Municipal Solid Waste Gasification: Technologies, Process Parameters, and Sustainable Valorization of By-Products in a Circular Economy

Article *in* Sustainability · July 2025

DOI: 10.3390/su17156704

5 authors, including:

Nicoleta Ungureanu
Universitatea Națională de Știință și Tehnologie Politehnica București
221 PUBLICATIONS **1,303** CITATIONS
SEE PROFILE

Valentin Vladut
The National Institute of Research – Development for Machines and Installations De…
379 PUBLICATIONS **1,757** CITATIONS
SEE PROFILE

Sorin-Stefan Biris
Universitatea Națională de Știință și Tehnologie Politehnica București
203 PUBLICATIONS **813** CITATIONS
SEE PROFILE

Ionescu Mariana
Universitatea Națională de Știință și Tehnologie Politehnica București
5 PUBLICATIONS **1** CITATION
SEE PROFILE

sustainability

MDPI

Review

Municipal Solid Waste Gasification: Technologies, Process Parameters, and Sustainable Valorization of By-Products in a Circular Economy

Nicoleta Ungureanu [1], Nicolae-Valentin Vlăduț [2,*], Sorin-Ștefan Biriș [1], Mariana Ionescu [1,*] and Neluș-Evelin Gheorghiță [1]

[1] Department of Biotechnical Systems, Faculty of Biotechnical Systems Engineering, National University of Science and Technology Politehnica Bucharest, 060042 Bucharest, Romania; nicoleta.ungureanu@upb.ro (N.U.); sorin.biris@upb.ro (S.-Ș.B.); nelus.gheorghita@upb.ro (N.-E.G.)

[2] National Institute of Research—Development for Machines and Installations Designed for Agriculture and Food Industry—INMA Bucharest, 013813 Bucharest, Romania

* Correspondence: valentin_vladut@yahoo.com or vladut@inma.ro (N.-V.V.); mariana.ionescu@upb.ro (M.I.)

Abstract

Gasification of municipal solid waste and other biogenic residues (e.g., biomass and bio-waste) is increasingly recognized as a promising thermochemical pathway for converting non-recyclable fractions into valuable energy carriers, with applications in electricity generation, district heating, hydrogen production, and synthetic fuels. This paper provides a comprehensive analysis of major gasification technologies, including fixed bed, fluidized bed, entrained flow, plasma, supercritical water, microwave-assisted, high-temperature steam, and rotary kiln systems. Key aspects such as feedstock compatibility, operating parameters, technology readiness level, and integration within circular economy frameworks are critically evaluated. A comparative assessment of incineration and pyrolysis highlights the environmental and energetic advantages of gasification. The valorization pathways for main product (syngas) and by-products (syngas, ash, tar, and biochar) are also explored, emphasizing their reuse in environmental, agricultural, and industrial applications. Despite progress, large-scale adoption in Europe is constrained by economic, legislative, and technical barriers. Future research should prioritize scaling emerging systems, optimizing by-product recovery, and improving integration with carbon capture and circular energy infrastructures. Supported by recent European policy frameworks, gasification is positioned to play a key role in sustainable waste-to-energy strategies, biomass valorization, and the transition to a low-emission economy.

Keywords: municipal solid waste; waste-to-energy; gasification; technology readiness level; syngas; ash; tar; biochar; environment; agriculture

Academic Editors: Serhiy Pyshyev, Denys Miroshnychenko and Bohdan Korchak

Received: 10 July 2025
Revised: 22 July 2025
Accepted: 22 July 2025
Published: 23 July 2025

Citation: Ungureanu, N.; Vlăduț, N.-V.; Biriș, S.-Ș.; Ionescu, M.; Gheorghiță, N.-E. Municipal Solid Waste Gasification: Technologies, Process Parameters, and Sustainable Valorization of By-Products in a Circular Economy. *Sustainability* **2025**, *17*, 6704. https://doi.org/10.3390/su17156704

1. Introduction

In today's global context of rapid urbanization, consumerism, and resource-intensive lifestyles, municipal solid waste (MSW) generation has reached unprecedented levels, creating complex environmental, economic, and social challenges. Globally, municipal solid waste generation is projected to increase from 2.1 billion tons in 2023 to 3.8 billion tons by 2050, while in the European Union (EU), each person generates, on average, nearly half a ton of MSW/year [1,2], a figure that continues to grow despite ongoing efforts in waste reduction and recycling.

When improperly managed, the various fractions of MSW (organic, inorganic, and mixed) contribute significantly to greenhouse gas (GHG) emissions, soil and groundwater contamination, and the depletion of valuable resources through landfilling. Additionally, the uncontrolled release of hazardous substances from waste, such as heavy metals, persistent organic pollutants, and microplastics, can degrade air quality, disrupt ecosystems, and pose serious risks to human health, including respiratory problems, waterborne diseases, and long-term exposure-related conditions such as cancer or neurological disorders [3,4].

In response to these environmental and health-related concerns, the EU and many countries worldwide have adopted the waste management hierarchy, which prioritizes prevention, followed by reuse, recycling, energy recovery, and, as a last resort, landfilling. Implementing integrated municipal solid waste management systems based on this hierarchy is essential for improving environmental performance, resource efficiency, and public health.

Figure 1 illustrates the distribution of municipal waste management methods in 2022: recycling (including composting), waste-to-energy, and landfilling, across each EU Member State, as well as Switzerland, Norway and Iceland. The countries are ordered by the proportion of waste sent to landfill. The graph highlights missing data, representing the discrepancy between the amount of waste generated and the amount of waste treated within each country.

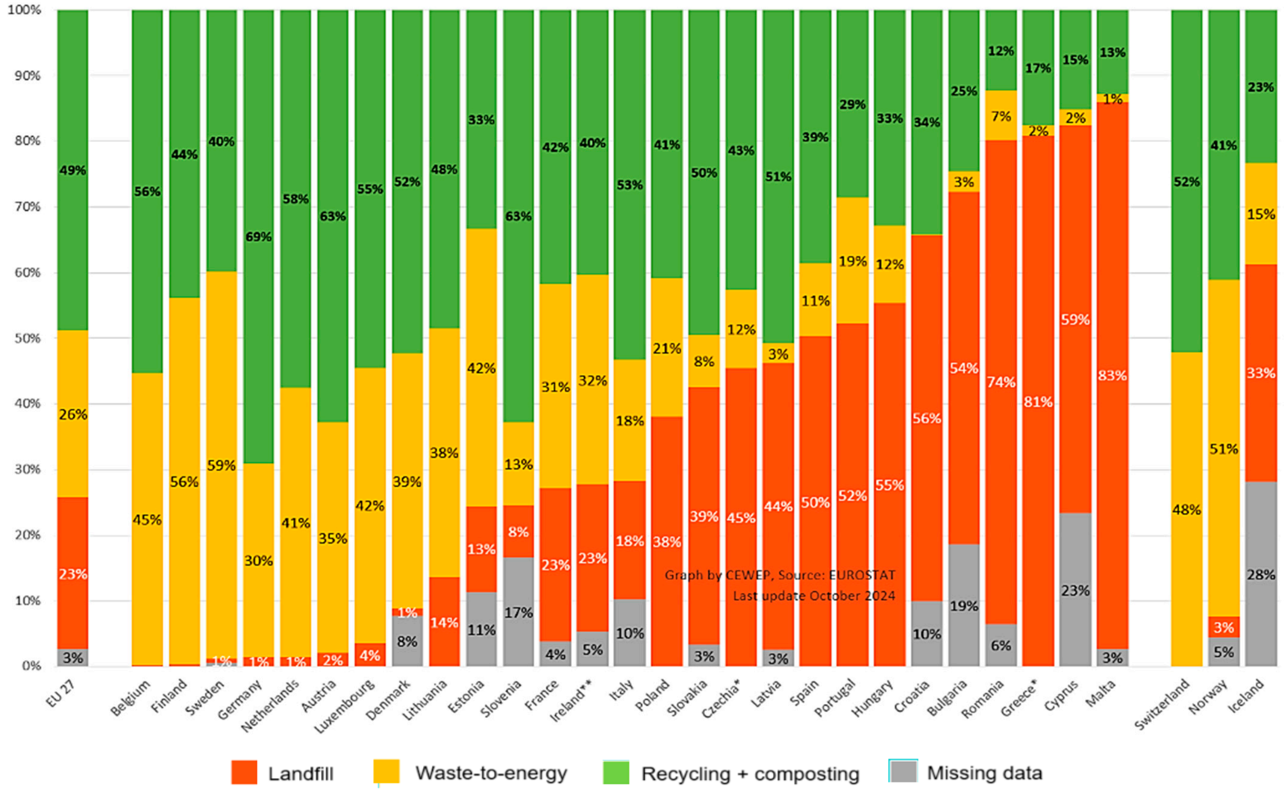


Figure 1. Municipal waste treatment in 2022 [5]; * indicates Eurostat estimated values for Greece and the Czech Republic; ** indicates missing or incomplete data for Ireland in Eurostat reporting.

In 2022, Germany emerged as the leader in municipal waste recycling, achieving a combined recycling and composting rate of 69%. Furthermore, nine Member States, including Slovenia (which reports a 17% discrepancy between waste generated and waste treated), landfilled less than 10% of their municipal waste, thereby aligning with the 2035 target set by the revised EU Landfill Directive. In contrast, another nine Member States continued to landfill over 50% of their municipal waste, indicating persistent disparities in waste management performance across the European Union [2].

Despite these pressing concerns, the perception of MSW is beginning to shift. Municipal solid waste is increasingly recognized as a potential strategic resource rather than merely an environmental burden. On a global scale, food and green waste constitute approximately 44% of MSW, while paper and cardboard (17%), plastic (12%), metals (5%), glass (4%), wood (2%), rubber and leather (2%), and other materials (14%) make up the remainder of the composition [6].

With substantial fractions of biodegradable matter, plastics, textiles, and other combustible materials, MSW holds considerable potential for energy and material recovery. As a result, sustainable MSW management has evolved beyond traditional disposal methods, moving toward integrated systems rooted in circular economy principles [5].

Traditionally, municipal solid waste management followed a linear model: collect, use, and dispose, which led to significant environmental pressures and the inefficient use of finite resources. In contrast, the circular economy promotes the recovery of materials and energy from waste [7,8], aiming to close loops, reduce dependency on raw inputs, and support long-term environmental sustainability [9]. This evolution reflects a broader shift in waste governance, where waste is no longer viewed solely as a burden, but as a resource to be reintegrated into the production cycle.

The European legislative framework recognizes the significant potential for energy and material recovery from municipal waste fractions. It actively promotes energy recovery solutions that align with circular economy principles and decarbonization targets. In this context, thermochemical waste-to-energy processes play a key role in diversifying energy sources and reducing the volume of landfilled waste. The legislation also defines specific requirements and limits for using waste and biomass for energy production, supporting the sustainable development of waste-to-energy technologies.

The utilization of MSW for energy generation, commonly referred to as Waste-to-Energy (WtE), represents a key strategy in the transition toward sustainable resource management and low-carbon energy systems. This approach enables the recovery of the intrinsic energy content of waste materials through thermal, biological, or chemical processes, transforming non-recyclable residues into electricity, heat, or fuels [10].

Waste-to-energy technologies encompass a diverse set of conversion processes, ranging from well-established methods such as mass incineration with energy recovery, anaerobic digestion, and landfill gas capture, to more advanced and innovative thermal and thermochemical pathways such as incineration with heat recovery, pyrolysis, and gasification [11]. While pyrolysis plants have reached high levels of technological maturity and commercialization, the gasification plants are currently in various stages of development and demonstration, depending on the feedstock, reactor design, and integration potential.

Recently, research in the field of waste gasification has highlighted significant developments in the optimization of thermochemical processes and the integration of hybrid technologies, which contribute to increasing energy efficiency and reducing pollutant emissions [12,13]. Also, recent studies have emphasized the importance of ensuring operational safety and compliance with environmental standards in the implementation of gasification plants [14]. In addition, the integration of the valorization of by-products, such as biochar and tar, within circular economy systems offers additional opportunities for sustainable and efficient resource management [15].

Before thermochemical treatments, MSW is often subjected to physical–mechanical, biological, or thermal pretreatment. These steps improve the performance of energy conversion technologies by protecting equipment and reducing operational costs. Additionally, pretreatment helps produce an alternative solid fuel with uniform and suitable energetic and physico–chemical properties.

Environmentally, WtE technologies contribute to the reduction of greenhouse gas emissions, particularly methane from landfills, and limit the dependence on fossil fuels by replacing them with energy recovered from waste. These systems also play a crucial role in reducing the volume of landfilled waste, thus mitigating long-term soil and groundwater contamination risks and reducing the pressure to develop new landfill sites.

In addition to their environmental benefits, WtE facilities offer economic and social advantages, including the creation of employment opportunities in waste collection, sorting, maintenance, and energy production, as well as the diversification of local energy portfolios [11]. By integrating WtE into modern waste management systems, municipalities can advance toward circular economy goals, ensuring that waste is not simply discarded but rather valorized as a resource.

As WtE technologies become increasingly integrated into circular economy strategies, understanding their technological maturity and scalability becomes essential for informed policy and investment decisions. To assess the development stage and deployment feasibility of these technologies, the Technology Readiness Level (TRL) framework is widely applied. This scale ranges from early concept validation (TRL 1–3), through laboratory and pilot stages (TRL 4–6), to full commercialization (TRL 7–9), offering a standardized metric for evaluating innovation readiness and market viability.

This paper aims to provide a comprehensive and up-to-date analysis of MSW gasification technologies by evaluating their current TRLs, operational parameters, and integration potential in circular economy frameworks. A novel contribution of this paper lies in the structured comparison across eight distinct gasification pathways, including emerging options such as microwave-assisted and supercritical water gasification, paired with a critical assessment of syngas and by-product valorization strategies. The paper further highlights how gasification by-products (syngas, ash, tar, and biochar) can be reintegrated into energy, agricultural, and industrial systems, offering a multidimensional perspective that supports sustainable waste-to-resource approaches. This integrative view addresses a knowledge gap by linking technological performance with valorization routes in a policy-relevant context shaped by the European Union's circular economy goals.

2. MSW Gasification: Process Description and Comparative Analysis with Pyrolysis and Incineration

This section first outlines the core process stages and underlying mechanisms of MSW gasification. Subsequently, a comparative analysis with alternative thermochemical conversion routes, such as pyrolysis and incineration, is provided to contextualize its performance and environmental relevance.

Gasification is a thermochemical conversion process in which carbon-rich materials (such as coal, biomass, or MSW) are transformed into synthesis gas (syngas) through reaction with a gasifying agent (typically air, oxygen, steam, or a combination thereof), at high temperatures (generally between 900–1200 °C) and, in some systems, under elevated pressure [11].

The resulting gaseous product, known as syngas, is primarily composed of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), methane (CH_4), and, to a lesser extent, higher hydrocarbons, depending on the feedstock and operating conditions. In addition to syngas, the gasification can yield by-products such as solid residues (ash or vitrified slag), tars, fine particulates, wastewater, and residual heat, depending on the reactor type, feedstock composition, and operating conditions.

Although the primary goal of gasification is the production of syngas, certain systems, particularly those operating under suboptimal conditions, may also produce minor amounts of char or biochar. While less prominent than in pyrolysis, this solid by-product can be valorized for energy recovery or agricultural use, provided it meets quality and contamination thresholds. These by-products require appropriate management or valorization pathways, especially in the context of integrated waste-to-energy strategies and circular economy frameworks.

Even if the fundamental principles of gasification remain consistent, the specific implementation of the process can vary significantly depending on the type of reactor configuration employed. These configurations differ in terms of heat transfer mechanisms, feedstock compatibility, and operational parameters such as temperature, pressure, and residence time.

A wide array of gasifier designs has been developed to optimize performance for diverse types of MSW. The main technological options, including both conventional and emerging gasification systems, are presented in detail in Section 4. Regardless of the reactor type, the gasification process follows a general sequence of thermochemical stages: drying, pyrolysis (or devolatilization), partial oxidation (or combustion), and reduction (or gasification) [16], as described in Figure 2 and Table 1.

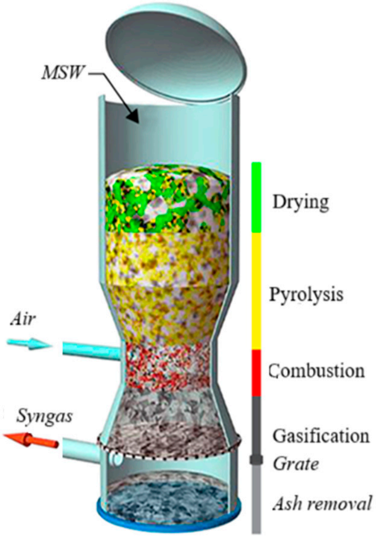


Figure 2. Diagram of a gasification reactor highlighting the four main process stages [11,17].

Table 1. Main stages of the gasification process MSW and biomass [Author's own elaboration].

Stage	Description
Drying	MSW and/or biomass, which typically contains a high moisture fraction (especially food waste and green waste), is dried at temperatures of 100–200 °C to reduce moisture content below 5–10%. Efficient drying is essential for thermal stability and improved reaction kinetics in the downstream stages.
Pyrolysis (devolatilization)	In the absence or limitation of oxygen, thermochemical decomposition occurs at temperatures between 150–900 °C, breaking down organic fractions of MSW and/or biomass into volatile gases, condensable tars, and a solid carbonaceous residue (char.) This char is the key reactive material for the subsequent gasification reactions. Some volatile compounds condense into a liquid phase upon cooling to room temperature, forming tar, a black, viscous, and corrosive substance composed of complex heavy organic and inorganic molecules.

Partial oxidation (combustion)	At temperatures over 750 °C, the fixed carbon (char) reacts exothermically with a limited amount of oxygen or air, generating CO_2 and releasing heat. This thermal energy supports the endothermic reduction reactions. Hydrogen from volatile components may also be oxidized to form H_2O.
Reduction (gasification)	At temperatures between 800–1000 °C, the remaining carbon reacts with CO_2 and/or H_2O (steam) to produce a combustible gas mixture (syngas) primarily composed of CO and H_2, with minor fractions of CH_4, CO, CO_2, N_2, and light hydrocarbons. This is the final and critical stage where energy-rich gas is recovered for downstream applications.

