air/steam. The preheater oxidizer unit supplies additional heat to the gasifier. Syngas post-combustion unit. Feeding rate: 50–70 kg/h, ER: 0.2, steam:biomass ratio: 1.2 Highest temperature at the bed bottom: around 980–1150 °C. Temperature at the top: 600–900 °C. Syngas LHV (air gasification): 6.–7.3 MJ/m^3, Syngas LHV (steam gasification): 8.2–10 MJ/m^3. CGE [1]: 74–77%. Steam gasification produced less tar (11.4 g/m^3).	[217]
Bubbling fluidized bed	Pine chips	Air/Air-steam gasification. Steam-to-biomass ratio of 0.5 and 1.05, ER: 0.15–0.25. No information regarding biomass loading conditions. CGE increased to 95% when adding steam as the gasifying agent. Syngas yield: 3 m^3/kg biomass. Air gasification showed higher profitability than air/steam gasification.	[186]
	Pine and eucalyptus residues	Gasifier 80 kWth. ER: 0.24–0.26. Syngas LHV: 3.9–3.6 MJ/m^3. CH_4 content ranged from 2.9 to 4.8% vol. Syngas yield: 1.5–1.8 m^3/kg biomass (dry syngas/dry biomass). The use of high-density biomass and char formation during gasification improved performance when steam was added (char-steam reforming reactions), resulting in higher syngas LHV and CGE. Optimum steam to biomass ratio: 0.5.	[183]

Table 6. *Cont.*

Types of Gasifiers	Biomass	Experimental Characteristics	Reference
Dual bubbling fluidized bed (DBFB)	Hazelnut shells	100 kWth using steam as a single gasifying agent to avoid N_2 dilution. Syngas LHV: 10.5 MJ/m^3 (H_2 content: 34.8%). Syngas yield: 1.33 m^3/kg biomass. High tar production: 12 g/m^3. This value was reduced to 3 g/m^3 after conditioning using a cyclone and water scrubber. Carbon conversion: 73%.	[184]
Fluidized bed gasifier	Soy hull pellets	Feeding rate: 5.5 kg/min. Temperature (750–950 °C), ER (0.2–0.4). Biomass loading and fluidification velocity were assessed. Lowering the ER improved the CGE. Higher fluidification velocity improved performance, particularly at higher biomass loading.	[223]
	Agricultural waste (mainly straw)	Air gasification with O_2 enrichment. ER: 0.11–0.24, O_2 content: 21–45%. Syngas LHV: 9.35 MJ/m^3, CGE: 51.62% at ER: 0.16. Increasing oxygen content resulted in higher CO and H_2 levels in syngas, thanks to the increase in gasification temperature, positively affecting performance.	[218]
Dual fluidized bed gasifier (combining bubbling fluidized bed (BFB) and fast fluidized combustion reactor)	Wood pellets	100 kW fuel input (20 kg/h). Temperature: 770–850 °C in gasifier and 920 °C in combustion reactor. Gasifying agent in BFB: steam (steam to fuel ratio: 0.74–1.10), gasifying agent in combustion reactor: air. Syngas yield: 0.99–1.13 m^3/kg biomass. Tar decomposition takes place at temperatures above 800 °C.	[185]
circulating fluidized bed	Wood pellets	500 kW pilot gasifier: comparison of model and pilot scale results previously published. H_2:CO ratio of 2 was obtained by coupling an electrolyzer to produce H_2 and using the O_2 released to achieve a desired oxidant proportion.	[219]
Rotary kiln plant	Digestate and almond shells	Feeding rate: 20 kg/h. ER: 0.22–0.39 Syngas LHV: 4–5 MJ/m^3, maximum CGE of 55% at ER: 0.3. Steam was added to increase the H_2/CO ratio in syngas, but the CGE dropped to 17%. A heat recovery unit can increase CGE to 72% for the mixture, but only to 35% when using steam as the gasification agent.	[232]
Coal-water slurry gasification technology with opposed multi-burners (OMB)	Torrefied biomass and coal (water containing slurry)	Pilot plant containing: Slurry unit, gasification, water scrubber, WGS [2] reactor (producing syngas with H_2/CO ratio of 11:1), acid gas removal unit (CO_2 and H_2S removal), Fischer–Tropsch synthesis reactor. The coal-torrefied biomass blend required a much higher water content to produce a pumpable slurry, thus reducing the energy efficiency. Feeding: 0.37 t/day of coal and 0.02 t/day torrefied biomass. 0.12 t/day of natural gas was required to keep the process running. 0.36 t/day of water was added to generate the slurry. Gasification temperature: 1400 °C. H_2 content was 22%, and CO content was 20% in syngas.	[233]

[1] CGE: cold gas efficiency. [2] WGS: water gas shift.