To represent the overall transformation occurring during gasification, a global stoichiometric reaction is often used. This simplified model is based on the ultimate analysis of the feedstock (typically expressed as CH_xO_y) and integrates the effects of multiple thermochemical processes, such as partial oxidation, reforming, cracking, and tar decomposition [18,19]:

$$CH_xO_\gamma + wH_2O + mO_2 + 3.76\ mN_2 \rightarrow aH_2 + bCO + cCO_2 + dH_2O + eCH_4 + fN_2 + gC \tag{1}$$

where CH_xO_γ—empirical formula of the feedstock, based on its ultimate analysis (representing carbon, hydrogen, and oxygen content); wH_2O—amount of steam added as a gasification agent; mO_2—amount of oxygen introduced into the system; 3.76 mN_2—nitrogen accompanying oxygen when air is used as the oxidant (air contains ~21% O_2 and ~79% N_2 by volume); aH_2—hydrogen produced in the syngas; bCO—carbon monoxide in the syngas; cCO_2—carbon dioxide formed during partial and complete oxidation; dH_2O—unconverted steam or water generated during reactions; eCH_4—methane formed via secondary reactions or devolatilization; fN_2—inert nitrogen from the air, not participating in the reactions; gC—residual solid carbon (char) remaining after incomplete conversion (all terms in moles).

The detailed main reactions are as follows [18,19]:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \qquad \text{(CH}_4\text{ decomposition)} \tag{2}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad \text{(water gas shift reaction)} \tag{3}$$

$$C + H_2O \rightarrow CO + H_2 \qquad \text{(heterogeneous water gas shift reaction)} \tag{4}$$

$$C + CO_2 \rightarrow 2CO \qquad \text{(Boudouard equilibrium)} \tag{5}$$

$$2C + O_2 \rightarrow 2CO \qquad \text{(partial oxidation)} \tag{6}$$

$$C + O_2 \rightarrow CO_2 \qquad \text{(complete oxidation)} \tag{7}$$

$$\text{Tar} \rightarrow CO + H_2 + CH_4 \qquad \text{(tar cracking)} \tag{8}$$

Based on data reported in the literature, we compiled Table 2, which provides the standard enthalpy of reaction (ΔH^0) for each reaction presented in Equations (2)–(8), expressed in kJ/mol. These values correspond to standard conditions, specifically a temperature of 25 °C and a pressure of 1 atm.

Table 2. Standard enthalpy of reaction (ΔH^0) for gasification-specific equations. [Author's own elaboration.]

Equation	ΔH^0 (kJ/mol)	Reaction Type	Reference
(2)	+206	Endothermic	[20,21]
(3)	−41	Exothermic	[20,21]

(4)	+131	Endothermic	[20,21]
(5)	+172	Endothermic	[20,21]
(6)	−221	Exothermic	[20,21]
(7)	−394	Exothermic	[20,21]
(8)	$\Delta H^0 > 0$	Presumed endothermic	[20,21]
(2)	+206	Endothermic	[22]

In the case of reaction (8), which involves tar (a complex mixture of aromatic and aliphatic compounds with variable composition depending on the type of waste and the gasification conditions) there is no single, universally accepted standard enthalpy value. However, it is widely acknowledged in the scientific literature that the conversion of tar is an endothermic reaction, typically associated with a positive ΔH^0, the exact value of which depends on the specific chemical composition of the tar fraction. This reaction is often exploited in practice to enhance the yield of H_2 and CH_4 in the produced syngas, thereby increasing the overall energy content of the gaseous output.

H_2 and CO generated through gasification constitute the primary combustible components of syngas, which can be utilized as a fuel in various energy conversion systems.

To better understand the distinct advantages of gasification, it is useful to compare it with other thermochemical MSW conversion methods, namely pyrolysis and incineration.

Unlike incineration, which operates in conditions of excess oxygen (typically >100% stoichiometric ratio), and at high temperatures ranging between 850 and 1100 °C [11], gasification is a partial oxidation process, employing only 25–30% of the oxygen required for complete combustion of organic matter [17]. This limited oxygen environment facilitates the thermal decomposition of carbonaceous materials into a combustible synthesis gas (syngas) rather than into flue gases and ash.

Pyrolysis is a thermochemical decomposition process that occurs in the complete absence of oxygen and is typically conducted at temperatures ranging between 300 and 700 °C [11]. Pyrolysis can function either as an independent conversion route or as the initial devolatilization phase in gasification. Under these anoxic and moderate-temperature conditions, the feedstock undergoes thermal degradation, yielding volatile components (condensable vapors and permanent gases) and a carbon-rich solid residue (char) that retains a substantial fraction of the original fixed carbon.

Compared to incineration, pyrolysis is an environmentally friendly alternative, as it takes place at lower temperatures and in inert environments, which significantly limits the formation of dioxins, furans, and nitrogen oxides. This makes pyrolysis a safer technology in terms of environmental impact when treating solid organic waste.

Both pyrolysis and gasification produce forms of combustible gas known generically as syngas. However, the composition and quality of this gas differ depending on the process used. The key distinction between pyrolysis and gasification lies in the fate of the fixed carbon: gasification further converts the (bio)char into syngas via reduction reactions, typically involving steam or CO_2. This additional conversion step enables higher carbon conversion efficiencies and a more energy-rich product gas, offering superior energy recovery performance compared to both incineration and pyrolysis.

From an environmental perspective, gasification systems operating under controlled conditions produce lower quantities of nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate emissions, particularly when combined with advanced syngas cleaning technologies. Furthermore, gasification of MSW allows for better handling of heterogeneous feedstocks and minimizes the production of hazardous residues such as dioxins and furans, commonly associated with incineration.

Table 3 offers a comparative overview of the three main thermochemical processes.

Table 3. Comparative overview: incineration vs. pyrolysis vs. gasification. [Author's own elaboration.]

Parameter	Incineration	Pyrolysis	Gasification
Oxygen supply	Excess air (>100%)	None (anaerobic)	Sub-stoichiometric (25–30%)
Temperature range (°C)	850–1100	300–700	900–1200
Main products	Heat + flue gases (CO_2, H_2O, NO_x, SO_x, particles, dioxins etc.) + bottom and fly ash	Char (solid) + condensable vapors (bio-oil or pyrolytic liquid) + non-condensable gases (pyrolysis gas)	Synthesis gas (syngas) + solid residues (slag or ash) + minor amounts of tars and unconverted char
Carbon conversion	Complete	Partial (fixed carbon remains)	Near-complete
Energy efficiency (% lower heating value)	15–25	35–50 (with valorization)	60–80 (with syngas utilization)
Air pollutants (NO_x, SO_x, PM)	High (needs advanced control)	Low–moderate	Low (if gas cleanup is applied)
Suitability for MSW	Very common	Limited (requires presorting)	Increasingly used, especially RDF/MSW
Dioxins and furans	Risk present	Minimal	Very low
Ash production	High	Medium	Low–medium (possible vitrified slag)

3. Key Factors Influencing the Gasification Performance

The gasification of MSW is a complex thermochemical process influenced by a range of parameters that directly affect syngas composition, process efficiency, energy yield, and the formation of undesirable by-products such as tar or slag. Unlike biomass, which tends to have a more homogeneous composition, MSW is heterogeneous in nature, comprising organic fractions, plastics, paper, textiles, inert materials, and varying moisture levels. Consequently, the optimization of gasification parameters requires careful consideration of the unique characteristics of MSW feedstocks.

3.1. Temperature

Temperature is a key parameter influencing the efficiency and by-products composition of MSW gasification. It influences the rate of chemical reactions, syngas composition, and the degree of tar decomposition. Higher temperatures favor the breakdown of complex hydrocarbons and increase the yield of H_2 and CO in the syngas, while significantly reducing tar formation [23].

The optimal gasification temperature for MSW varies depending on factors such as feedstock characteristics and reactor configuration. A suitable operational range of 550–900 °C was reported in [19], while other studies identified narrower or higher optimal intervals. For instance, using integrated simulation and performance analysis, it was found that 800 °C is the optimal temperature for maximizing hydrogen production, with significantly higher hydrogen yields compared to lower temperatures [24]. However, it was observed that although overall syngas production increased between 700 and 800 °C, the hydrogen fraction remained relatively constant [25]. These differences emphasize the importance of aligning the operational temperature with the specific objectives of the process, whether focused on hydrogen enrichment, energy recovery, or tar minimization.

Operating at temperatures above 850 °C generally ensures more complete feedstock conversion and improved syngas quality, particularly through enhanced CO and H_2 generation and reduced tar production [19]. However, such high-temperature operation requires careful control, as it can lead to increased thermal stress on reactor components and may necessitate the use of heat-resistant materials. This introduces trade-offs between performance and system durability, especially in large-scale or continuous processes. Therefore, temperature must be optimized not only for gas quality, but also considering technical feasibility, material constraints, and long-term operational stability.

Reactor configuration plays a decisive role in determining feasible temperature windows. Fluidized bed gasifiers perform best within the 850–950 °C range, benefitting from better heat transfer and mixing efficiency. In contrast, fixed bed systems often operate at slightly lower temperatures due to design and material limitations [11,17]. These constraints must be considered when selecting or designing the reactor, especially for decentralized or modular systems.

Thus, temperature optimization is essential for achieving high-quality syngas and stable gasification. It must be adapted to the specific configuration and goals of each system, considering both thermodynamic and economic considerations. A well-chosen temperature range can enhance performance, reduce undesired by-products, and contribute to the overall reliability and sustainability of MSW gasification systems.

3.2. Pressure

Pressure plays a critical role in the efficiency and product distribution of MSW gasification. Elevated pressures can shift the chemical equilibrium of gasification reactions, favoring the formation of desirable gaseous products such as H_2 and CO. This enhances feedstock conversion and improves overall process efficiency [26]. Higher pressures also increase reaction rates, reduce the required reactor volume, and improve reactant contact, contributing to a more compact and efficient gasification system.

In addition, elevated pressures influence the formation of light hydrocarbons such as CH_4, depending on the feedstock characteristics and temperature regime; this affects both the syngas composition and its calorific value, which are critical parameters when the gas is intended for combustion or chemical synthesis. Pressure also impacts secondary reactions, such as tar reforming and cracking, potentially leading to lower tar yields under optimized thermal and catalytic conditions. However, operating under high pressure introduces several technical challenges. These include the need for robust reactor designs, advanced sealing systems, and high-pressure gas cleaning technologies to handle the increased density and potential condensation of impurities. Such systems are more expensive to construct and maintain, and their complexity must be justified by tangible performance improvements.

While atmospheric pressure gasification is simpler and widely used in small-scale or experimental systems, studies have shown that moderate pressurization (5–10 bar) can significantly improve syngas yield and heating value, especially when the process is optimized for hydrogen-rich gas production [27]. This makes pressurized gasification particularly attractive for integrated energy systems or downstream chemical synthesis where gas quality is critical. Nevertheless, increasing pressure beyond 20 bar tends to offer diminishing returns, particularly for complex and heterogeneous feedstocks like MSW. Excessive pressurization may result in higher operational costs and technical risks without a proportional improvement in gas quality or energy efficiency [19].

Therefore, pressure should be carefully optimized based on reactor configuration, feedstock characteristics, and the target application of syngas. In most cases, moderate pressure strikes a balance between improved performance and manageable system complexity, offering a practical compromise for advanced MSW gasification technologies.

3.3. Waste Moisture Content

Moisture content is one of the most critical factors in the gasification of MSW. High moisture levels reduce the reactor temperature and energy conversion efficiency, as a significant portion of the thermal energy is consumed in evaporating water. The latent heat of vaporization is approximately 2260 kJ/kg of water, representing an irreversible energy loss. For effective gasification, a moisture content below 20% is generally recommended, with an ideal range of 10–15% [28]. MSW often contains wet fractions such as food and green waste, which necessitate pre-drying or co-gasification with drier feedstocks, such as refuse-derived fuel (RDF), to stabilize the process.

In practice, maintaining low moisture content is essential to ensure stable operation and optimal syngas quality. Excessive moisture not only decreases the gasification temperature but also leads to lower carbon conversion efficiency and increased tar formation, which can cause operational issues like tar clogging in downstream equipment [29]. Pretreatment methods such as mechanical dewatering, thermal drying, or blending with low-moisture materials have proven effective to achieve the desired moisture range [30].

From a technological standpoint, gasifiers designed for feedstocks with variable moisture content often incorporate internal drying zones or staged feeding to accommodate moisture fluctuations without compromising performance. However, these adaptations can increase capital and operational costs. Therefore, thorough feedstock characterization and moisture control are recommended as part of process design and optimization.

Moreover, the moisture content influences the choice of gasifier type: fluidized bed gasifiers are more tolerant to moisture variations compared to fixed bed gasifiers, which require stricter moisture limits to avoid temperature drops and incomplete gasification. Overall, controlling moisture content is critical for maximizing energy efficiency and minimizing operational challenges in MSW gasification systems.

3.4. Waste Particle Size and Shape

Particle size and shape significantly influence heat and mass transfer kinetics, residence time, and compatibility with different types of gasifiers. In the case of MSW, pretreatment processes such as shredding and screening are used to achieve particle sizes suitable for gasification, typically ranging between 10 and 50 mm. The smaller the particle size, the greater the available surface area, which enhances reaction rates and improves overall gasification efficiency [31].

Fixed bed gasifiers operate best with coarse and relatively uniform particles, as they rely on laminar flow and stable thermal gradients for efficient conversion. These systems can process feedstock with particle sizes up to 51 mm [32], but require consistent sizing to avoid problems such as channeling, poor gas–solid contact, and incomplete conversion. Variations in particle size disrupt temperature distribution and flow dynamics, leading to increased tar formation and reduced performance [17].

Bubbling fluidized bed gasifiers, by contrast, are better suited to finer and more heterogeneous mixtures, offering enhanced mixing and thermal uniformity. They typically accommodate particle sizes up to approximately 6 mm. However, particles larger than this threshold can impair fluidization quality and reduce reaction efficiency [32]. Moreover, excessively fine particles may destabilize the bed, leading to entrainment from the reaction zone and reduced residence time. This effect has been observed in dual fluidized bed systems, where coarse or unevenly sized particles were prone to entrainment into the freeboard, increasing tar production and highlighting the need for precise pretreatment strategies [27].

Entrained flow gasifiers are the most demanding in terms of particle fineness, requiring feedstocks to be ground below 0.15 mm [32] to ensure uniform flow and complete conversion. These systems rely on high-temperature, high-velocity flows and thus demand homogenous particle characteristics for optimal performance.

From a technological standpoint, aligning particle size and distribution with the specific requirements of each gasifier type is critical to minimizing operational issues and maximizing efficiency. In fixed bed systems, maintaining uniform particle distribution is essential to preserve laminar flow, while in fluidized bed configurations, advanced control strategies are needed to manage entrainment and avoid localized temperature gradients [19].

Furthermore, particle morphology plays a key role in gasification performance. Irregularly shaped or rough-surfaced particles can disturb fluid dynamics by generating non-uniform flow paths and localized hot spots. These disruptions reduce heat transfer efficiency, degrade syngas quality, and may accelerate wear of reactor internals. Therefore, optimizing not only the size, but also the shape and surface properties of the feedstock is essential to ensure stable, efficient, and long-term gasifier operation.

3.5. Ash Content and Inorganic Composition of MSW

The ash content and inorganic composition of MSW present operational challenges in gasification reactors. MSW often contains high levels of mineral impurities, including glass, metals, and treated textiles, resulting in elevated ash generation. If not managed appropriately, this can lead to slagging or agglomeration inside the reactor. The slagging tendency depends on the ash fusion temperature; thus, the reactor must be operated either below the ash deformation point (typically <800 °C) or significantly above the melting point (>1200 °C) to avoid blockages. An ash content below 10% is desirable, although untreated MSW may exhibit values exceeding 15–20% [11].

In addition to operational issues, high ash content may reduce the calorific value of the produced syngas and increase the burden on gas cleaning systems. Moreover, specific inorganic constituents such as sodium, potassium, and chlorine can intensify slagging, fouling, and corrosion processes at elevated temperatures. As a result, pretreatment strategies, including inert removal and feedstock homogenization, are essential for improving process stability and equipment longevity.

From a practical perspective, effective ash management is key to minimizing unplanned downtimes and maintaining thermal efficiency. Heberlein et al. (2021) [33] demonstrated that slag accumulation in high-temperature MSW gasification disrupts the uniform distribution of heat and gas flow within the reactor, often leading to operational instabilities and necessitating periodic shutdowns for cleaning and maintenance. Moreover, Dunayevska et al. (2025) [34] found that the presence of alkali metals such as potassium and sodium significantly lowers the ash fusion temperature, increasing the risk of localized slag formation and corrosion, particularly in areas exposed to sustained thermal gradients. These effects underline the importance of controlling feedstock composition and operating temperature to protect refractory linings and prolong equipment life. To mitigate these effects, it is essential to recognize the significant economic impact associated with corrosion-related failures in gasification systems. Early identification of critical ash-forming elements during feedstock assessment plays a crucial role in preventing operational issues. This underscores the importance of thorough feedstock characterization and the implementation of targeted removal or pretreatment strategies prior to gasification to enhance process stability and reduce maintenance costs.

Recent advancements in mechanical separation methods, including magnetic extraction of ferrous contaminants and particle size classification, have significantly enhanced the efficacy of feedstock pretreatment. Implementing these techniques not only reduces the ash content but also improves feedstock uniformity, which contributes to more stable and predictable gasifier operation. Furthermore, tailoring operational parameters, including gasifier temperature profiles and material selection (e.g., corrosion-resistant alloys), contributes significantly to extending system lifetime and reducing maintenance needs. Therefore, thorough analysis of MSW ash content and composition should be integrated into the design and operational strategies of gasification plants to optimize performance and minimize equipment degradation.

3.6. Gasification Agents

Gasification agents include steam, air, O_2, CO_2, and various combinations thereof. In practical terms, the selection of the gasifying agent must balance syngas quality, process efficiency, and economic feasibility.

Steam is well-suited for both small- and large-scale systems, as it generates syngas with a high hydrogen content (typically exceeding 60 vol%) and reduced levels of CO_2 and CH_4. Steam-based systems are especially advantageous when the target application is hydrogen production or chemical synthesis, due to their ability to maximize hydrogen yield [35]. Nonetheless, the energetic cost associated with steam generation can significantly impact net efficiency, especially in smaller-scale or off-grid setups [36].