Fixed bed gasification is a reliable technology for converting biomass, capable of operating with a wide range of particle sizes and high moisture content. Although in updraft gasifiers, high tar formation is considered a major drawback, this effect exacerbates with increasing biomass moisture levels [151]. Fluidized bed gasification, on the contrary, offers better control of many operating parameters such as fluidized bed velocity, pressure, temperature, and biomass/gasification agent ratio, which have a critical effect on performance and syngas quality [187]. Bubbling fluidized bed gasification is a technology that offers the advantage of high conversion efficiency, facilitating a uniform temperature profile in the reactor and enhancing gas–solid interactions [63].

Plasma gasification is another technology that has found niche applications, mainly for the treatment of municipal solid waste, industrial, medical, and hazardous waste, thanks to its high operating temperature, which ensures the production of a clean syngas stream and an inert vitrified ash residue [234,235]. However, the high installation and operating

costs constrain its application to projects with extremely high throughput, also slowing the technology's deployment [236,237]. Westinghouse Plasma Corporation (acquired by Alter NRG Corp in 2007, and later in 2015, Harvest International New Energy acquired this group) has provided the technology to build gasification plants in Japan, India, and the United States, among other countries, and has long-term experience in this technology.

Despite efforts to develop gasifiers capable of handling various biomass types to increase plant flexibility, several challenges remain, including operational issues with syngas cleaning and tar removal, low energy production efficiency, and high installation and operating costs. These issues, identified by Heyne et al. [238] and Asadullah [239] more than a decade ago, persist in recent gasification work. Gasification units that include a subsequent combustion stage effectively destroy tar components, which simplifies the design of syngas cleaning processes. Consequently, many biogas gasification technologies currently utilize syngas in boilers or CHP engines. Table 7 lists some biomass gasification plants currently in operation, and Table 8 lists some commercial companies offering small-scale biomass gasification units.

Table 7. Biomass gasification plants.

Type of Gasifier	Company	Plant Location	Raw Materials	Characteristics	Reference
Fixed bed downdraft	Aries Clean Energy (Franklin, TN, USA)	Lebanon, Tennessee, US	Biosolids, commercial wood waste, and scrap tires	420 kWe, Feedstock throughput capacity: 64 t/d	[240]
Fixed bed downdraft	URBAS Energy Technology (Völkermarkt, Austria)	15 installed plants in Austria, Italy, Japan, Croatia, and Bosnia and Herzegovina	Wood biomass	150–450 kWe	[241]
Fixed bed updraft	Harboøre updraft biomass gasification plant constructed by Babcock & Wilcox Vølund (now part of Babcock & Wilcox) (Gothenburg, Sweden)	Harboøre, Denmark	Wood chips	No longer in operation. Demonstration plant. 3.5–4 MWth	[242]
Fixed bed	Neoelectra (Sant Just Desvern, Barcelona) using Careco Technology: "gasógeno", no specification of flow direction conditions [1] (Barcelone, Spain)	Villacañas, Toledo, Spain	Industrial wood residue and forest residue	380 000 t/year, 8 Mwe.	[243]
		Santa Perpétua de Mogoda (Barcelona)	Woodchips, plastics, rubber, residual biomass, and combustible solid residue	20 MWth	[243]
Fluidized bed	Aries Clean Energy (Franklin, TN, USA)	Linden, New Jersey, USA	Biosolids	Feedstock throughput capacity: 430 t/d. Commercialize ashes as Bio-Fly-Ash™ to be used as a concrete additive.	[240]
Circulating fluidized bed gasification	Valmet (Spoo, Finland)	4 gasifiers in Finland, and another 3 located in Indonesia, China, and Brazil	Mainly bark and wood residues and waste (solid residue fuel)	Thermal capacity 50–150 MW	[244]
Air fluidized bed	Sumitomo SHI/FW (Spoo, Finland)	Varkaus, Finland	Biomass, forestry residues	12 MWth	[245]

[1] Neoelectra is currently under insolvency proceedings.

Table 8. Companies offering small-scale gasification biomass plants.

Company	Gasification Technology	Plants	Characteristics	Reference
GEMCO Energy, (Anyang, Henan, China)	Fixed bed (up-draft and down-draft) and circulating fluidized bed (CFB)	No installed gasification plants reported	The company offers modular biomass power stations (small scale), with an installed capacity ranging between 200 and 500 kW. The CFB is for large-scale and can operate on wood powder, sawdust, rice husks, bagasse, and crushed straw with a biomass flow range of 1500–5000 kg/h	[246]
SynTech Bioenergy (Englewood, CO, USA)	BioMax® system: Modular units. Using downdraft gasifiers operating at above 800 °C	Installed plants in California, Texas and United Kingdom (West Midlands)	Feedstock: agricultural waste. Offers the production of certified biochar and low level of tars in syngas using a dry filter for gas clean-up without releasing wastewater. 165 kW–2 MW	[247]
Ankur Scientific Energy Technologies (Sama Vadodara, Gujarat, India)	downdraft gasifiers generating combustible gases for thermal applications (boilers, furnaces or CHP grid/off grid)	Installed plants in more than 35 countries	Feedstock: MSW, poultry litter, empty fruit bunch (EFB), fecal/sewage sludge, agricultural residues, paper. A wide range of plants with a treatment capacity of 5–100 t/day in the case of MSW and 16–2000 kg/h for biomass material (EFB and agricultural residues)	[248]
CMN Industry Inc. (Sacramento, CA, USA)	No description given of the gasification technology used. Process temperature 700–1200 °C	Installed plants located in USA, Germany, India and Brazil	Feedstock: Crop straw and forestry waste. No description of treatment capacity	[249]
Powermax Renewable Energy (Wuxi, Jiangsu, China)	Fixed bed (up-draft and downdraft), CFB, and twin fire-fixed bed gasifier. Modular plants (50 kW–2 MW) and large-scale units	Myanmar gasification plant. Collaboration in gasification plant project in Canada	Feedstock: rice husk Power: 12 MW	[250]
Compact Syngas Solutions (Sandycroft, Flintshire, UK)	MicroHub 500 and MicroHub 1000: modular waste management technology	No installation plants reported. Participation in project for tea biomass gasification in Kericho district (Kenya)	Feedstock: Biomass and solid recovered fuel. Treatment capacity of 3570 t/year. Power: 500 and 1000 kWe	[251]
SPANNER RE^2 GMBH (Neufahrn, Niederbayern, Germany)	Gasification plants for heat and electricity production	Installed plants in Slovenia, Germany, Austria, Italy (South Tyrol region)	Feedstock: Wood biomass 35–700 kWe	[252]
Meva Energy (Hisings Backa, Sweden)	Large- and small-scale gasification plants. Entrained gasification technology.	Demonstration plant. Agreement with Elcowire Group AB group for providing 9 MW of syngas.	Feedstock: Organic residues from agriculture, industry, and forestry	[253]
Syncraft® (Schwaz, Austria)	floating fixed-bed gasification technology. Small gasification plants with CHP engines	Installed plants in Austria (Tyrol region, Vorarlberg), Croatia and Switzerland	Feedstock: Wood biomass 270, 400 and 550 kWe	[254]
The Stadtwerke Rosenheim (Rosenheim Municipal Utilities) (Rosenheim, Germany)	Double stage fluidized bed reactor	Demonstration plant	Feedstock: Wood gasification, 60 and 250 kWe	[255]
Kombi Power System (Regawatt GbmH) (Abensberg, Germany)	Updraft gasifier. The system can be implemented for heat (boiler) or electricity production (CHP). It can also be used to produce syngas or bio-oil	Installed plants in Netherlands, Japan, Switzerland and Germany	Feedstock: Waste wood, forest chips, landscape wood, screenings from composting plants. 250–2000 kWe	[256]
Lipro Energy (Wardenburg, Germany)	Multi-stage gasification	Several installed plants in Germany	Feedstock: Wood biomass and waste biomass. 50–85 kWe	[257]