Air, by contrast, is more appropriate for small or laboratory-scale applications, yielding a syngas with 5–40 vol% H_2 along with significant levels of CO and N_2, the latter resulting from atmospheric dilution [37]. While air gasification offers the benefit of simplicity and low capital expenditures, the resulting diluted syngas often limits its applicability in value-added fuel synthesis, unless extensive upgrading is applied [38]. This makes air more suitable for direct combustion or CHP systems, rather than for high-purity applications.

O_2 is often used in medium- to large-scale facilities, enabling the production of N_2-free syngas with higher heating value and increased H_2 and CO concentrations. One of the key advantages of oxygen-blown gasifiers is the ability to reach higher operating temperatures, which enhances carbon conversion and results in a cleaner syngas. However, this benefit comes at the expense of added system complexity and cost, primarily due to the need for cryogenic air separation units [39]. Ongoing developments in membrane-based or chemical-looping separation technologies may help reduce these drawbacks and improve the economic feasibility of O_2-based gasification.

The application of CO_2 as a gasifying agent supports low-carbon technologies by reintegrating CO_2 into the thermochemical conversion process, thereby promoting carbon recycling and reducing net greenhouse gas emissions [40]. In addition to its role in carbon circularity, CO_2 acts as a mild oxidant that can influence reaction selectivity and thermodynamic equilibrium [41]. Despite these environmental advantages, CO_2 gasification remains largely experimental due to its slow reaction kinetics, necessitating the use of enhanced catalysts or modified reactor conditions for industrial viability.

3.7. The Equivalence Ratio

The equivalence ratio (ER), defined as the actual air-to-fuel ratio divided by the stoichiometric air-to-fuel ratio, governs the oxidation–reduction balance in the reactor and plays a crucial role in determining the properties of the final products, especially the tar content [42]. For air-blown gasification, an ER of 0.2–0.4 is generally considered optimal, enabling partial oxidation that supplies the necessary heat for endothermic reactions without triggering complete combustion. In steam- or oxygen-blown systems, the steam-to-carbon molar ratio is typically maintained between 0.6–1.2 to promote hydrogen production and regulate temperature profiles. Deviations from these optimal values can result in excessive CO_2 formation, incomplete gasification, or thermal instability.

Additionally, the ER has a direct impact on syngas composition, particularly the H_2/CO ratio, and on the efficiency of the process. A low ER tends to enhance hydrogen yield but may lead to poor carbon conversion and increased tar formation. In contrast, a high ER favors complete combustion, which lowers the calorific value of syngas and increases thermal losses. Therefore, selecting the appropriate ER involves trade-offs between fuel conversion efficiency and syngas quality, depending on the target application of the syngas.

From a technological perspective, modern gasifiers increasingly incorporate real-time monitoring and adaptive control systems to maintain ER within optimal limits, even under conditions of variable feedstock composition. Moreover, ER must be carefully adjusted in accordance with both the gasifying agent used and the specific reactor configuration, as improper settings can compromise system performance or require costly post-treatment stages. Integrating ER control into the early design phase helps ensure stable operation, higher energy efficiency, and consistent syngas output in full-scale waste-to-energy applications.

3.8. Residence Time

The residence time (RT), defined as the average duration the feedstock remains in the reactor's reaction zone, is a critical parameter for achieving complete thermochemical conversion. Insufficient RT may result in unconverted char, tar carryover, and reduced syngas quality. Conversely, extended RT allows more thorough completion of heterogeneous and homogeneous reactions, enhancing carbon conversion and increasing the yield of valuable gases such as hydrogen and carbon monoxide.

Fluidized bed gasifiers typically operate at short RT values (1–3 s) due to intense mixing and rapid heat transfer, whereas fixed bed systems often require longer RT (10–20 s or more) to ensure full conversion, particularly when processing coarse, wet, or heterogeneous feedstocks [43,44]. Therefore, optimizing RT is essential not only for maximizing carbon conversion efficiency, but also for reducing tar formation and ensuring consistent syngas composition and energy content.

Inadequate RT can seriously impair gasifier performance by increasing tar and char residues, which complicate downstream cleaning and reduce overall system efficiency. Conversely, overly long RT values may lower throughput, increase reactor volume, and raise capital costs without proportional gains in gas quality [45].

From a technological perspective, fluidized bed reactors maintain shorter RT while achieving high conversion rates, due to superior internal mixing and heat transfer. In contrast, fixed bed gasifiers require stricter control of feedstock particle size and moisture to ensure an appropriate RT and avoid incomplete reactions.

As such, careful design and dynamic operational control of RT are critical for balancing conversion efficiency, minimizing operational problems, and maintaining economic viability. Integrating RT considerations from the early design phase can prevent over-dimensioning and reduce the need for costly post-processing systems.

3.9. Gasifier Configuration

Gasifier configuration has a direct impact on process efficiency, feedstock compatibility, and product quality.

Fixed bed gasifiers offer a relatively simple and cost-effective design but exhibit limited tolerance to feedstock heterogeneity, particularly with respect to particle size, composition, and moisture content. As a result, they require well-prepared, uniform input materials and are best suited for waste streams with consistent properties [46].

Fluidized bed gasifiers, by contrast, provide greater operational flexibility, particularly when processing MSW with heterogeneous and non-uniform composition, due to their superior mixing, and heat and mass transfer capabilities [26]. This design feature not only improves the consistency of the gasification reactions but also minimizes the risk of localized hotspots and slagging, leading to more stable and efficient operation over time. Moreover, their adaptability to varying feedstock properties makes them especially suitable for decentralized waste-to-energy applications in urban areas, where waste composition can fluctuate significantly.

More advanced configurations, such as rotary kilns and plasma gasifiers, can handle a broad spectrum of complex, heterogeneous, or even hazardous waste streams. While plasma gasification enables near-complete waste destruction and yields cleaner syngas, these systems are often associated with high energy demands, elevated capital and operational costs, and increased technical complexity, limiting their feasibility for large-scale municipal deployment. Therefore, their use remains largely confined to niche applications where regulatory constraints, environmental risk, or waste toxicity justify the investment.

Choosing the appropriate gasifier type thus requires balancing capital expenditure, operational requirements, and feedstock characteristics. A thorough feedstock characterization and pilot-scale validation are essential to ensure process reliability, optimize energy efficiency, and avoid over-dimensioning or technology mismatches [47].

4. Technologies for Municipal Solid Waste Gasification

The gasification process was first developed in Germany, a country that played a key role in the conceptual foundation of the three major technological configurations of gasification reactors: fixed bed, fluidized bed, and entrained flow.

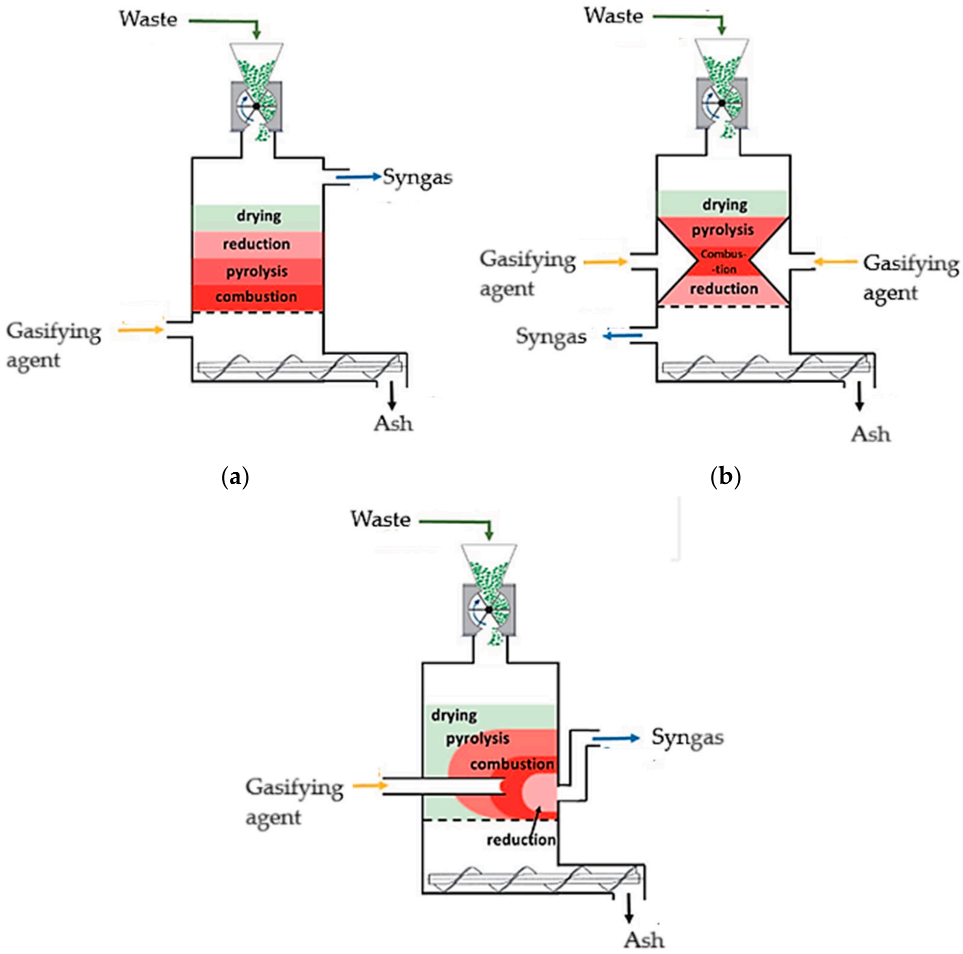
Building on these foundational designs, a range of advanced gasification technologies have since been developed to accommodate diverse feedstocks, improve energy efficiency, and reduce environmental impact. These include plasma gasification, which utilizes extremely high temperatures to decompose complex materials; supercritical water gasification, effective for wet biomass and sewage sludge; microwave-assisted gasification, which enables selective and uniform heating; high-temperature steam gasification, which enhances hydrogen yield and syngas purity; and rotary kiln systems, typically employed for heterogeneous or low-reactivity materials.

In addition to these, other configurations and hybrid systems, such as dual fluidized bed, spouted bed, and indirectly heated reactors, continue to be explored, reflecting the ongoing innovation in this field to meet the evolving demands of sustainable energy and waste valorization.

4.1. Fixed Bed Gasification

Fixed bed gasification represents one of the most established and mechanically simple thermochemical technologies for converting solid carbonaceous feedstocks into syngas. Three main configurations are employed: updraft, downdraft, and crossdraft [48,49] (Figure 3). In the updraft design, syngas is extracted from the top of the reactor, resulting in higher tar content due to limited thermal cracking. In contrast, downdraft gasifiers allow for greater thermal contact between the syngas and hot char, promoting tar reduction and cleaner gas output.

Updraft and downdraft systems are suitable for small to medium-scale applications and can accommodate a wide variety of dry, homogenous biomass types, such as wood chips, pellets, sewage sludge, and agricultural residues [48]. In a crossdraft gasifier, biomass is fed from the top, while air is introduced laterally through the side of the reactor. As the biomass descends, it undergoes sequential drying and gasification. Concurrently, pyrolysis, oxidation, and reduction reactions are concentrated in the lateral zone where the air enters, resulting in localized high-temperature zones and rapid reaction kinetics [49].



(**a**) (**b**) (**c**)

Figure 3. Fixed bed gasifier types and flow directions: (**a**) updraft; (**b**) downdraft; (**c**) crossdraft. (Adapted from [50], under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/3.0)) accessed on 16 July 2025.

These reactors typically consist of a vertical, cylindrical vessel where the feedstock is introduced from the top, while the gasifying agent (which may be air, oxygen, or steam) is injected from the bottom (in updraft configurations) or from the top or side (in downdraft configurations). The process occurs over extended residence times, generally between 900 and 1800 s, under operating temperatures ranging between 500 and 1200 °C and pressures between 1 and 100 bar [51,52]. This setup enables high carbon conversion efficiency and relatively simple thermal control due to stratified reaction zones.

Fixed bed reactors have been explored for processing pretreated fractions of MSW, especially refuse-derived fuel (RDF) with reduced moisture and inert content, but their application to untreated MSW remains limited. This limitation is primarily due to the strict feedstock requirements regarding particle size, low moisture content (<15%), and relatively uniform composition [11].

Nonetheless, recent advances in mechanical–biological treatment (MBT) and torrefaction technologies offer potential pathways for integrating fixed bed gasification with urban waste management strategies in decentralized energy systems. From a performance perspective, fixed bed gasifiers offer robust design, low maintenance, and high thermal efficiency at small scale, but are challenged by poor scalability, high tar content in updraft configurations, and the inability to process moist or heterogeneous waste without significant preprocessing.

Although this technology is commercially mature for biomass gasification and small-scale heat and power generation (TRL 8–9), its application to MSW remains at a lower TRL of 5–6, depending on the degree of feedstock conditioning and process integration [52,53].

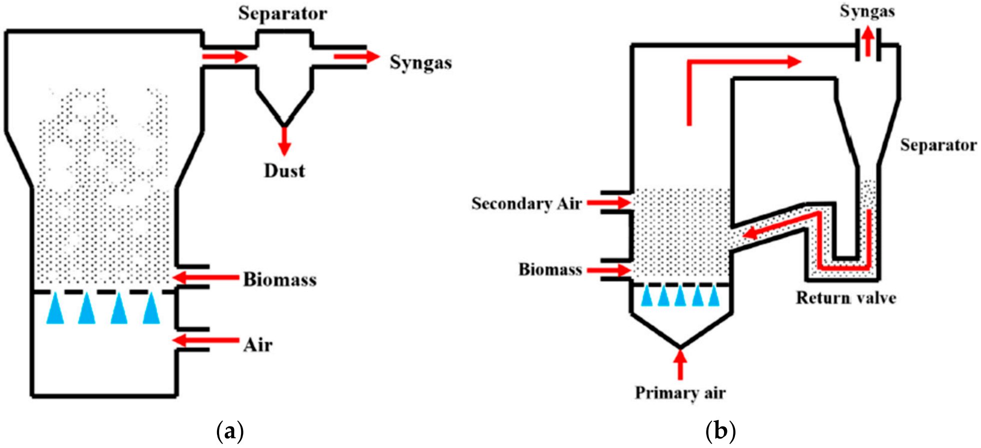
Given its simplicity, robustness, and compatibility with pretreated waste streams such as RDF, fixed bed gasification offers promising integration potential in decentralized MSW management systems, especially for rural or small-scale applications.

4.2. Fluidized Bed Gasification

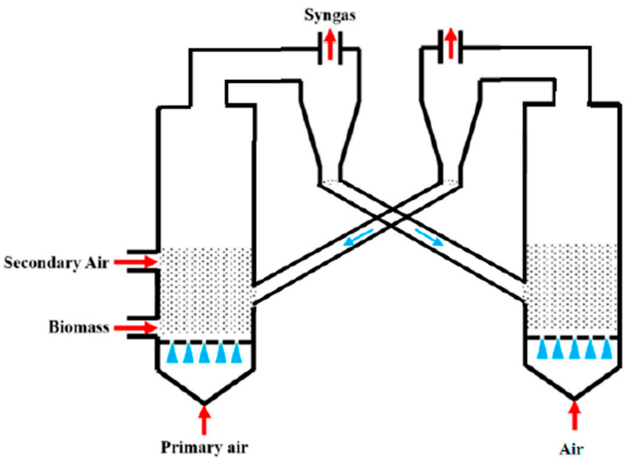
Fluidized bed gasification is a widely implemented and highly flexible thermochemical conversion technology that enables efficient processing of various solid waste streams, including MSW, biomass, sludge, and refuse-derived fuels [51].

In these systems, the feedstock is introduced into a reactor vessel containing a bed of inert particles (typically silica sand) that is fluidized by the upward injection of a gasifying agent such as air, oxygen, or steam. This fluidization ensures excellent heat and mass transfer, allowing uniform temperature distribution within the reactor and promoting higher carbon conversion rates [54]. Operating temperatures typically range between 700 and 1000 °C, with most commercial systems functioning within 800–900 °C. Fluidized bed gasifiers are categorized into three configurations: bubbling fluidized beds, circulating fluidized beds, and dual fluidized beds (Figure 4) [44].

In bubbling fluidized bed gasifiers, the gasifying agent is introduced at low superficial gas velocities (1–3 m/s), generating a bubbling regime that suspends the feedstock and bed material. The syngas produced rise through the reactor, while unreacted char and particulates are separated via cyclones or other particle removal systems. These reactors are suitable for medium-scale installations and relatively homogeneous feedstocks with moderate ash content.



(**a**) (**b**)



(**c**)

Figure 4. Fluidized bed gasifier types and flow directions: (**a**) bubbling fluidized bed; (**b**) circulating fluidized bed; (**c**) dual fluidized bed. (Adapted from [44], under the terms of the Creative Commons Attribution License (CC BY 4.0).

In contrast, circulating fluidized bed gasifiers operate at higher gas velocities (3–10 m/s), enabling a continuous circulation of bed material and solid particles between the reactor and a separator (typically a cyclone), from which solids are recirculated back into the gasification zone [55]. This configuration allows for longer residence times and improved conversion efficiency, particularly beneficial when processing heterogeneous and high-ash-content waste such as MSW or RDF. In a dual fluidized bed system, the gasification and combustion processes occur in separate fluidized reactors, enabling enhanced hydrogen production, greater feedstock flexibility, and improved energy efficiency through internal heat and material recirculation [56].

Fluidized bed gasifiers are widely considered among the most promising and scalable technologies for waste-to-energy conversion, especially in contexts requiring decentralized or medium-to-large-scale deployment. Their performance varies depending on operational parameters, but the energy content of the resulting syngas typically ranges between 3.7–8.4 MJ/Nm^3 for bubbling fluidized bed and 4.5–13 MJ/Nm^3 for circulating fluidized bed reactors. The gas composition is usually rich in hydrogen (35–40%) and carbon monoxide (25–30%), making it suitable for downstream applications such as hydrogen production, synthetic fuel synthesis, or combined heat and power (CHP) systems [54]. Despite these advantages, fluidized bed gasifiers face challenges related to feedstock pretreatment, bed agglomeration risks, tar formation, and the complexity of reactor control systems.