Table 8. *Cont.*

Company	Gasification Technology	Plants	Characteristics	Reference
Holzenergie Wegscheid GmbH (Sonnen, Germany). Merger with WegscheidEntrenco GmbH since 2023	Down-draft gasifier with CHP engines	Several installed plants in Germany	Feedstock: Wood biomass. 70 kW–2 MWe	[258]
Burkhardt GmbH (Mühlhausen, Germany)	Multi-stage gasification system: Updraught co-current flow gasification forming a stationary fluidized bed	Several plants in Austria, Germany, and Japan	Feedstock: Wood biomass (wood pellets and wood chips). 190–390 kWe	[259]
CMD (Costruzioni Motori Diesel SPA) (Caserta, Italia)	ECO20x gasifier: Pyrogasification process	Demonstration plant in Salerno (Campania), Italy	Feedstock: Wood biomass (wood chips). 20 kWe (40 kWth)	[260]
ESPE Energy expertise (Padua, Italy)	CHiP50 gasifier: Pyrogasification process	3 plants installed (Italy, Japan)	Feedstock: Wood biomass (wood chips)	[261]
RESET (Rieti, Italy)	SyngaSmart gasifier configurations available: Electricity production using CHP, heat production using thermal power units and syngas production (biomass to biofuel generator)	1 medium size (250 kg/h input) gas producing plant in Rome (Italy) for the treatment of briquetted organic fraction of MSW)	Feedstock: Agroforestry residues, organic by-products, and waste. 19–200 kWe (28–292 kWth). Biomass consumption rate: 22.8–240 kg/h	[262]
VOLTER (Tupos, Finland)	Walter CHP Modular gasification: Gasifier + CHP (gas cleaning and energy recovery)	No reports available of installed gasification plants	Feedstock: Wood chips. 50 kWe (130 kWth)	[263]
Xylergy SA (Lovain-La-Nueve, Belgium)	NOTAR®: Downdraft gasifier with CHP unit	1 demonstration plant in Belgium and 2 plants installed in Belgium and France	Feedstock: Wood chips. 200–750 kWe	[264]

Yadav et al. [265] and Dhamodharan et al. [266] identified several key factors affecting the feasibility of biomass gasification plants. These include the handling of biomass and its logistics, installation costs, operational complexities, and issues such as frequent clogging and blockages due to the heavy hydrocarbons present in syngas. As a result, biomass gasification units rely heavily on scale to achieve profitability. However, this reliance also presents challenges due to the associated collection and transportation costs. To address these issues, using a mixture of raw materials, including organics and high-energy-density waste like plastics and tires, has emerged as a more efficient option because it improves the overall energy balance [267,268].

In the context of decentralized energy systems, the South Tyrol region represents a significant pilot environment for small-scale biomass gasification. This area has served as a living laboratory for iterative optimization and technology refinement (to assess operational reliability), integration with combined heat and power (CHP) units, and adaptation to local feedstock variability under real-world conditions. As reported by Patuzzi et al. [269], the technologies installed in this area use high-quality biomass with low moisture content (<12%) and low ash content (<1%). Despite this feature, the char obtained cannot be considered suitable for agronomic applications, given its metal content (mainly chrome and zinc, derived from the gasifier itself and comminution operations) and the presence of polycyclic aromatic hydrocarbons (PAHs).

A hypothetical key advantage of gasification is its ability to process a broad spectrum of biomass feedstocks with diverse physicochemical properties while simultaneously enabling the valorization of organic waste streams. This flexibility facilitates its integration into circular economy frameworks by converting heterogeneous materials into valuable energy carriers and by-products. The inability of small-scale gasifiers to manage syngas

trace contaminants when operating with low-quality biomass, and the excessive cost of char disposal when this material falls into the out-of-specification category, make the process incapable of meeting the sustainability goals. A more viable approach is partial decentralization, in which syngas is conditioned and valorized at a large-scale, centralized facility. This configuration leverages economies of scale to enable advanced tar reforming technologies and efficient energy recovery from char while minimizing the biomass transport requirements. The concept is not new; in fact, the use of a multi-stage approach is already observed in currently small gasification technologies, as the separate control of each step allows for optimizing the overall outcome. The bioliq® process is the major exponent of stage separation. The process was developed at the Karlsruhe Institute of Technology (KIT) and involves the in situ fast pyrolysis (small scale) of the biomass, thus producing Biosyncrude® (a mixture of pyro-oils and coke) and subsequent gasification in a large-scale gasifier high pressure (40–80 bars) entrained-flow unit followed by syngas up-grading and conditioning [270]. Although very promising, this technology is not yet commercially available.

The study by Menin et al. [271] found that small-scale gasification, when combined with syngas valorization through combined heat and power (CHP) units, is not currently a competitive alternative to photovoltaic electricity generation with battery storage or to biogas electricity production. However, when externalities are factored into the analysis, biomass gasification significantly reduces greenhouse gas (GHG) emissions, which is a notable advantage that should not be overlooked [272]. The feasibility of a plant relies not only on the economic performance of the technology but also on its profitability compared to existing renewable energy technologies. Biomass gasification offers more than just electricity; the technology can also be adapted to produce liquid fuels. Unlike other processes for generating synthetic fuels, such as converting hydrogen and carbon dioxide using water electrolyzers and carbon capture technologies, gasification has the advantage that biomass naturally absorbs CO_2 from the atmosphere at a significantly lower energy cost.

Technical progress achieved by commercial developers, particularly in contaminant control and the integration of solar-assisted heating technologies, offers new opportunities to improve process efficiency. These advances may enable air-free operation, resulting in higher-energy-density syngas, or facilitate more efficient steam gasification, enhancing hydrogen production without the substantial thermal demand typically associated with steam generation. Zhumagulov et al. [273] reviewed registered global patents regarding solar-driven gasification, indicating that the decrease in installation costs and the current development of the technology, although still at an infant state, may become a relevant player in future technological developments. Laboratory-scale experiments have been reported, but with treatment capacities of a few grams and reactor volumes ranging from milliliters to a few liters [274–278].

8. Gasification of Low-Quality Biomass

The term low-quality biomass is used in this document to refer to biomass with low energetic content due to its high mineral composition and high moisture levels. Manures, sewage sludge, digestates, and municipal solid waste are the leading exponents of this classification. Several research studies address this subject, reporting that one of the main disadvantages of these materials is the high energy required for drying, which is often supplied by fossil fuels [279,280]. Table 9 presents the results from gasification experiments using this type of biomass. The findings indicate a low performance concerning the CGE values, which can be attributed to the low volatile content available for syngas production and the physical and chemical characteristics of the material. Consequently, many

researchers have evaluated the process using mixtures that include materials with higher energy content [233,267,268,281,282]. However, the type of materials involved in creating the mixture may adversely affect other properties such as char adsorption characteristics, as demonstrated by Ani et al. [283] when testing a mixture of refuse-derived fuel and oak pellets.

Table 9. Summary of gasification experiments reported in the scientific literature using low-quality biomass as feedstock.