Nonetheless, both bubbling fluidized bed and circulating fluidized bed systems have reached a high level of technological maturity. The TRL of fluidized bed gasification systems ranges from 7 to 9, with circulating fluidized bed reactors being commercially available and deployed in several European waste-to-energy plants. Bubbling fluidized bed systems are also well validated for RDF and biomass but may require optimization when dealing with highly variable MSW streams [52,53].

Given its scalability and ability to process heterogeneous waste streams, fluidized bed gasification shows significant potential for integration into medium-to-large-scale urban MSW management systems.

4.3. Entrained Flow Gasification

Entrained flow gasification represents a commercially mature and industrially validated technology, predominantly employed for the large-scale conversion of carbonaceous feedstocks such as coal, lignite, and, more recently, biomass-derived materials. This reactor type (Figure 5) is characterized by its high throughput capacity, enhanced process availability, and production of relatively clean syngas with low tar content, rendering it suitable for downstream applications such as Fischer–Tropsch synthesis or hydrogen production [57].

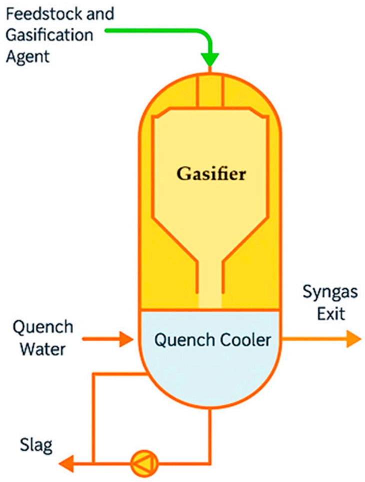


Figure 5. Entrained flow gasifier [11,17].

The gasification process occurs at elevated temperatures, typically ranging from 1200 to 1500 °C, and at pressures between 20 and 80 bar, under conditions that promote nearly complete feedstock conversion. The finely pulverized feed is introduced co-currently with the gasifying agent (oxygen and/or steam), allowing for short residence times (1–5 s) and uniform reaction kinetics [58].

Among the key advantages of entrained flow gasifiers are high carbon conversion efficiencies (up to 99%), low tar and char residues, and compact reactor design, which minimizes heat losses and facilitates process control [51]. However, the technology requires dry and finely ground feedstock (<100 μm) and involves complex syngas cleaning systems, especially when used for MSW-derived feedstocks, due to variability in ash content and contaminants [57].

Entrained flow gasification is currently considered a commercial-scale, fully mature technology, with a TRL of 9, particularly in coal-based applications. When adapted for biomass and MSW-derived feedstocks, the TRL remains high (7–8), although further optimization is often required for feedstock preprocessing and syngas cleaning stages [52,53].

Due to its high carbon conversion efficiency and compatibility with large-scale syngas production, entrained flow gasification could be integrated into advanced MSW valorization platforms, particularly where extensive feedstock preprocessing and syngas upgrading infrastructure are available.

4.4. Plasma Gasification

Plasma, often referred to as the fourth state of matter, is a gas at extremely high temperatures, in which atoms are partially or completely ionized, generating a mixture of free electrons and positive ions. Due to this structure, plasma can conduct electricity and respond to electromagnetic fields. Examples of natural plasma include lightning, the auroras, and the incandescent gases on the surface of the Sun.

Artificial plasma is generated by passing an electric current through a gas (such as air, nitrogen, argon, or oxygen), using a plasma torch or an electric arc. This process dissociates the gas molecules into ions and electrons, increasing the temperature of the medium to values of the order of 5000–15,000 °C, comparable to those on the surface of the Sun [59]. These extreme conditions make plasma a very efficient heat carrier for applications such as waste gasification, metal smelting, or the treatment of hazardous materials.

Plasma generation can be achieved using various torch configurations (Table 4). In direct current (DC) transferred arc plasma systems, the target material (or a metal bath) serves as one of the electrodes, either the cathode or the anode, forming a direct arc between it and the electrode inside the torch. This configuration ensures maximum energy concentration on the substrate. By contrast, DC non-transferred arc plasma systems contain both electrodes within the torch, and the arc remains confined inside. The resulting plasma jet is expelled toward the treated material without establishing a direct arc, offering greater versatility but lower energy density at the surface. Hybrid plasma systems, which combine DC arcs with radio frequency (RF) plasma sources, are gaining interest for their enhanced arc stability, improved ionization efficiency, and lower operational costs. These advanced configurations show promise in applications such as waste gasification, sewage sludge treatment, and nanomaterial synthesis [60–62].

Table 4. Comparison of plasma torch types [11].

Parameter	Direct Current Transferred	Direct Current Non-Transferred	Radiofrequency
Temperature (°C)	11,727–19,727	9727–13,727	2727–7727
Input power (kW)	Maximum 80	Maximum 80	30–35
Electrode erosion	Yes	Yes	No
Electrode material	Graphite, copper	Graphite, brass, tungsten	Without electrodes
Cooling method	Needed	Not needed	Not needed
Plasma gas	N_2, Ar, CO_2, air	N_2, Ar, CO_2, H_2O, air	Ar, O_2, H_2
Input waste conductivity	Needed	Not needed	Not needed
Thermal efficiency (%)	70–95	70–95	40–50

Plasma gasification is a cutting-edge waste-treatment technology that uses extreme temperatures, generated by an electric arc, to decompose waste into its fundamental chemical components [63]. Inside the reactor (Figure 6), the plasma is produced by an electric torch that generates temperatures in the range of 3500–6500 °C, and in certain regions of the plasma arc it can even reach 10,000 °C [49]. At these temperatures, the molecular bonds of organic and inorganic materials are completely broken, resulting in a high degree of conversion of the waste, regardless of its composition. The process takes place in an environment with a limited supply of O_2, which favors gasification reactions over combustion reactions. Under these conditions, rapid thermal decomposition produces a synthesis gas (syngas) composed mainly of CO and H_2, with the possibility of further use in the production of electricity, green hydrogen, synthetic biofuels or as raw material in the chemical industry [63,64]. Due to the extremely high operating temperatures, plasma gasifiers enable almost total thermal decomposition of biomass waste, thereby producing negligible amounts of biochar and maximizing syngas yield [49].

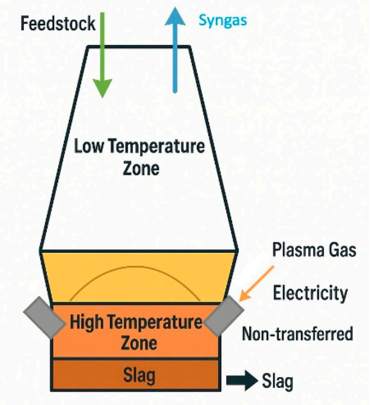


Figure 6. Plasma gasification reactor [11,17].

Following the first experimental applications for MSW treatment in Japan in the late 1990s, plasma gasification technology has been adopted or investigated on a commercial and pilot scale in several countries, including South Korea, Canada, the United Kingdom, France, the United States, India, and China, reflecting the global interest in waste-to-energy recovery through advanced conversion processes. Thus, plasma gasification represents a promising technology for the energy recovery of MSW, contributing to the objectives of the transition towards a circular economy and climate neutrality. By using extreme temperatures, generated by plasma electric arcs, this process allows the conversion of organic and carbon fractions from waste into synthesis gas (syngas), rich in hydrogen and carbon monoxide, with applications in the production of electricity, renewable fuels, or chemical raw materials. At the same time, inorganic materials are vitrified, resulting in an inert residue, with potential for reuse as a construction material, thus reducing the need for final disposal.

In waste treatment facilities, plasma gasification can be operated either as a single-stage process, utilizing thermal plasma exclusively for waste conversion, or as a two-stage system, where conventional gasification first generates raw syngas, followed by plasma treatment for gas cleaning and upgrading [65]. Two-stage plasma treatment is generally preferred over the single-stage approach, as it reduces the high electrical energy demand by limiting plasma application to the decomposition of tar and minor contaminants, rather than treating the entire waste feedstock [66].

With its ability to treat heterogeneous waste streams, and even non-recyclable fractions, including hazardous and medical waste (especially those from the recent COVID-19 pandemic) [67], MSW, RDF, household and kitchen waste, tires, plastics, industrial waste, sewage sludge, and bones of animal origin [40], and to reduce the total volume of waste by up to 95%, plasma gasification is directly aligned with zero waste and full resource recovery strategies. Also, the absence of free oxygen in the process limits the formation of polluting compounds such as NO_x and dioxins, making this technology attractive from an environmental protection perspective [68]. One of the major limitations to the commercial deployment of plasma gasification systems is their high electricity demand, which typically ranges between 1200 and 2500 MJ/ton of processed feedstock [19]. This substantial energy input poses economic and efficiency challenges, especially when compared to other thermochemical conversion technologies.

The commercial applicability of the technology is still limited, with most facilities existing at the laboratory or pilot scale, corresponding to a TRL of between 4 and 6, depending on the system configuration and the type of waste treated [52,53]. Various technical and economic challenges, such as high equipment costs, the need to use advanced materials resistant to extreme temperatures, control of the synthesis gas composition, and efficient integration into the existing energy infrastructure, require further research and development to facilitate industrial scale-up [69]. Despite these limitations, plasma gasification remains a technological direction with strategic potential for the future of sustainable municipal waste management, especially in the context of the transition towards climate neutrality and reducing pressure on landfills.

Owing to its ability to handle complex and hazardous MSW fractions with minimal environmental emissions, plasma gasification presents a strong potential for integration into high-value, low-emission waste management systems aligned with zero waste and circular economy goals.

4.5. Supercritical Water Gasification

Supercritical water gasification (SCWG) is considered one of the most promising and innovative thermochemical technologies currently under development for the sustainable conversion of high-moisture organic waste into hydrogen-rich syngas. Operating at temperatures above 374 °C and pressures exceeding 22.1 MPa, SCWG exploits the unique physicochemical properties of water in its supercritical phase, where it no longer exhibits a clear distinction between liquid and gas [70]. In this state, water acts simultaneously as a solvent, reactant, and catalyst, enabling rapid and efficient decomposition of wet biomass and organic fractions of MSW without the need for energy-intensive drying (Figure 7).

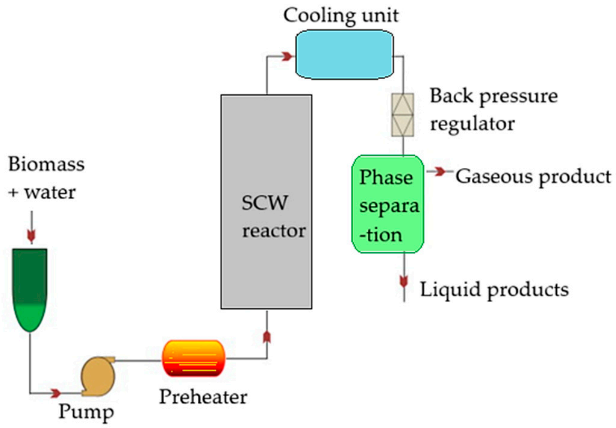


Figure 7. Supercritical water gasification reactor [11,17].

The SCWG technology enables the direct gasification of feedstocks with moisture contents exceeding 70–80% [71], such as food waste, sewage sludge, pig manure, algae, agricultural residues, and increasingly, the biodegradable and organic fractions of MSW, which are notoriously difficult to treat using conventional dry-based gasification systems. The resulting gas product is primarily composed of hydrogen, carbon dioxide, and to a lesser extent methane and carbon monoxide, depending on operating conditions and feedstock characteristics. In addition, the CO_2 generated can be readily captured and utilized in downstream processes such as synthetic fuel production or carbon capture and storage (CCS), aligning SCWG with carbon-neutral and circular economy objectives [72].

Due to the unique hydrothermal environment, SCWG achieves very fast reaction kinetics, often requiring residence times of only a few seconds, and leads to minimal tar and char formation, thus producing a clean syngas stream with high H_2 content. Research in this area is currently focused on overcoming material challenges associated with corrosion at high pressure and temperature, scaling up from laboratory to pilot systems, and integrating SCWG with wastewater treatment and energy recovery infrastructure [71].

From a technological perspective, SCWG offers multiple advantages: it can treat wet waste directly without pre-drying, maximizes hydrogen yield, operates with rapid kinetics, and generates little to no secondary pollutants. Moreover, the potential to couple SCWG with CO_2 capture and hydrogen purification systems enhances its strategic role in green hydrogen production and net-zero carbon pathways. On the downside, the process faces significant technical and economic challenges, including the need for high-pressure reactor systems, corrosion-resistant alloys, complex feedstock preconditioning, and limited demonstration at commercial scale. Despite these limitations, SCWG remains a highly innovative pathway with growing interest for treating organic MSW streams, especially in urban contexts seeking low-carbon waste valorization solutions.

Although SCWG demonstrates significant potential for wet waste valorization and hydrogen production, its TRL is currently estimated to be between 4 and 6, depending on the specific system configuration and feedstock. Most research remains at laboratory and pilot scale, with only a few experimental demonstrations conducted under continuous or semi-continuous operation conditions [52,53].

Given its unique suitability for wet organic waste and potential for clean hydrogen production, SCWG holds strategic integration potential in future MSW systems targeting the valorization of biodegradable waste streams and carbon-neutral pathways.

4.6. Microwave-Assisted Gasification

Microwave-assisted gasification (MAG) is an emerging thermochemical process that integrates conventional gasification principles with microwave irradiation to enhance the heating uniformity and reaction kinetics during the thermal conversion of carbonaceous feedstocks. One of the main challenges in traditional gasification, particularly when processing wet biomass or low-conductivity solids, is the non-uniform heat distribution within the reactor bed. MAG addresses this limitation by enabling volumetric and selective heating, in which electromagnetic energy is absorbed directly by the feedstock or by microwave susceptors (e.g., activated carbon, silicon carbide, metal oxides), generating internal heat via dielectric loss mechanisms [73].

The process typically operates at moderate temperatures (600–900 °C) under inert or gasifying atmospheres (steam, air, or CO_2), depending on the desired syngas composition. MAG reactors can be configured in fixed bed, rotary, or fluidized bed setups, with the microwaves supplied by magnetrons or solid-state generators operating commonly at 2.45 GHz [74]. Feedstocks explored in MAG studies include lignocellulosic biomass, sewage sludge, plastics, food waste, and more recently, fractions of MSW, especially after mechanical–biological treatment (MBT) or preconditioning [75]. The ability to process moist and heterogeneous waste makes MAG a promising technology in decentralized or modular waste-to-energy systems.

Among the advantages of MAG are its high heating efficiency, rapid startup and shutdown, and the potential for precise control of reaction zones, which results in faster gasification rates and reduced tar formation. Furthermore, the process is scalable to small or medium installations, and its compactness allows on-site deployment in urban or industrial waste management facilities. However, several technical challenges limit its current commercialization: the high capital cost of microwave generators, low penetration depth of microwaves in large feed volumes, and the complexity of uniformly heating mixed or non-polar materials.

Despite its promising features and growing interest in decentralized waste-to-energy applications, MAG remains at a relatively low TRL, typically estimated between 3 and 5, depending on the reactor configuration and type of feedstock [52,53]. While various laboratory-scale studies have demonstrated the technical feasibility of MAG and its advantages in terms of selective heating and tar suppression, pilot-scale implementations are still limited and lack standardized design frameworks, especially when applied to complex waste streams such as MSW. Further research and investment are needed to overcome scaling challenges, improve reactor efficiency, and validate long-term operational stability under real-world conditions.

Due to its modularity and ability to process moist and heterogeneous waste, microwave-assisted gasification shows integration potential in decentralized, small-to-medium-scale MSW systems, particularly when paired with MBT technologies.

4.7. High-Temperature Steam Gasification

High-temperature steam gasification (HTSG) is an emerging and thermodynamically favorable technology for converting various carbonaceous materials, including wood biomass, plastics, rubber, and MSW, into hydrogen-rich synthesis gas. Unlike conventional air- or oxygen-blown gasification, this process employs superheated steam at temperatures approaching 1000 °C as the primary gasifying agent, in a strictly oxygen-free atmosphere, thereby promoting endothermic reactions that enhance hydrogen yield and minimize nitrogen dilution in the syngas stream [76].

The absence of oxygen inhibits partial combustion, shifting the reaction pathways predominantly toward steam-reforming and water–gas shift mechanisms. This results in a syngas composition characterized by elevated H_2 concentrations (often exceeding 50%) and reduced CO and CO_2 content, making the process particularly attractive for green hydrogen production and fuel-cell applications [77]. However, due to its endothermic nature, HTSG requires a continuous external heat source, which adds complexity to reactor design and process integration [78]. Recent experimental and pilot-scale studies have explored various configurations, such as indirect heating through fluidized bed reactors, electrically heated systems, or solar-assisted designs, aiming to improve energy efficiency and scalability [76].

Among the main advantages of high-temperature steam gasification are its potential to maximize hydrogen output, its negligible tar formation under optimized conditions, and the production of high-purity syngas with minimal environmental emissions. Furthermore, the process demonstrates good adaptability to heterogeneous feedstocks, including waste plastics and mixed MSW.

This technology remains at an early demonstration stage, with TRLs generally between 4 and 6 [52,53], and presents challenges such as high energy input requirements, complex thermal management, and the need for high-grade materials resistant to extreme steam temperatures and corrosion. These factors currently limit its large-scale deployment, but ongoing research efforts continue to address these barriers.

Recent advances in catalyst development have shown promise in further enhancing the efficiency of HTSG. The incorporation of nickel-based and transition metal catalysts has been demonstrated to promote the reforming of tar precursors and improve hydrogen selectivity, thereby reducing tar-related operational issues and extending catalyst lifetime [76]. Additionally, catalyst supports with high thermal stability and surface area, such as alumina and ceria, have been explored to sustain activity under harsh steam-rich conditions. Optimization of catalyst composition and reactor design could significantly improve process economics and operational stability, enabling a more widespread adoption of HTSG technology [78,79].

From an environmental standpoint, HTSG presents substantial benefits over traditional fossil fuel-based hydrogen production methods, primarily through the reduction of greenhouse gas emissions and pollutant formation. The oxygen-free environment minimizes NO_x emissions, while the process's potential for integrating with carbon capture and storage (CCS) technologies further mitigate CO_2 emissions [75]. However, the lifecycle environmental impact of HTSG depends largely on the feedstock composition and energy source used to supply the endothermic heat. Utilizing renewable electricity or waste heat for reactor operation can substantially lower the overall carbon footprint, aligning HTSG with circular economy and sustainable energy goals [25,52].