Raw Material	Gasification Characteristics	Main Results	Reference
Sewage sludge. Ash content: 47.6%	Bubbling fluidized bed gasifier (20 kW fuel input). Steam-O_2 gasification. Temperature: 650–900 °C. ER: 0.2–0.28. Steam to carbon ratio: 0.6–2.0	The addition of limestone helps reduce H_2S and COS species. Fluidization needs to be carefully controlled to avoid undesired hot spots that could lead to particle agglomeration.	[220]
Digestate and almond shells. Digestate ash content: 32%, almond shell ash content: 1.65%	Rotary kiln pilot scale gasifier. Gasification of digestate pellets as single raw material and mixture with almond shells. Digestate provided 60% of the mix. Feeding rate: 14–27.5 kg/h. ER: 0.26–0.39	The CGE of digestate gasification was 47% and increased to 55% when almond shells were added to the mixture. Steam injection enabled the production of syngas with a higher H_2/CO ratio, but CGE dropped to 17%. A heat recovery unit can increase CGE to 72% for the mixture, but only to 35% when using steam as a gasification agent.	[232]
Sewage sludge. Ash content: 24.3–30.6%	Fluidized bed reactor. Temperature: 850 °C. Bench scale. ER: 0.1–0.2. Feed rate: 68 and 138 g/h	Syngas LHV: 5.8 MJ/m^3 (ER: 0.2) and 12.1 MJ/m^3 (ER: 0.1). CGE: 50–57%. The study focused on tar and bottom ash quality. Operating conditions had a greater influence on the types of tar components obtained than the characteristics of the raw sludge had. Lower tar production was obtained at an ER of 0.2, but operating at a lower ER resulted in ash with a higher surface area.	[284]
Sewage sludge. Ash content: 24.3–30.6%	Entrained flow gasifier (90 kW). Evaluated the effect of gasifying agents (air and O_2)	Syngas LHV: 8.4 MJ/m^3 (using O_2). Syngas volume was reduced by 60%. CGE: 45–51%. The presence of KCl increased performance by favoring carbon conversion.	[285]
Sewage sludge. Ash content: 25.6%	Fluidized bed gasifier. ER: 0.12–0.27	Syngas LHV: 3.1–4.8 MJ/m^3. Reactor profile temperature range: 690–1000 °C	[286]
Sewage sludge. Ash content: 49–51%	Bubbling fluidized bed gasifier. Input rate: 2 kg/h. ER: 0.2. Steam to carbon ratio: 1.0–1.8. CaO used for CO_2 absorption during gasification	The combination of steam injection and CaO (used as bed material) enabled tripling of the syngas H_2 content. Air addition improved the carbon conversion but reduced H_2 yield.	[287]
Digestate from a plant treating manure and straw (fresh weight ratio of 1:0.3). Ash content: 23.03%	Downdraft fixed bed gasifier. Temperature: 600–800 °C. ER: 0.25–0.30.	Syngas LHV: 4.78 MJ/m^3, CGE: 67% at ER: 0.28. CGE efficiency increased from 30 to 67% with increasing temperature from 600 to 800 °C	[288]
Digestate and lignite (mass ratio 1:1). Digestate ash content: 41.5%	Downdraft fixed bed gasifier. Laboratory scale with a test capacity of 20 g of feedstock. Temperature: 650–950 °C. CO_2 atmosphere.	Syngas LHV: 4.0–6.5 MJ/m^3. Increasing the temperature led to higher LHV. Increasing the temperature also reduced the tar content in syngas.	[289,290]
Digestate and sewage sludge. Digestate ash content: 13.5%, sewage sludge ash content: 47.1%	Pilot-scale fluidized bed gasifier (thermal output of 100 kWth). Temperature: 750 °C. Steam addition.	Syngas LHV (from digestate): 4.06 MJ/m^3. Syngas LHV (from sewage sludge): 4.11 MJ/m^3. Adding steam helps reduce the tar concentration in syngas.	[291]
Diary manure. Ash content: 48.8%	Bench and pilot scale reactor. Application of RSM [1] for process optimization. Factors: Temperature, ER and O_2 concentration.	Syngas LHV: 8 MJ/m^3, maximum value obtained at 800 °C, ER: 0.25 and O_2 content: 40%. CGE increased with oxygen enrichment.	[292]
Chicken manure (CM)–oily sludge (50% mixture) CM Ash content: 27.7%	Fixed-bed (up-draft) gasifier. T: 600–800 °C. Batch process (laboratory scale).	Syngas LHV: 2487–2838 kcal/m^3 (10.4–11.9 MJ/m^3). Methane content was increased by using oily sludge as a raw material, thereby increasing the syngas energy density.	[293]

Table 9. *Cont.*

Raw Material	Gasification Characteristics	Main Results	Reference
Chicken manure (CM)–woody biomass (30% CM in mixture) CM Ash content: 25.3%	Fixed-bed (downdraft 10 kW) gasifier. Pilot plant. Temperature: 850–900 °C Feedstock rate: 10 kg/h.	Syngas LHV: 5.23 MJ/m^3. CGE improvement (6.7%). The mixture containing 30 wt% chicken manure produced syngas with quality comparable to wood gasification. The char obtained was tested as low-cost activated carbon.	[294]

[1] RSM: response surface methodology.

Although the deployment of gasification technology is considered feasible for low-quality biomass, many studies did not account for the drying energy requirements and assumed an ash content below 20% [286,294,295]. The experiment reported by Judex et al. [296] involved a pilot demonstration plant running on sewage sludge. The plant operated at 850–900 °C with steam injection. The experiment used sewage sludge with an ash content of 57% and yielded syngas with an LHV of 3.2 MJ/m^3. However, when testing a different sludge with a 39.5% ash content, the syngas LHV reached 4.7 MJ/m^3, which is much closer to values reported in the literature [289,290]. When treating this type of biomass, the main disadvantages are associated with the high amount of inert material contained in the input, which needs to be heated up to the desired operating temperature and the melting characteristics of the ash, setting constraints to the operating temperature to avoid agglomeration and therefore penalizing syngas yield (volumetric flow and energetic density) along with increasing tar production.

Digestates have recently been considered a suitable raw material for gasification [291,297]. Biogas plants treating organic waste utilize readily biodegradable materials but tend to accumulate lignin-based components. The slurry derived from the digestion process has characteristics that are dependent on the type of feed and the reactor operating conditions [298,299]. Substances with high lignocellulosic content tend to accumulate recalcitrant compounds in the digestate since they are not easily accessible to anaerobic microorganisms. In contrast, those with a high proportion of biodegradable components produce more biogas and lead to a greater accumulation of inorganic material in the digestate.

Using air as a gasification agent results in significant syngas dilution due to the presence of nitrogen. However, using pure oxygen to mitigate this issue is not feasible for small-scale systems due to the high installation costs of air separation units. A novel strategy for increasing the syngas calorific value is the removal of CO_2 by using lime or Ca-based materials as a bed. The trapping of CO_2 shifts the equilibrium toward H_2 production, and the exothermic reaction provides the extra heat required to maintain the gasification temperature. The process requires stage separation to regenerate $CaCO_3$, releasing CO_2 and recovering CaO, which is circulated back to the central gasification unit. In addition, the use of mixtures of limestone with other materials, such as coal bottom ash or MgO as the bed, enhances H_2 production at low temperatures, with syngas H_2 concentrations reaching up to 75% [300,301]. Other catalysts have been proposed to enhance carbon conversion, such as Rh- and Ce-based catalysts, which allow operation at lower temperatures, thereby preventing tar formation and char accumulation [302]. Ni- and Fe-based catalysts have also been proposed because of their lower costs and great catalytic activity for tar reforming [303,304]. However, deactivation problems, along with an overall cost still too high to make them practical for widespread industrial use, make this option unfeasible [305]. Low-cost options, such as slag-based waste impregnated with Ni, may serve as an alternative [306]. Valizadeh et al. [307] proposed the CO_2 gasification of manure using Ni-Al_2O_3 and alkaline-earth metals (Mg and Sr), reporting higher syngas yields and H_2/CO ratio under a CO_2 atmosphere than under a N_2 atmosphere. Li et al. [308] also

reported better syngas quality, in terms of H_2-CO content, under a CO_2 atmosphere than under N_2 when testing the gasification of manure blends with rice husks.

The use of dolomite and olivine has also been proposed, with the former offering the added advantage of CO_2 capture, as well as combinations of these bed materials with metal catalysts [121]. Dolomite has demonstrated better performance regarding syngas yield and H_2 production but suffers from higher coke deposition than olivine [309]. The use of char generated in the same gasification process (as a catalyst) has also been studied as a way to overcome the issues of coke deactivation and as an in situ alternative for the conversion of heavy tars [122,310]. Char can be used as a low-cost catalyst thanks to the presence of Fe and alkali and alkaline-earth metals, which promote tar decomposition, or can be doped with Ni to increase its catalytic performance [311]. Although deactivation is not suppressed, the production costs of this type of catalyst may be significantly reduced.

Several studies on the catalytic gasification of biomass have been reviewed by Siddiqui et al. [143], Ramadhani et al. [135], and Jothiprakash et al. [120]. However, the application of the catalytic gasification of waste biomass is still far from becoming a reality at an industrial scale. The development of specific gasification technologies is essential for achieving sustainability goals and promoting circular economy principles. An example of this is the gasification technology developed by Fraunhofer UMSICHT [312], which was specifically designed to process high-ash biomass. This type of reactor provides a solution to the growing amounts of sewage sludge produced each year, which may not be suitable for land use due to restrictions on metals, pharmaceutical and personal care compounds, or microplastics. The technology is based on a fixed-bed countercurrent gasifier, where temperature is carefully controlled and gradually increased from 500 °C to 900 °C, thereby significantly increasing the H_2 yield (from 15.7 to 35.7 g H_2/kg Feed). The syngas produced from the process, when tested at various temperature conditions for the different stages (Roaster, gasifier, and reformer), showed an LHV between 5.13–7.92 MJ/m^3 thanks to the low ER values applied (0.12–0.13).