With its high hydrogen yield and clean syngas output, HTSG could be effectively integrated into emerging waste-to-hydrogen infrastructures, particularly in urban MSW systems focusing on low-emission energy recovery.

4.8. Rotary Kiln Gasification

Inclined rotary reactors, originally developed for use in cement manufacturing, have also been widely adopted in waste thermal treatment, particularly for hazardous waste incineration. More recently, these systems have been adapted to operate under reducing atmospheres and are now emerging as promising candidates in the field of thermal gasification, due to their ability to process heterogeneous, large-particle, and high-ash-content waste streams [80]. The system in Figure 8 consists of a rotating, cylindrical chamber, slightly inclined (2–5°) toward the discharge end, which enables the gradual movement of feedstock as it is subjected to thermal decomposition under controlled atmospheres. Operating temperatures for gasification typically range from 300–600 °C, though they may exceed 850 °C in incineration configurations [81]. Feedstock is introduced at the upper end of the reactor, while the gasifying agent (air, oxygen, or steam) is injected along the chamber, either co-currently or counter-currently to the material flow, depending on the specific process design.

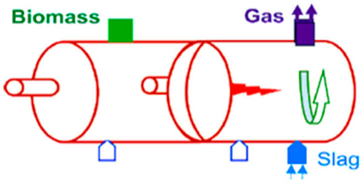


Figure 8. Rotary kiln reactor (adapted from [42], under the terms of the Creative Commons Attribution License (CC BY 4.0)).

Rotary kilns are valued for their mechanical simplicity and robust design, which allows for relatively easy operation and maintenance. They offer notable feedstock flexibility, being capable of processing unsorted or variably composed materials such as MSW, RDF, sewage sludge, and industrial residues. In addition, the long residence time, often exceeding 60 min [81], favors the complete thermal decomposition of complex waste fractions and facilitates the coupling with energy recovery systems.

However, these benefits are offset by several limitations. The thermal efficiency of rotary kilns is generally lower compared to more advanced gasification technologies, such as entrained flow or fluidized bed systems. Moreover, the quality of the syngas produced is typically inferior, due to incomplete carbon conversion and increased formation of tar and particulate matter [82]. The requirement for large physical space and the challenges associated with precise temperature control further constrain their scalability and overall energy performance [51].

Although rotary kilns are widely commercialized, they are mostly used in waste incineration and cement manufacturing. Their application to thermal gasification remains at an intermediate TRL of 6–7, particularly when treating MSW or RDF [52,53]. While numerous pilot and semi-industrial facilities have validated their operational feasibility in reducing atmospheres, further advancements are required in terms of syngas cleaning, process integration, and emissions control before large-scale deployment becomes economically competitive.

Due to its mechanical simplicity and tolerance for heterogeneous and bulky MSW feedstocks, rotary kiln gasification can be integrated into hybrid waste treatment plants, particularly where space and energy recovery constraints are manageable.

4.9. Synthetic Comparison of Gasification Technologies

While biomass gasification technologies have generally reached a TRL of 8–9, indicating a high degree of technological maturity and commercial viability, this is not uniformly the case across all applications.

Syngas cleaning systems designed for integration with internal combustion engines and gas turbines have similarly attained TRLs of 8–9. In contrast, when syngas is intended for use in fuel cell applications, purification technologies remain at a low maturity level, typically within the TRL 1–4 range.

In the specific context of power generation, syngas-fueled combustion engines and biomass gasification systems usually fall within TRLs 4–6, reflecting progress from laboratory validation to early pilot-scale demonstrations [83]. Combined Heat and Power (CHP) systems are more established, with many operational units worldwide, and are generally positioned at TRLs between 4 and 7, depending on system configuration and integration complexity [84].

A comparative analysis of the eight municipal solid waste MSW gasification technologies described above, and their respective TRLs, is presented in Table 5.

Table 5. Comparative analysis of gasification technologies [Authors' own elaboration.]

Technology	Optimal Feedstock	Operating Conditions	Advantages	Limitations	TRL (for MSW)
Fixed bed	Dry biomass, pretreated RDF	500–1200 °C, 1–100 bar; limited oxygen; 900–1800 s	Robust design, high efficiency, low tar in downdraft mode	Requires dry, homogeneous feedstock; high tar in updraft mode	5–6
Fluidized bed	MSW, RDF, biomass, sludges	700–1000 °C, atmospheric pressure; air/steam; 1–10 s	Excellent heat transfer, scalable, suitable for MSW	Risk of bed agglomeration, requires pretreatment, complex control	7–9
Entrained flow	Fine coal powders, dry RDF, finely milled biomass	1200–1500 °C, 20–80 bar; oxygen/steam; 1–5 s	High conversion efficiency, low tar, clean syngas	Requires fine, dry feedstock; high equipment cost	7–9
Plasma	MSW, hazardous waste, sludges, non-recyclables	3500–6500+ °C (localized); reducing atmosphere	Complete conversion, handles difficult waste, vitrification of residue	High energy consumption, high cost	4–6
Supercritical water gasification	Wet organic waste, sludges, biodegradable MSW fractions	T > 374 °C, >221 bar; hydrothermal medium	Direct treatment of wet waste, high H_2 yield	Corrosive conditions, high pressure, pilot scale only	4–6
Microwave-assisted gasification	Biomass, plastics, sludges, MBT-treated MSW	600–900 °C; inert or gasifying atmosphere; 2.45 GHz microwaves	Volumetric heating, reduced tar, suitable for small-scale systems	High capital cost, uneven heating	3–5

High-temperature steam gasification	Plastics, rubber, mixed MSW, RDF	~1000 °C; oxygen-free; requires external heat source	High H_2 yield, low emissions, clean syngas	Needs external heat, advanced materials	4–6
Rotary kiln	MSW, RDF, sludges, industrial residues	300–600 °C; air/steam/oxygen; slow rotation; >60 min residence time	High feedstock flexibility, mechanically simple	Low efficiency, poor syngas quality, high tar	6–7

Microwave-assisted gasification (MAG) and supercritical water gasification (SCWG) represent innovative and promising approaches in the waste-to-energy sector.

MAG enhances traditional gasification by providing volumetric and selective heating, improving reaction uniformity and kinetics, especially for heterogeneous or moist feedstocks such as mechanically treated municipal solid waste fractions. Its modularity and rapid startup/shutdown capability make it well-suited for decentralized applications. Despite promising laboratory results demonstrating tar reduction and improved heating efficiency, MAG is still in early development (TRL 3–5), facing challenges related to capital costs, scaling, and uniform heating in larger reactors.

SCWG enables the efficient conversion of wet organic waste without the need for energy-intensive drying by exploiting the unique properties of water in its supercritical state, producing hydrogen-rich syngas with minimal tar and char formation.

This technology addresses a key limitation of conventional gasification, handling high-moisture feedstocks, and offers strategic potential for integration into carbon-neutral and circular economy pathways. However, SCWG remains at a pilot and demonstration stage (TRL 4–6), with ongoing research focused on material durability under extreme conditions and process scale-up.

Together, MAG and SCWG address critical challenges inherent to conventional gasification technology, such as feedstock moisture content and heating uniformity, thereby enriching the spectrum of potential waste-to-energy pathways. Their inclusion in this review highlights emerging trends and opportunities for future research and commercialization within the evolving waste gasification landscape.

5. Potential Applications of the Gasification Products

In multi-output gasification systems, syngas is the primary product, accompanied by secondary by-products such as ash, tar, and biochar. Proper assessment and optimization of the overall system require the allocation of mass and energy flows across the main and secondary outputs. Common allocation rules include mass-based and energy-based splits, each with implications on performance evaluation and environmental impact assessments. Sensitivity analyses comparing energy- versus mass-based allocation methods are often performed in the literature to understand how these different approaches influence the interpretation of system efficiencies and product valorization pathways.

While allocation methods and sensitivity analyses are commonly applied in original research to assess multi-output gasification systems, this review focuses on summarizing existing technologies and valorization pathways without performing independent mass or energy balances.

5.1. Syngas

Syngas, or synthesis gas, plays a central role in thermochemical waste valorization chains as an intermediate product. While it can be combusted directly for power or heat, its highest value arises when it is converted into platform chemicals and advanced fuels such as hydrogen, methanol, dimethyl ether, or Fischer–Tropsch hydrocarbons. In these cases, precise control of the H_2/CO ratio, as well as extensive gas cleaning, becomes essential to ensure compatibility with catalytic conversion routes and to maximize overall efficiency. Therefore, the performance of gasification processes must be evaluated not only in terms of energy yield, but also in terms of how effectively the resulting syngas can be tuned, cleaned, and integrated into downstream synthesis applications.

In this context, a presentation of the composition and characteristics of syngas is essential for understanding its application potential.

Syngas is a combustible gas mixture primarily composed of hydrogen (H_2), carbon monoxide (CO), and methane (CH_4), along with varying amounts of non-combustible gases such as nitrogen (N_2) and carbon dioxide (CO_2). Its composition and calorific value are influenced by multiple factors, including the type of biomass or waste feedstock, the gasifying agent used (air, steam, or oxygen), and the design and operating parameters of the gasifier, such as temperature, pressure, and residence time [11]. Depending on these variables, syngas typically has a low to medium heating value, ranging between 4000 and 12,000 kJ/kg, which makes it suitable for various energy applications. However, its energy density is up to 30% lower than that of natural gas, which limits its direct injection into natural gas grids [17].

The choice of gasifying agent has a major impact on syngas quality. Air gasification introduces significant nitrogen into the product gas, diluting its combustible components and reducing its heating value to around 4–6 MJ/Nm^3. This nitrogen dilution also increases the cost and complexity of downstream gas cleaning. Conversely, oxygen gasification avoids this issue and yields syngas with higher calorific value, though at a higher operational cost due to the production and handling of pure oxygen. A commonly adopted compromise is the use of oxygen-enriched air, which balances performance and cost. Steam gasification leads to a syngas with a higher hydrogen content, making it especially suitable for hydrogen production and catalytic synthesis processes.

Despite its energetic value, raw syngas contains various contaminants, including sulfur compounds, alkali metals, tar vapors, particulates, halides, and trace elements [85]. These impurities can cause operational problems such as corrosion, fouling, and catalyst deactivation in downstream systems.

Syngas produced from gasification processes typically requires extensive cleaning and conditioning to comply with the stringent quality criteria demanded by downstream combustion or catalytic conversion applications. To achieve the desired gas composition and enhance overall process efficiency, upgrading technologies are often integrated with gasification systems. This integration facilitates the tailoring of syngas properties, enabling its effective use across various energy and chemical production pathways.

Syngas cleaning technologies can be broadly classified into primary and secondary approaches.

Primary methods are implemented within the gasification process itself and involve strategies such as optimizing operational parameters, incorporating catalysts directly within the reaction bed, and modifying the gasifier design to reduce tar formation and other impurities at the source. While primary methods can effectively separate tar compounds from the syngas stream, they do not eliminate them entirely. Instead, these methods transfer the tars to another phase, typically liquid or solid, thus requiring additional, often complex, downstream treatment steps for their complete removal or destruction [19,86].

Secondary methods, on the other hand, are applied downstream of the gasifier and consist of physical and chemical treatment techniques. These include the deployment of separation devices, such as scrubbers, cyclones, and filters, and the application of post-gasification thermal cracking at elevated temperatures to further break down tar compounds, thus achieving a higher degree of syngas purification [87].

According to European Union legislation, syngas derived from biomass or waste is classified as a gaseous biofuel and is officially recognized as a renewable energy carrier, if it meets the sustainability criteria outlined in the Renewable Energy Directive 2018/2001 (RED III). This regulatory recognition opens opportunities for syngas to play a significant role in the EU's decarbonization and renewable energy strategies. In this context, syngas produced by MSW gasification not only contributes to waste reduction and resource efficiency but also offers a flexible energy vector for combined heat and power (CHP) systems, green hydrogen production, and synthetic fuel synthesis. Moreover, its compatibility with carbon capture and storage (CCS) or utilization (CCU) technologies further enhances its strategic relevance in achieving net-zero targets by 2050.

Syngas has diverse applications in both the energy and chemical sectors (Figure 9). It can be used directly as a fuel in internal combustion engines or in combined heat and power (CHP) systems for efficient electricity and heat generation. In addition, syngas serves as a key feedstock for catalytic synthesis routes that produce valuable chemicals and liquid biofuels, including methanol [88], dimethyl ether (DME), synthetic natural gas (SNG), hydrogen, and Fischer–Tropsch diesel [89,90].

The specific H_2/CO ratio of the syngas determines its suitability for each synthesis route: a ratio near 2:1 is ideal for methanol and Fischer–Tropsch synthesis, while hydrogen-rich syngas favors DME production and direct hydrogen extraction. These biofuels, derived from biomass and waste, offer a renewable alternative to fossil fuels and contribute to reducing greenhouse gas emissions in transportation and industry.

When rich in hydrogen, typically achieved through steam gasification, syngas is particularly valuable for hydrogen fuel production [91,92]. Hydrogen can be efficiently extracted via the water–gas shift (WGS) reaction, followed by pressure swing adsorption (PSA), providing a flexible and scalable pathway for clean hydrogen generation, especially when renewable feedstocks such as MSW are used.

Moreover, syngas can be further utilized to synthesize ammonia through the Haber–Bosch process, which combines hydrogen from syngas with atmospheric nitrogen, reinforcing its role in fertilizer production and broader industrial chemistry [17].

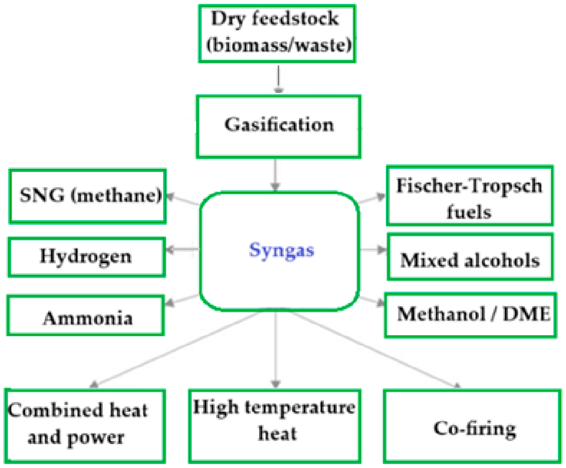


Figure 9. Main technological pathways for syngas valorization [Drawn by the authors].

5.2. Ash

Municipal solid waste, sewage sludge, and animal waste typically exhibit highly variable ash content due to their heterogeneous composition of organic and inorganic matter. Ash content in animal waste generally ranges between 10 and 30%, depending on factors such as diet and bedding material. In contrast, wood-based biomass contains significantly lower ash levels, typically ranging from 0.3 to 3%, depending on species and processing conditions, compared to the 15–50% observed in sewage sludge and 5–30% in municipal solid waste [93]. Agricultural residues exhibit a wide range of ash content, from as low as 0.3% to as high as 16%, depending on the type of biomass and preprocessing conditions, on a dry basis [94].

The solid ash generated from the gasification of MSW is a mineral-rich residue composed primarily of inorganic constituents, including metal oxides and silicates derived from the non-combustible fraction of the feedstock [95]. Its composition is strongly influenced by the nature of the input material and the operating conditions of the gasification process, particularly temperature and gasifying agent [11]. Typically, gasification ash contains a variety of major and trace elements, such as silicon (Si), aluminum (Al), calcium (Ca), iron (Fe), potassium (K), magnesium (Mg), and phosphorus (P), present in the form of oxides (e.g., SiO_2, Al_2O_3, CaO, Fe_2O_3, and K_2O) [17]. These components confer both agronomic and industrial potential. In agricultural contexts, such ash may be utilized as a soil amendment or fertilizer, due to its nutrient content and alkalinity, which can enhance soil structure, correct pH, and supplement essential macronutrients.

Beyond its agronomic applications, gasification ash exhibits pozzolanic behavior and chemical stability, which make it suitable for use in construction materials. It can be incorporated as a supplementary cementitious material in blended cement, used as a filler in asphalt and road base layers, or serve as a raw material for the fabrication of bricks, ceramics, geopolymers, and insulating panels. Such valorization strategies contribute to circular economy objectives by diverting solid waste from landfilling, reducing reliance on raw materials, and lowering the carbon footprint of construction materials.

Recent studies have explored the use of biomass ash as a precursor for nanomaterials in electronic, catalytic material in esterification and biodiesel production, or in hydrogen production via dry reforming of methane, and biomedical applications [93].

Nevertheless, the reuse of gasification ash requires rigorous physicochemical characterization to ensure its environmental safety and compliance with applicable regulatory frameworks. Parameters such as particle size distribution, heavy metal concentration, leaching potential, and mineralogical composition must be evaluated to assess its suitability for end-use applications. Attention must be paid to the possible presence of toxic elements such as cadmium (Cd), lead (Pb), arsenic (As), or mercury (Hg), which may originate from certain waste streams [17].

Thus, gasification ash represents a potentially valuable by-product with multiple pathways for beneficial reuse, provided that adequate control and assessment procedures are in place to mitigate environmental and health risks.

5.3. Tar

Tars generated during gasification are complex hydrocarbon byproducts consisting of viscous liquids, typically comprising a diverse range of aromatic and heterocyclic compounds such as polycyclic aromatic hydrocarbons (PAHs), phenols, cresols, and long-chain oxygenated hydrocarbons. These substances result primarily from the incomplete thermal decomposition of lignin and other macromolecules during the pyrolytic and gasification stages, especially under suboptimal conditions such as low temperature or insufficient residence time [17].

The estimated mass distribution of the main constituents in tar is as follows: benzene (38%), toluene (24%), single-ring aromatic hydrocarbons (22%), naphthalene (15%), dual-ring aromatic hydrocarbons (13%), heterocyclic compounds (10%), phenolic compounds (7%), triple-ring aromatic hydrocarbons (6%), and quadruple-ring aromatic hydrocarbons (1%), with other trace components present in negligible amounts [16]. Another composition of tars was reported by [96]: benzene (38%), toluene (14.5%), single-ring aromatic hydrocarbons (14%), naphthalene (9.5%), dual-ring aromatic hydrocarbons (8%), heterocyclic compounds (6.5%), phenolic compounds (4.5%), triple-ring aromatic hydrocarbons (3.5%), quadruple-ring aromatic hydrocarbons (1%), and other compounds in trace amounts.

Tar compounds generated during the gasification process are commonly classified into five major classes, based on their molecular structure and physical–chemical properties. Class 1 tars consist of high-molecular-weight compounds that are typically undetectable by gas chromatography due to their complexity and low volatility. These compounds generally account for less than 2 wt% of the total tar content. Class 2 includes oxygenated species that are readily soluble in water, such as acids, phenols, and ketones, contributing approximately 7 wt% to the overall tar composition. Class 3 comprises single-ring aromatic hydrocarbons, whereas classes 4 and 5 consist of polycyclic aromatic hydrocarbons containing two to seven aromatic rings. These classes can all be identified in tars produced from gasification processes, although their relative concentrations are strongly influenced by operational parameters. Variables such as temperature, type of gasifying agent, reactor design, and the presence or absence of catalysts significantly affect both the yield and distribution of tar components in the resulting syngas [10,84]. Notably, the formation of Class 3, 4, and 5 compounds is often associated with the thermal cracking and secondary decomposition of Class 1 and 2 constituents as pyrolysis temperatures increase [97].

In thermochemical conversion systems, tars are generally considered undesirable due to their ability to condense at lower temperatures, leading to operational challenges such as fouling, corrosion, clogging of pipelines and filters, formation of phenolic species contaminating process water, reduction in gasification efficiency, deactivation of catalysts in downstream syngas applications, and environmental issues harmful to human health because most tars are carcinogenic [98]. Consequently, their minimization and management are essential for the stable and efficient operation of gasification plants.

Tars generated in gasification processes can be treated by two main types of methods: primary treatments and secondary treatments. Primary treatments consist of optimizing the operating conditions in the gasifier (such as temperature, pressure, equivalence ratio, waste/gas volume ratio), and the use of catalysts (such as dolomite, olivine, or activated carbon), as well as in the appropriate design of the reactor. As for secondary treatments, they are divided into chemical treatments and physical treatments. Chemical treatments include processes such as thermal cracking, catalytic cracking, tar reforming and plasma cracking [99]. On the other hand, physical treatments can be of the wet type, using various technologies such as spray towers, wash towers, impingement scrubbers, Venturi scrubbers, wet electrostatic precipitators, wet cyclones, oil-based gas washer technology, conventional cyclones and bag filters [100,101]. Tar reforming, a process that decomposes tars into lighter gaseous compounds, is essential for efficient gasification; however, it requires the use of costly catalysts and durable reactor designs [102].

From a circular economy perspective, tars also present opportunities for valorization. Through catalytic reforming or thermal cracking processes, tars can be decomposed into lighter gaseous products, primarily H_2, CH_4, CO, and other light hydrocarbons, which contribute to the enhancement of syngas yield and calorific value [99].

Alternatively, chemical extraction methods can isolate valuable aromatic compounds and phenolic fractions for use as industrial intermediates in the chemical and pharmaceutical sectors. In specific applications, such as in the production of asphalt, carbon black, or binder materials for construction, tars may serve as raw materials, provided their composition meets safety and performance standards. Advanced processing routes, such as hydrotreating or plasma-assisted reforming, are currently under investigation to further expand the potential uses of tars, particularly when derived from MSW, which tends to yield more heterogeneous and contaminated fractions.

Hence, while tars are operationally problematic and require careful treatment, they also offer significant potential for material and energetic recovery if properly processed. Their valorization aligns with the objectives of sustainable waste management and the development of integrated waste-to-resource systems.

5.4. Biochar

Although gasification processes are primarily designed to maximize the yield of syngas, certain configurations, particularly under suboptimal or controlled operating conditions, may also generate small quantities of biochar as a by-product.

Biochar is a carbon-rich, porous solid material composed mainly of fixed carbon and inorganic minerals, resulting from the thermochemical decomposition of organic matter in a low-oxygen environment. The chemical composition of biochar is primarily dominated by carbon, typically ranging between 40 and 90%, depending on the feedstock and gasification conditions [103]. In addition to carbon, biochar contains varying amounts of hydrogen (1–5%), nitrogen (0.5–3%), and oxygen (5–30%) [11], as well as inorganic elements such as alkali and alkaline earth metals (e.g., potassium, calcium, magnesium, and sodium) [104].

It is important to note that the formation of biochar during the gasification of MSW occurs primarily from the biodegradable organic fraction of the input, such as food waste, paper, wood, and other lignocellulosic materials. Inorganic components commonly present in MSW, including plastics, metals, and glass, do not contribute to biochar formation and may, in fact, degrade the quality of the resulting solid residue or require additional treatment. Therefore, proper presorting and characterization of the MSW input are essential steps for optimizing both the yield and quality of biochar generated through gasification.

The surface of biochar is rich in diverse functional groups, including hydroxyl (−OH), carboxyl (−COOH), carbonyl (C=O), and other oxygen-containing moieties, which contribute to its chemical reactivity and sorption properties. Its structure is predominantly amorphous, interspersed with microcrystalline carbon domains that contribute to its high porosity and adsorption capacity [105]. Its physicochemical characteristics, such as high surface area, alkaline pH, and functional chemical groups, vary according to the type of feedstock and gasification parameters.

Despite being a minor output of gasification compared to pyrolysis, biochar offers valuable applications in agriculture, environment and industry, that justify its recovery and utilization [17].

- Agriculture

In the agricultural sector, biochar is increasingly recognized as an effective soil amendment and a potentially long-term carbon sink for enhanced carbon sequestration. Biochar can be applied to soils through three main approaches: mixing with the topsoil, deep incorporation into the soil profile, and surface application without incorporation [106]. When incorporated into soil, it improves physical properties such as porosity, aeration, and water retention, particularly in sandy or degraded soils [107]. Its high cation exchange capacity enhances nutrient retention and reduces leaching [108].

Most biochars exhibit alkaline properties and possess an acid-neutralizing capacity of up to 33% compared to conventional agricultural lime [109]. The addition of alkaline biochar can increase the pH of acidic soils by approximately 0.1–0.2 units under typical application rates. However, at higher application rates, the pH may rise by as much as 2.0 units. Hence, biochar application is generally recommended based on specific soil characteristics, with the most significant benefits observed in soils that are acidic, low in organic matter, and exhibiting poor physical properties [110]. In acidic soils, biochar can contribute to pH buffering and enhance the availability of essential nutrients such as potassium, phosphorus, and calcium [28].

Biochar application can increase soil electrical conductivity due to its high content of soluble salts. A sudden rise in conductivity (e.g., from 0 to 2 dS/m) may negatively affect soil by increasing osmotic pressure, which limits water and nutrient availability to plants [111]. This occurs because higher soil electrical conductivity reflects a greater concentration of soluble salts in the soil solution, which can create an osmotic gradient that reduces the ability of plant roots to take up water efficiently. As a result, plants may experience water stress and nutrient deficiencies, leading to reduced growth and yield. Therefore, the salt content and application rates of biochar need to be carefully managed to avoid adverse effects on sensitive crops.

The physical properties of biochar enhance soil aggregate stability and water-holding capacity, providing a buffer against drought stress and mitigating the moisture limitations commonly associated with saline soils [112]. Also, biochar addition has positive effects and improves the water-holding capacity of sandy soils especially in arid and semi-arid areas [95,113], primarily due to biochar's porous structure, which increases soil aeration and facilitates water retention in the root zone. The addition of biochar has been shown to increase plant-available water content by 33–45% in coarse-textured soils and by 9–14% in clay-rich soils [114].

Potassium-rich biochar has the potential to improve the nutrient status of potassium-deficient soils, especially in agricultural systems where traditional fertilization practices are either cost-prohibitive or pose environmental concerns [115]. In addition, biochar can modulate the sodium-to-potassium (Na^+/K^+) ratio in plants under salt stress conditions, facilitating osmotic balance and enhancing physiological functions [116]. By promoting potassium uptake and reducing sodium accumulation, biochar contributes to improved plant growth, stress tolerance, and overall health.

While biochar application can increase soil electrical conductivity due to its soluble salt content, potentially limiting plant water uptake in saline or sensitive soils, its overall impact on crop productivity is often positive when managed appropriately. The beneficial effects of biochar, such as enhanced seed germination, increased root density, and improved growth parameters, contribute to higher yields and more sustainable agricultural practices [117]. These advantages are especially evident in soils with low to moderate salinity, where biochar improves soil structure, water retention, and nutrient availability without causing harmful salt buildup. Therefore, understanding the initial soil conditions and carefully controlling biochar application rates are crucial to maximizing its benefits while minimizing any negative impacts on plant growth.

Biochar application to soils has been shown to facilitate the adsorption and neutralization of agrochemicals, such as herbicides and fertilizers, thereby potentially reducing their mobility and environmental impact [118]. In addition, certain types of biochar can decrease the oxidation rates of carbon and hydrogen in soil, contributing to reduced soil carbon loss and lower N_2O emissions [119]. Biochar also influences key soil physical and chemical properties, often increasing porosity and bulk density.

Figure 10 illustrates the multiple roles of biochar in plant growth, soil remediation, carbon sequestration, and reduction of GHG emissions.

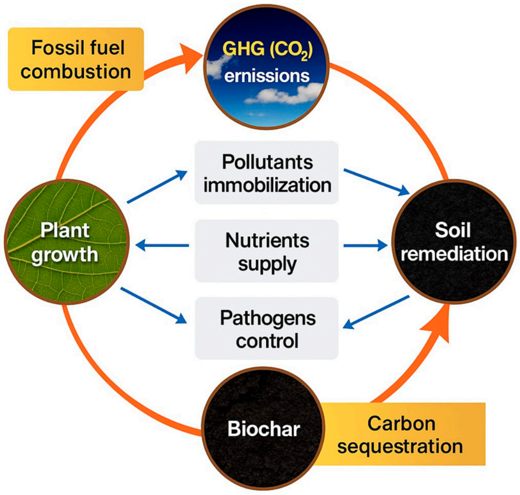


Figure 10. Biochar interactions with plant growth, soil remediation, carbon sequestration, and GHG emissions (adapted from [120], under the terms of the Creative Commons Attribution License (CC BY 4.0)).

Moreover, biochar has the potential to reduce the incidence of soil-borne pests and pathogens, acting as a physical barrier or altering microbial communities in a way that supports natural pest control mechanisms. As a stable form of carbon, biochar also enables long-term carbon sequestration in soils, contributing to climate change mitigation by reducing net greenhouse gas emissions from agricultural practices [121].

Biochar positively influences soil microbial communities by providing a porous structure that serves as a new habitat for microbial colonization. Pore size plays a critical role in determining colonization dynamics: larger pores facilitate more rapid microbial entry but offer limited protection for soil microfauna [122]. Additionally, the aging of biochar significantly affects its interactions with soil microbiota. Fresh biochar releases labile organic compounds that can serve as carbon sources, thereby initially supporting bacterial growth and promoting colonization. However, it may also release phytotoxic substances that can suppress microbial activity. In contrast, aged biochar has been shown to enhance microbial activity, suggesting that temporal transformations in biochar properties are key to its long-term effects on soil microbial ecology.

Nevertheless, there are some potential risks associated with biochar application, so careful consideration is required when using it as a soil amendment. Biochar applications may compromise the integrity of soil porous structure. Some chemical constituents in biochar may inhibit plant growth during germination [123], while others may introduce contaminants such as heavy metals, dissolved organic carbon, volatile organic compounds, or polycyclic aromatic hydrocarbons [124]. Changes in soil pH and disruptions to soil microbial communities may occur, depending on the feedstock used and pyrolysis conditions [125]. Additionally, crop yields may decline because of water and nutrient sorption by biochar, which can reduce their availability to plants [126]. After 25 days of biochar application, a reduction in nitrate concentration in the soil leachate was observed, with the extent of reduction being proportional to the amount of biochar applied. This suggests that nitrogen was adsorbed onto the surface of the biochar, thereby decreasing the availability of inorganic nitrogen in the soil and potentially inhibiting plant growth [127].

- Additive in animal feed

Biochar is also employed as an animal feed additive, where its porous structure and large surface area enable it to adsorb harmful toxins and gases within the digestive system. This property contributes to reducing methane emissions from manure, thereby lowering greenhouse gas outputs in livestock farming. Additionally, biochar inclusion in feed can improve animal performance, health, and digestion by enhancing nutrient absorption and supporting beneficial microbial activity, leading to more sustainable and efficient animal husbandry practices [128,129]. It has also been reported that adding biochar to animal feed positively impacts the adsorption of toxins, blood biochemistry, feed conversion rate, and meat quality [130].

- Environment

From an environmental perspective, biochar demonstrates promising performance as a low-cost, sustainable biosorbent for a wide range of contaminants [131]. Its large specific surface area and abundance of functional groups facilitate the adsorption of heavy metals (such as lead, cadmium, and arsenic), dyes, pharmaceuticals, phenol compounds, and pesticides from industrial effluents and municipal wastewater [132]. It has also been used effectively to capture excess nutrients, such as nitrogen and phosphorus, that contribute to eutrophication in water bodies.

Furthermore, biochar exhibits remarkable versatility in wastewater treatment applications due to its physicochemical properties, including high porosity, surface charge, and the presence of oxygen-containing functional groups (e.g., hydroxyl, carboxyl, and carbonyl) [133]. These features enable a variety of adsorption mechanisms, such as ion exchange and surface complexation, tailored to both organic and inorganic pollutants. Moreover, biochar can be applied as a filtration medium or integrated into treatment wetlands and biofilters, where it enhances pollutant and pathogen removal efficiency while reducing operational costs [134]. In the case of municipal wastewater, it aids in the retention of emerging contaminants and improves sludge dewaterability. For industrial effluents, biochar has been shown to effectively remove persistent and toxic compounds, offering a more sustainable alternative to conventional sorbents [135,136]. Post-treatment, biochar may also be regenerated or repurposed, contributing to circular economy strategies and sustainable wastewater management. Also, biochar can immobilize organic pollutants in contaminated soils, reducing their bioavailability and ecological risk.

Biochar use in air filtration systems has shown efficacy in absorbing volatile organic compounds and mitigating odorous or hazardous emissions [137]. This is primarily attributed to its high porosity, large surface area, and tunable surface chemistry, which enable the capture of a wide range of gaseous pollutants. Moreover, chemically modified or activated biochar has demonstrated enhanced performance in removing specific compounds such as ammonia, hydrogen sulfide, and formaldehyde, making it a promising material for indoor and industrial air purification applications.

In addition to its role in pollutants removal, biochar also contributes to climate change mitigation by acting as a long-term carbon sink [116]. Its highly aromatic and stable carbon structure resists microbial degradation, enabling the long-term storage of carbon when applied to soils or incorporated into materials, thus preventing its release as CO_2 into the atmosphere. However, an offset is that long transportation distances of biochar can result in a large amount of carbon emissions [138]. Biochar derived from agricultural waste has been estimated to sequester up to 1.2 tons of C/ha/year [139], while manure-based biochar may achieve sequestration rates of up to 0.6 tons of C/ha/year [140].

The global-scale application of biochar could contribute to a 12% reduction in GHG emissions [141–143] and even 38% [144]. When applied under optimal conditions, biochar has been reported to reduce N_2O emissions by approximately 24.7% and CH_4 emissions by around 40.5% [145]. Application of biochar to agricultural soils resulted in a reduction of N_2O emissions, while no significant effect was observed on CO_2 emissions [146], and reduced CH_4 emissions from livestock manure by up to 70% [147]. While numerous studies support the potential of biochar-amended soils to lower GHG emissions [148], other studies cast doubt on the persistence of these beneficial effects over the long term [149].

The temporal variability in biochar's impact is largely attributed to its aging process under field conditions, which modifies its physicochemical characteristics. Specifically, prolonged exposure leads to an increase in oxygen-containing functional groups, such as carboxylic and phenolic moieties, on the biochar surface, enhancing its cation exchange capacity. Additionally, biochar interacts with soil minerals to form organo-mineral coatings, further altering its behavior. These transformations influence key soil processes including nitrogen retention and microbial activity, both of which are critical determinants of soil GHG emissions. Consequently, the effectiveness of biochar in mitigating GHG may evolve over time, resulting in a variable influence on emission dynamics.

Figure 11 summarizes the main environmental applications and integration pathways of biochar derived from municipal solid waste.

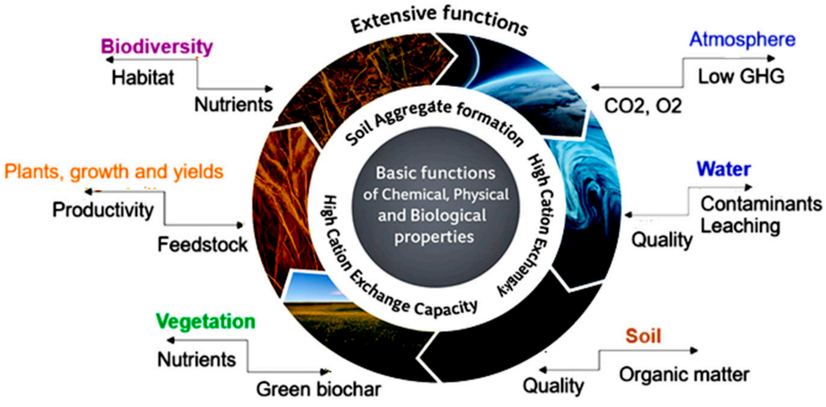


Figure 11. Biochar contributions to environmental sustainability (adapted from [150], under the terms of the Creative Commons Attribution License (CC BY 4.0)).

The addition of biochar to compost enhances microbial activity, accelerates the composting process, improves nutrient retention, reduces heavy metals uptake, and reduces greenhouse gas emissions such as methane and nitrous oxide, resulting in a more stable and nutrient-rich final product [151,152]. When used as an additive in anaerobic digestion processes, biochar has been shown to improve efficiency by enhancing microbial activity and stability, increasing biogas production, and facilitating nutrient retention [153–155]. This makes biochar a promising amendment for optimizing waste-to-energy conversion and promoting sustainable bioenergy production.