9. Future Perspectives and Limitations

The gasification of biomass and waste is a strategic pathway for producing renewable energy and building blocks for high-value-added products while simultaneously valorizing waste within a circular economy framework. The main advantage of the process lies in the ability to convert heterogeneous, low-value feedstocks—such as sewage sludge, digestates, manures, and mixed organic wastes—into syngas suitable for heat and power generation, hydrogen production, or synthetic fuels. The growing regulatory pressure to divert organic waste from landfills, along with restrictions on the land application of sewage sludge, is likely to promote the development of thermal treatments, particularly gasification technology, as a viable option for waste valorization. The technology can be easily integrated into existing wastewater treatment plants (WWTPs), centralized waste treatment centers, and anaerobic digestion facilities, thereby facilitating broader implementation. Furthermore, the search for secure sources of gaseous fuels has become increasingly important in light of recent global conflicts that have exposed the vulnerabilities of natural gas and petroleum supply chains. This situation provides an added incentive to further develop and implement technologies that support biofuel and bioenergy production infrastructure.

From a technological perspective, future developments are expected to focus on multistage configurations, where drying, pyrolysis, gasification, and gas conditioning are optimized to enable heat recovery and leverage energy storage cycles. Such configurations can mitigate key drawbacks associated with low-quality biomass, including high moisture content, ash-induced temperature limitations, and the need for tar removal. Additional advances are anticipated in the field of in situ and low-cost catalytic materials, including

ash-derived catalysts, char-based materials, and multifunctional bed additives that enhance tar reforming and carbon conversion while tolerating high inorganic loads.

Despite these perspectives, several structural limitations still hinder the widespread deployment of biomass/waste gasification. The high moisture and ash content typical of low-quality biomass significantly penalize energy efficiency due to drying requirements and the need to heat large inert fractions. Ash-related phenomena, including slagging, sintering, fouling, and catalyst deactivation, impose strict constraints on operating temperature, often leading to sub-optimal gasification conditions and elevated tar formation, resulting in low CGE. Tar removal and syngas cleaning remain major economic and technical bottlenecks, especially for applications requiring high-purity syngas, such as hydrogen separation or Fischer–Tropsch synthesis.

Economic feasibility remains closely linked to scale, feedstock logistics, and system integration. Small-scale gasifiers struggle to manage syngas contaminants and cost-effectively dispose of ash when processing low-quality biomass. At the same time, large-scale plants face challenges with biomass transport and supply consistency. As a result, partially centralized or hybrid concepts—combining decentralized preprocessing with centralized gasification and upgrading—are emerging as more realistic long-term solutions. Overall, while biomass and waste gasification cannot yet be considered universally mature technologies, continued advances in process design, catalysis, and systems integration support their future role as complementary technologies for sustainable waste valorization and renewable fuel production.

10. Conclusions

Gasification emerged in this review as a strategically relevant pathway for the valorization of biomass and waste streams due to its flexibility in converting a wide range of feedstocks into syngas suitable for power generation, hydrogen production, and the manufacture of synthetic fuels. Gasification performance is strongly governed by feedstock properties—such as moisture content, volatile matter, and inorganic composition— and reactor operating conditions, including temperature, equivalence ratio, pressure, and the choice of the gasifying agent. These factors directly influence syngas quality, cold gas efficiency, tar formation, and overall process stability. Although biomass gasification cannot yet be considered fully mature for all types of feedstocks, the process represents a robust alternative for supporting energy system resilience and contributing to decarbonization goals within circular economy and net zero carbon frameworks.

The main challenges are associated with the gasification of low-quality biomass that are characterized by high moisture and ash content. These features increase the drying energy requirements, constrain operating temperatures due to ash melting and agglomeration risks, and often lead to lower syngas quality and efficiency. These limitations can be partially mitigated through integrated strategies, including biomass pretreatment, feedstock blending with higher energy containing feedstocks, and the use of suitable catalysts and bed materials to enhance tar reforming and carbon conversion. Nevertheless, issues related to catalyst deactivation, process complexity, and costs remain significant. From a system perspective, the findings suggest that scale and process integration are critical for economic feasibility, and that partially centralized or multistage gasification concepts may offer a more realistic route for the sustainable valorization of heterogeneous and low-quality biomass resources.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/environments13050261/s1, Table S1: List of pilot scale experimental studies on biomass gasification [313–332].

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