Thus, biochar production aligns with circular economy principles by transforming biomass waste into a value-added product, reducing the environmental burden associated with landfilling and open burning.Integrated into environmental systems, such as wastewater treatment, air purification, or construction applications, biochar helps reduce overall greenhouse gas emissions and supports resource recovery, reinforcing its multifunctional role in environmental protection.

- Industry

In industrial applications, biochar serves as a versatile additive, enhancing the properties of various materials such as plastics, concrete, and composites [156]. Due to its porous structure and high specific surface area, biochar serves as an effective catalyst support, enhancing both catalytic activity and long-term stability in various chemical processes. When incorporated into construction materials such as concrete and mortars, biochar can improve mechanical strength, reduce overall density, and enhance thermal insulation performance [157–159]. In addition, its high carbon sequestration capacity and low thermal conductivity make it a promising insulating material [160], while its porous architecture also contributes to the absorption of airborne sound, offering potential benefits for acoustic management in both building and environmental applications.

These multifunctional properties position biochar as a valuable component in sustainable material development and green manufacturing technologies (Figure 12). Given these properties, biochar is also being explored as a reactive component in stormwater treatment systems, constructed wetlands, and engineered soils used in green infrastructure. Furthermore, it can serve as a microbial carrier in bioremediation or biofertilization processes, enhancing the stability and activity of inoculated microorganisms.

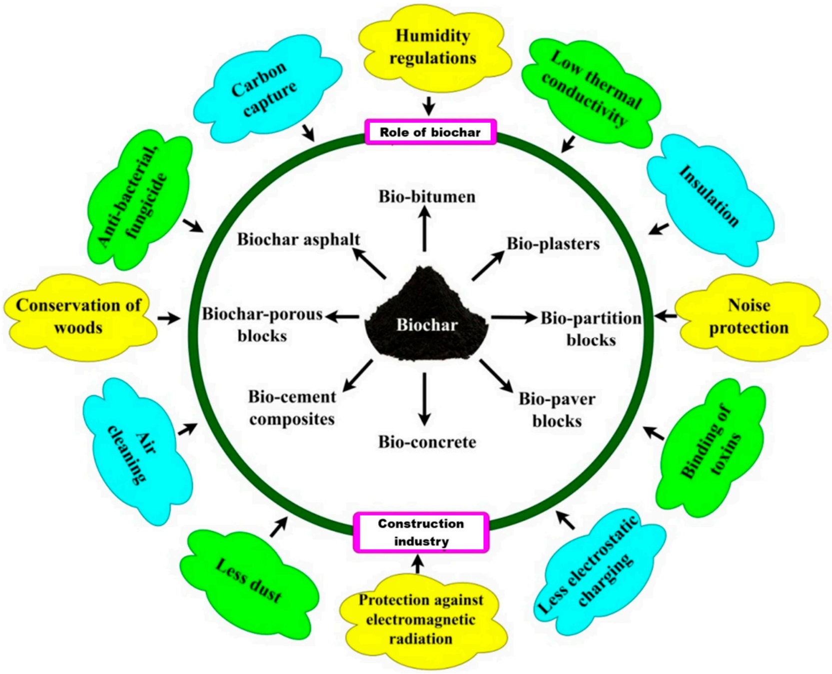


Figure 12. Use of biochar in the construction industry to improve conventional material properties (adapted from [132], under the terms of the Creative Commons Attribution License (CC BY 4.0)).

Collectively, these applications illustrate that the valorization of biochar, even when produced in small quantities during gasification, aligns with the principles of circular economy and environmental sustainability, making it a strategic by-product in integrated waste-to-energy systems.

Additional considerations should be made regarding the differences between biochar produced via gasification and pyrolysis. Although biochar is a common by-product in both processes, their physicochemical properties differ significantly due to the distinct operating conditions involved. Biochar from gasification typically exhibits lower fixed carbon content, higher ash content, and reduced surface area compared to pyrolysis biochar, which is attributable to the higher temperatures and partial oxidation environment characteristic of gasification [161,162]. These differences influence application suitability: pyrolysis biochar, with its higher porosity and cation exchange capacity, is more widely applied as a soil amendment and for carbon sequestration, whereas gasification biochar's higher mineral and alkaline content make it more appropriate for pollutant adsorption or as an additive in construction materials [163,164]. Typical differences are summarized in Table 6, where values vary depending on feedstock and operating conditions.

Table 6. Typical differences between pyrolysis and gasification biochar (author's own elaboration, based on data provided in [161–164]).

Property	Pyrolysis Biochar	Gasification Biochar
Fixed carbon (%)	70–85	40–60
Ash content (%)	5–20	20–40
Surface area (m^2/g)	200–400	10–100
pH	6–8	9–11
Cation exchange capacity (cmol/kg)	20–30	5–15
BET [1] porosity (m^2/g)	High	Low–moderate
Application suitability	Soil, carbon sequestration	Adsorption, construction

[1] BET porosity refers to the specific surface area of the biochar, determined by the Brunauer–Emmett–Teller (BET) gas adsorption method, indicative of internal porosity and adsorption capacity, critical for applications such as soil improvement or pollutant retention. Higher BET values indicate a more porous and chemically reactive biochar structure. Pyrolysis biochar, especially if produced at lower temperatures (~350–550 °C), typically exhibits higher BET porosity (200–400 m^2/g), and thus a larger internal surface area. Gasification biochar, produced at higher temperatures (~800–1000 °C), may have larger pores but sometimes a lower BET surface area (20–100 m^2/g) because its carbon structure is more "aromatized" and inert.

6. Current Deployment of Waste Gasification and Waste-to-Energy Technologies in Europe

A notable increase in the development of gasification power plants was observed in the late 2000s and early 2010s, likely driven by legislative measures introduced between 2008 and 2009. However, a succession of crises beginning in the early 2020s has hindered the advancement of new gasification projects. Despite these setbacks, recent trends suggest a gradual revitalization of the sector.

In 2023, there were approximately 141 biomass and waste gasification plants in Europe and 54 plants in various stages of development or with an unknown construction date (Figure 13). Germany stands out as the leading country in the field of gasification technologies, with a total of 61 facilities. However, most of these installations are currently in the pilot or demonstration phase (corresponding to TRL 5–7), often located within research institutions and universities due to their emphasis on innovative and emerging process configurations. France ranks second, with 5 gasification plants in operation and 34 under development. Finland and Italy follow with 18 plants each, and over 80% have already been tested under real operating conditions. The high level of technological maturity in these two countries indicates that many of their systems have reached advanced TRLs (8–9), showing readiness for commercial-scale implementation and integration into national WtE strategies [53].

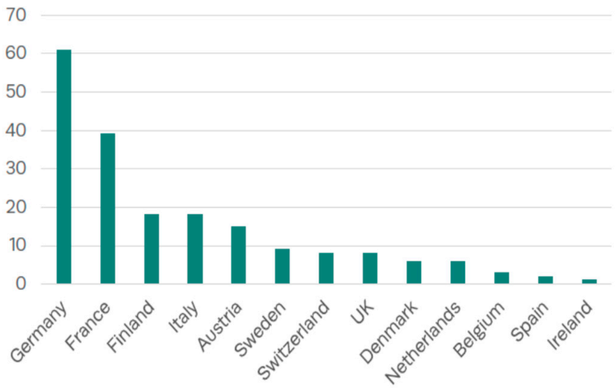


Figure 13. Number of gasification plants (existing and under development) in European countries in 2023 [53].

Among the gasification plants currently operating in Europe, the most frequently adopted reactor configurations are fixed bed and fluidized bed systems (Table 7). Fixed bed gasifiers, such as downdraft and updraft types, are often employed in small-scale or decentralized applications, particularly in Germany and Finland, due to their lower complexity and cost. Fluidized bed reactors, including bubbling and circulating types, are widely used for mid- to large-scale projects, owing to their superior feedstock flexibility and thermal uniformity. In a few demonstration projects, more advanced technologies such as dual fluidized bed and plasma gasification have also been tested, particularly in France and the UK. However, these remain limited to pilot or semi-commercial stages [19,165].

Table 7. Examples of waste gasification plants in selected European countries, classified by reactor type, application, and technological readiness level (author's own elaboration, based on data provided in [19,53,165]).

Country	Type of Reactor	Examples of Applications/Projects	TRL
Germany	Fixed bed (updraft, downdraft)	Local decentralized initiatives, academic institutions (Fraunhofer IGB)	7–9
France	Dual fluidized bed, plasma	GAYA Project (ENGIE), CHO Power	6–8
Finland	Circulating fluidized bed	VTT Technology Centre, Lahti Energia	8–9
Italy	Bubbling fluidized bed	ENEA pilot plants, research consortia	7–8
United Kingdom	Plasma arc, moving bed	Tetronics, Advanced Plasma Power	6–7
Sweden	Circulating fluidized bed, fixed bed hybrid systems	Valmet demo units, Goteborg Energi	8–9
Austria	Dual fluidized bed	Güssing plant (2001–2011)	9 (before shutdown)

As depicted in Figure 14, the majority (61%) of operational gasification plants in Europe have achieved a technology TRL of 9, indicating full commercial maturity. Nevertheless, a significant proportion of earlier projects remain at lower stages of development, with 24% of installations built before 2018 still operating below full maturity (TRL ≤ 7), reflecting persistent technological and implementation challenges.

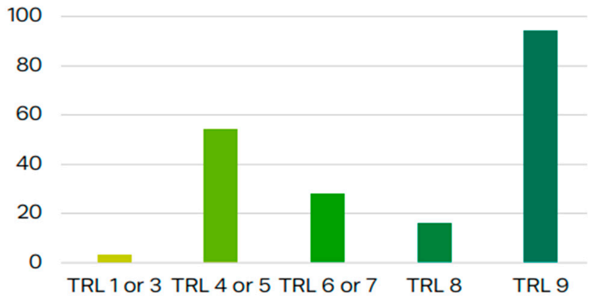


Figure 14. Technological readiness level for European gasification plants [53].

In 2023, lignocellulosic biomass, predominantly from forestry and agricultural residues, served as the primary feedstock for approximately 74.9% of gasification plants, followed by mixed feedstock (14.9%), streams of organic residues and other waste (5.6%), forest residues (3.1%), and biomass and mixed biomass-coal (1.5%) respectively (Figure 15) [53].

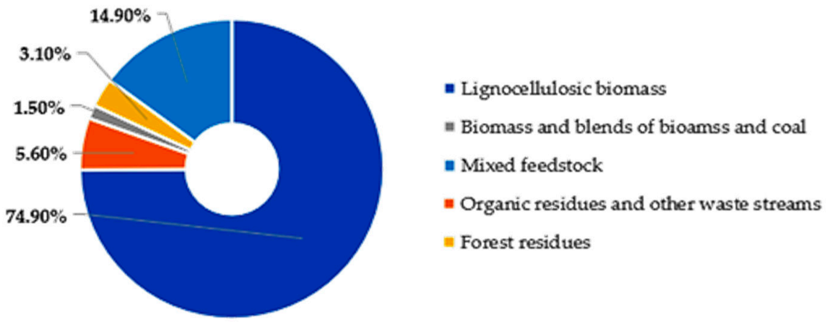


Figure 15. Proportion of raw materials (%) in gasification plants in Europe, in 2023 [Drawn by the authors].

Several factors currently limit the widespread adoption of gasification technologies as a major contributor to the global energy transition. One of the primary constraints is the limited availability of biomass feedstock. Biomass resources often compete with agricultural land use for food production, which restricts the sustainable harvesting volumes. Moreover, biomass supply is subject to significant seasonal variability, leading to fluctuations in feedstock availability throughout the year. This variability complicates the planning and continuous operation of gasification facilities. Additionally, the heterogeneous nature of biomass, varying in moisture content, chemical composition, and physical characteristics, poses substantial challenges for developing standardized processing technologies and reliable supply chains. Efficient logistics and transportation networks are required to collect and deliver biomass from widely dispersed sources, which often results in increased operational costs and environmental impacts.

In this context, MSW emerges as an attractive and more stable alternative feedstock for gasification reactors. MSW is generated continuously in large and increasing volumes worldwide, offering a concentrated and relatively predictable source of organic material. Utilizing MSW for gasification not only provides a renewable energy resource but also addresses waste management issues by reducing landfill volumes and associated environmental problems. However, MSW's heterogeneous composition, including plastics, organics, metals, and inert materials, needs advanced sorting and pretreatment processes to optimize gasification performance and minimize the production of harmful emissions and residues.

A practical example highlighting the challenges of implementing advanced waste-to-energy technologies at the local level is the pilot-scale industrial waste gasification facility commissioned in 2009 in the city of Săcele (Brașov County, Romania). Designed with a processing capacity of 100,000 tons/year, the facility operated intermittently between 2010 and 2015 for a total of approximately 100 days. It processed only MSW transported from various counties, despite being located at only 200 m from the Brașov sanitary landfill (which captures and processes landfill gas). By 2023, the facility was decommissioned and listed for sale. The closure underscores several critical issues that hindered its success, including poor resource management, the absence of a clear and supportive legislative framework, financial difficulties, and operational challenges such as maintaining consistent feedstock quality and plant uptime. Furthermore, limited public acceptance and inadequate stakeholder engagement contributed to obstacles in sustainable operation. Lessons learned from this experience emphasize the importance of comprehensive planning, ensuring stable financial backing, and developing robust regulatory policies to foster the sustainable development and deployment of innovative waste-to-energy technologies [11,17].

Looking towards the future, the report "Biogases towards 2040 and Beyond" projects that the theoretical potential for thermal gasification could reach approximately 37 billion m^3 by 2040, with about 33 billion m^3 feasible within the EU-27 [166]. Achieving this ambitious target would require harnessing a diverse range of biomass sources, including emerging feedstock such as crops cultivated on marginal or contaminated lands, seaweed, digestate from anaerobic digestion, and landfill gas. These alternative sources could supplement traditional biomass supplies, helping to overcome some of the limitations posed by land-use competition and seasonal availability.

Despite the promising outlook, several barriers remain. The high capital expenditures necessary for constructing and commissioning gasification plants pose significant financial risks, especially in the absence of guaranteed feedstock supply contracts or supportive policy incentives. Additionally, gasification processes require sophisticated gas cleaning and upgrading systems to remove contaminants such as tar, sulfur compounds, and particulates, which add complexity and operational costs.

Regulatory uncertainties and evolving environmental standards further complicate investment decisions, as developers must ensure compliance with strict emission limits and waste handling regulations. Public concerns about potential environmental impacts, including emissions, ash disposal, and odor, also influence project acceptance and social license to operate. Moreover, integrating gasification technology into existing energy infrastructures demands advanced technical expertise and coordination among multiple stakeholders, representing further challenges to widespread commercialization.

Regarding technological readiness, small-scale gasification units have reached full commercial maturity, classified as TRL 9. In contrast, large-scale biomass gasification technologies remain largely at demonstration or pilot stages, between TRL 6 and 7, indicating that further development, optimization, and validation are required before broad market adoption can be achieved.

Continued research, innovation, and pilot projects will be essential to address technical challenges, improve process efficiencies, and reduce costs, ultimately enabling gasification to play a significant role in the global transition to sustainable energy systems.

In 2021, WtE plants across Europe processed approximately 103 million tons of household and similar municipal waste. The recovered energy contributed to the supply of electricity for an estimated 21 million European citizens and district heating for an additional 17 million. Depending on the type of fossil fuel displaced by energy-from-waste processes, ranging from natural gas and oil to coal and lignite, this recovery potentially avoided the consumption of 10 to 56 million tons of fossil fuels, thereby preventing the emission of 22 to 44 million tons of CO_2 by conventional thermal power plants.

The number of WtE facilities operating in Europe in 2022 (excluding hazardous waste incineration plants) was 498, and the volume of thermally treated residual waste was 100 million tons [167]. As shown in Figure 16, the distribution of WtE plants across EU Member States in 2022 reveals significant disparities. Countries such as Germany, France, and Italy operate the largest number of WtE facilities, reflecting their long-standing commitment to thermal waste valorization. In contrast, several Eastern European countries, including Romania, Bulgaria, and Croatia, have a very limited number of WtE plants or none, which highlights infrastructural and investment gaps in the waste management sector. These differences underscore the uneven adoption of thermal valorization technologies across the EU, with potential implications for achieving waste reduction and decarbonization targets.

According to Statista [168], in 2024, the total waste-to-energy installed capacity in Europe was approximately 4.9. GW, with Germany having the largest installed capacity in municipal waste-to-energy plants in Europe, reaching approximately 1004 MW (Figure 17).

Figure 16. Number of WtE plants in 2022, in the Member States. Last data update: 16 October 2024 [167].

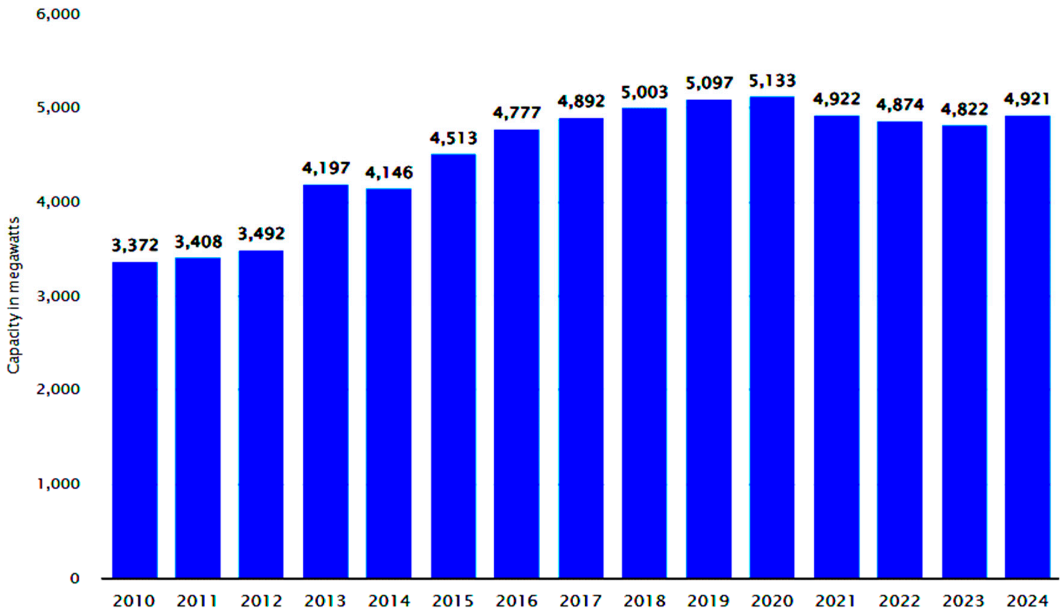


Figure 17. Installed capacity of energy from municipal waste in Europe in the period 2010–2024, by country (in MW) [168].

Globally, 106 power plants generate electricity from biomass-derived syngas, with a combined capacity of approximately 356 MW. An additional 185 MW of thermal energy is produced in dedicated heat plants. Biomass-based syngas is also used in 24 facilities for liquid fuel production (such as methanol, ethanol, DME, FT-diesel) totaling around

750,000 tons/year. Eight plants produce gaseous fuels (synthetic natural gas and hydrogen), with an output of about 3.2×10^8 Nm^3/year, while seven facilities convert syngas into chemicals, reaching 9000 tons/year. Notably, four facilities are integrated plants producing both power and fuel [169].

While Figure 17 shows the total installed capacity for energy generation from municipal waste across various European countries between 2010 and 2024, it is important to note that gasification-based facilities still represent a minor share of this capacity. According to available data, over 90% of the reported installed capacity is attributed to conventional incineration technologies with energy recovery. Gasification plants remain at pilot or early commercial stage in most countries, contributing less than 5–7% of the total WtE capacity in countries such as Germany, Sweden, and the Netherlands, where such systems have been partially integrated with RDF processing or circular hydrogen production schemes. Despite their limited contribution at present, gasification technologies are expected to gain more traction due to their higher syngas quality, lower emission profile, and compatibility with carbon-neutral strategies.

7. Conclusions and Perspectives

Gasification technologies represent a promising and technically viable solution for the valorization of non-recyclable fractions of municipal solid waste, positioning themselves as complementary to conventional recycling strategies.

Unlike incineration, gasification enables a more controlled conversion of heterogeneous waste into syngas, a versatile energy carrier that can be used for electricity, heat, green hydrogen production, or as a platform for the synthesis of advanced biofuels and chemical intermediates. As such, gasification contributes not only to waste minimization, but also to circular economy objectives through material and energy recovery from residues that would otherwise be landfilled or incinerated.

The diversity of gasification technologies, ranging from fixed bed and fluidized bed reactors to plasma and microwave-assisted systems, allows for adaptation to various waste compositions and treatment scales, from local decentralized applications to industrial-scale installations. These systems are particularly suitable for treating abundantly available municipal solid waste, but also offer strong potential for valorizing biomass and biowaste, thereby supporting renewable energy and circular resource recovery goals.

Beyond the technological dimension, the valorization of gasification by-products plays a crucial role in enhancing process sustainability. Ash, when properly characterized, holds potential for use in construction materials or as a soil amendment in agriculture. Tar, although considered a processing challenge, can be upgraded into valuable chemical compounds or energy vectors through reforming or cracking techniques. Biochar, even if obtained in smaller quantities, presents notable opportunities for soil enhancement, carbon sequestration, and pollutant adsorption. These valorization pathways contribute not only to improving the energy and material efficiency of gasification systems but also to reinforcing their alignment with circular economy principles.

Despite its advantages, the wider deployment of waste gasification faces barriers including high capital costs, complex syngas cleaning requirements, and regulatory uncertainty. Most existing plants in Europe remain at the pilot or demonstration stage, with relatively few reaching full commercial maturity. To unlock the full potential of gasification in sustainable waste-to-energy strategies, significant investments in infrastructure, targeted research and innovation, and supportive policy frameworks are essential.

The objectives of the European Green Deal and REPowerEU initiative create a strategic context favorable to the expansion of gasification technologies, particularly through their emphasis on renewable energy, energy independence, and sustainable resource use. Supporting the development and scaling-up of gasification plants through regulatory clarity, technology-neutral incentives, and integration into national waste management plans could accelerate their commercial viability and environmental impact.

Thus, waste gasification stands as a critical enabling technology for the energy transition, capable of transforming residual MSW into clean energy carriers while reducing greenhouse gas emissions and reliance on fossil resources. Its integration into future energy and waste strategies will depend on coherent public policy, investment confidence, and continued scientific advancement.

Looking ahead, in our opinion, the future development of MSW gasification technologies is likely to focus on several key directions. First, process modularization and decentralized systems will gain momentum, enabling local waste-to-energy conversion at community or industrial park scale. Second, plasma-assisted and hybrid reactors are expected to address the challenges of feedstock heterogeneity and improve conversion efficiencies. Third, digitalization and AI-integrated process control will play a growing role in optimizing reactor performance and emissions compliance. In parallel, carbon-negative applications, such as syngas upgrading with integrated carbon capture and biochar valorization, are emerging as strategic innovation areas aligned with climate goals.

Technological maturity, coupled with supportive policies and market mechanisms (e.g., carbon pricing, green hydrogen credits), will determine the pace and scale of commercial deployment. As a result, the convergence of advanced gasification with circular economy principles and decarbonization targets marks the most promising pathway forward.

Author Contributions: Conceptualization, N.U., N.-V.V. and S.-Ș.B.; methodology, N.U., N.-V.V., S.-Ș.B., M.I. and N.-E.G.; software, S.-Ș.B. and N.-E.G.; validation, N.U. and N.-V.V.; formal analysis, N.U., N.-V.V. and S.-Ș.B.; investigation, N.U. and M.I.; resources, N.U., N.-V.V., S.-Ș.B., M.I. and N.-E.G.; data curation, N.U., N.-V.V. and S.-Ș.B.; writing—original draft preparation, N.U., M.I. and N.-E.G.; writing—review and editing, N.U. and M.I.; visualization, N.-V.V. and S.-Ș.B.; supervision, N.U. and N.-V.V.; project administration, N.U.; funding acquisition, N.U., M.I. and N.-E.G. All authors have read and agreed to the published version of the manuscript.

Funding: The APC was funded by the National University of Science and Technology Politehnica Bucharest, Romania, within the PubArt Program.

Institutional Review Board Statement: Not applicable.

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

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

References

1. Iqbal, A.; Liu, X.; Chen. G.H. Municipal solid waste: Review of best practices in application of life cycle assessment and sustainable management technique. *Sci. Total Environ*. **2020**, *729*, 138622. https://doi.org/10.1016/j.scitotenv.2020.138622.
2. United Nations Environmental Program. Global Waste Management Outlook 2024. 2024. Available online: https://www.unep.org/ietc/resources/report/global-waste-management-outlook-2024 (accessed on 13 June 2025).
3. Abubakar, I.R.; Maniruzzaman, K.M.; Dano, U.L.; AlShihri, F.S.; AlShammari, M.S.; Ahmed, S.M.S.; Al-Gehlani, W.A.G.; Alrawaf, T.I. Environmental sustainability impacts of solid waste management practices in the Global South. *Int. J. Env. Res. Public Health* **2022**, *19*, 12717. https://doi.org/10.3390/ijerph191912717.
4. Saif, S.; Razia, E.T.; Khan, M.; Hatshan, M.R.; Adil, S.F. A comprehensive introduction to solid waste issues. *Waste Deriv. Carbon Nanomater.* **2025**, *1*, 1–16.
5. European Confederation of Waste-to-Energy Plants—CEWEP. Latest Eurostat Figures: Municipal Waste Treatment. 2024. Available online: https://www.cewep.eu/municipal-waste-treatment-2022/ (accessed on 13 June 2025).

6. Kaza, S.; Yao, L.C.; Bhada-Tata, P.; Van Woerden, F. *What a Waste 2.0. A Global Snapshot of Solid Waste Management to 2050. Urban Development*; International Bank for Reconstruction and Development; The World Bank: Washington, DC, USA, 2018.
7. Batista, M.; Gusmao Caiado, R.G.; Goncalves Quelhas, O.L.; Alves Lima, G.B.; Leal Filho, W.; Rocha Yparraguirre, I.T. A framework for sustainable and integrated municipal solid waste management: Barriers and critical factors to developing countries. *J. Clean. Prod.* **2021**, *312*, 127516. https://doi.org/10.1016/j.jclepro.2021.127516.
8. Islam, N.F.; Gagoi, B.; Saikia, R.; Ypusaf, B.; Narayan, M.; Sarma, H. Encouraging circular economy and sustainable environmental practices by addressing waste management and biomass energy production. *Reg. Sust.* **2024**, *5*, 100174. https://doi.org/10.1016/j.regsus.2024.100174.
9. Paiva e Silva Muller, L.N.; Delai, I.; Chicarelli Alcantara, R.L. Circular value chain practices for developing resource value retention options. *J. Clean. Prod*. **2022**, *359*, 131925. https://doi.org/10.1016/j.jclepro.2022.131925.
10. Ungureanu, N.; Rusănescu, C.O. Biomass and bioenergy. *Energies* **2025**, *18*, 2233. https://doi.org/10.3390/en18092233.
11. Paraschiv, G.; Dincă, N.M.; Ungureanu, N.; Moiceanu, G.; Toma, M.L. *Waste Recycling Installations*; Politehnica Press Publishing House: Bucharest, Romania, 2017.
12. Singh, S.K.; Tiwari, A.K. Solar-powered hydrogen production: Advancements, challenges, and the path to net-zero emissions. *Int. J. Hydrogen Energy* **2024**, *84*, 549–579. https://doi.org/10.1016/j.ijhydene.2024.08.209.
13. Ma, W.; Han, W.; Liu, Q.; Song, X.; Li, J.; Zhang, N.; Xu, G. Hydrogen generation system with zero carbon emission based on synergistic conversion of methane and solar energy. *Energy* **2025**, *316*, 134609. https://doi.org/10.1016/j.energy.2025.134609.
14. Boddula, R.; Lee, Y.Y.; Masimukku, S.; Chang-Chien, G.P.; Pothu, R.; Srivastava, R.K.; Sarangi, P.K.; Selvaraj, M.; Basumatary, S.; Al-Qahtani, N. Sustainable hydrogen production: Solar-powered biomass conversion explored through (photo)electrochemical advancements. *Process Saf. Environ. Prot.* **2024**, *186*, 1149–1168. https://doi.org/10.1016/j.psep.2024.04.068.
15. Xue, X.; Li, G.; Wang, Y.; Han, W.; Liu, C.; Jiao, F. Proposal and evaluation of a near-zero carbon emissions hydrogen production system coupled with photovoltaic, photothermal and coal gasification. *Appl. Energy* **2025**, *377*, 124400. https://doi.org/10.1016/j.apenergy.2024.124400.
16. Ungureanu, N. *Biomass-Based Energy Systems (Part II). Gasification Technology and by-Products Valorization*; Course for Specialization of Informatics Applied to Environmental Engineering; Faculty of Biotechnical Systems Engineering, National University of Science and Technology Politehnica: Bucharest, Romania, 2023. Available online: https://curs.upb.ro/2024/course/view.php?id=8900 (accessed on 13 June 2025).
17. Guan, G.; Kaewpanha, M.; Hao, X.; Abudula, A. Catalytic steam reforming of biomass tar: Prospects and challenges. *Renew. Sustain. Energy Rev.* **2016**, *58*, 450–461. https://doi.org/10.1016/j.rser.2015.12.316.
18. Montouris, A.; Voutsas, E.; Tassios, D. Solid waste plasma gasification: Equilibrium model development and exergy analysis. *Energy Convers. Manag.* **2006**, *47*, 1723–1737. https://doi.org/10.1016/j.enconman.2005.10.015.
19. Arena, U. Process and technological aspects of municipal solid waste gasification. A review. *Waste Manag.* **2012**, *32*, 625–639. https://doi.org/10.1016/j.wasman.2011.09.025.
20. Perry, R.H. *Perry's Chemical Engineers' Handbook*, 7th ed.; McGraw-Hill: New York, NY, USA, 1999.
21. Smith, J.M.; Van Ness, H.C.; Abbott, M.M.; Swihart, M.T. *Introduction to Chemical Engineering Thermodynamics*, 8th ed.; McGraw-Hill: New York, NY, USA, 2018.
22. Devi, L.; Ptasinski, K.J.; Janssen, F.J.J.G. A review of the primary measures for tar elimination in biomass gasification processes. *Biomass Bioenerg.* **2003**, *24*, 125–140. https://doi.org/10.1016/S0961-9534(02)00102-2.
23. Peng, M.-Q.; Chen, T.-H.; Jin, T.; Su, Y.-C.; Luo, S.-T.; Xu, H. A novel first-order kinetic model for simultaneous anaerobic–aerobic degradation of municipal solid waste in landfills. *Processes* **2024**, *12*, 2225. https://doi.org/10.3390/pr12102225.
24. Alouani, Y.; Saifaoui, D.; Alouani, A.; Alouani, M.A. Municipal solid waste gasification to produce hydrogen: Integrated simulation model and performance analysis. *Int. J. Energy Res.* **2022**, *46*, 20068–20078. https://doi.org/10.1002/er.8591.
25. Singh, D.; Yadav, S.; Bharadwaj, N.; Verma, R. Low temperature steam gasification to produce hydrogen rich gas from kitchen food waste: Influence of steam flow rate and temperature. *Int. J. Hydrogen Energy* **2020**, *45*, 20843–2084350. https://doi.org/10.1016/j.ijhydene.2020.05.168.
26. Gao, Y.; Wang, M.; Raheem, A.; Wang, F.; Wei, J.; Xu, D.; Song, X.; Bao, W.; Huang, A.; Zhang, S.; et al. Syngas production from biomass gasification: Influences of feedstock properties, reactor type, and reaction parameters. *ACS Omega* **2023**, *8*, 31620–31631. https://doi.org/10.1021/acsomega.3c03050.
27. Wilk, V.; Hofbauer, H. Influence of fuel particle size on gasification in a dual fluidized bed steam gasifier. *Fuel Process. Technol.* **2013**, *115*, 139–151. https://doi.org/10.1016/j.fuproc.2013.04.013.

28. Vlăduțoiu, L.C.; Cristea, M.; Nenciu, F.; Vlăduț, V.; Olan, M.; Grigore, I.; Sorică, C.; Vanghele, N.; Cristea, O.D. Innovative pyrolysis reactor design for enhanced performance and superior biochar quality. *INMATEH Agric. Eng.* **2025**, *75*, 414–422. https://doi.org/10.35633/inmateh-75-35.
29. Lopes Motta, I.; Toscano Miranda, N.; Maciel Filho, R.; Wolf Maciel, M.R. Biomass gasification in fluidized beds: A review of biomass moisture content and operating pressure effects. *Renew. Sustain. Energy Rev.* **2018**, *94*, 998–1023. https://doi.org/10.1016/j.rser.2018.06.042.
30. Stapf, D.; Ciceri, G.; Johansson, I.; Whitty, K. Biomass pre-treatment for bioenergy. In *Case Study 3—Pretreatment of Municipal Solid Waste (MSW) for Gasification*; IEA Bioenergy: Ottawa, ON, Canada, 2019.
31. Mishra, S.; Upadhyay, R.K. Review on biomass gasification: Gasifiers, gasifying mediums, and operational parameters. *Mater. Sci. Energy Technol.* **2021**, *4*, 329–340. https://doi.org/10.1016/j.mset.2021.08.009.
32. Brandenberger, M.; Matzenberger, J.; Vogel, F.; Ludwig, C. Producing synthetic natural gas from microalgae via supercritical water gasification: A technoeconomic sensitivity analysis. *Biomass Bioenerg.* **2013**, *51*, 26–34. https://doi.org/10.1016/j.biombioe.2012.12.038.
33. Heberlein, S.; Chan, W.P.; Veksha, A.; Giannis, A.; Hupa, L.; Lisak, G. High temperature slagging gasification of municipal solid waste with biomass charcoal. *J. Hazard. Mater.* **2021**, *423*, 127057. https://doi.org/10.1016/j.jhazmat.2021.127057.
34. Dunayevska, N.; Shendrik, T.; Fataiev, A. The approach for reducing of slagging and corrosion properties of fuels with a high content of alkali and alkaline earth metals. *Fuel* **2025**, *381*, 133359. https://doi.org/10.1016/j.fuel.2024.133359.
35. Parthasarathy, P.; Narayanan, K.S. Hydrogen production from steam gasification of biomass: Influence of process parameters on hydrogen yield—A review. *Renew. Energy* **2014**, *66*, 570–579. https://doi.org/10.1016/j.renene.2013.12.025.
36. Kuo, P.-C.; Wu, W. Design, optimization and energetic efficiency of producing hydrogen-rich gas from biomass steam gasification. *Energies* **2015**, *8*, 94–110. https://doi.org/10.3390/en8010094.
37. Inayat, M.; Sulaiman, S.A.; Shahbaz, M.; Bhayo, B.A. Application of response surface methodology in catalytic co-gasification of palm wastes for bioenergy conversion using mineral catalysts. *Biomass Bioenerg.* **2020**, *132*, 105418. https://doi.org/10.1016/j.biombioe.2019.105418.
38. Lourinho, G.; Alves, O.; Garcia, B.; Rijo, B.; Brito, P.; Nobre, C. Costs of gasification technologies for energy and fuel production: Overview, analysis, and numerical estimation. *Recycling* **2023**, *8*, 49. https://doi.org/10.3390/recycling8030049.
39. Weiland, F.; Lundström, S.; Ögren, Y. Oxygen-blown gasification of pulp mill bark residues for synthetic fuel production. *Processes* **2021**, *9*, 163. https://doi.org/10.3390/pr9010163.
40. Kun, U.H.; Ksepko, E. Advancing municipal solid waste management through gasification technology. *Processes* **2025**, *13*, 2000. https://doi.org/10.3390/pr13072000.
41. Ofuani, N.; Bhoi, P. Carbon dioxide gasification of biochar: A sustainable way of utilizing captured CO_2 to mitigate greenhouse gas emission. *Sustainability* **2024**, *16*, 5044. https://doi.org/10.3390/su16125044.
42. Sher, F.; Hameed, S.; Smjecanin Omerbegovic, N.; Chupin, A.; Ul Hai, I.; Wang, B.; Teoh, Y.H.; Yildiz, M.J. Cutting-edge biomass gasification technologies for renewable energy generation and achieving net zero emissions. *Energy Convers. Manag.* **2025**, *323*, 119213. https://doi.org/10.1016/j.enconman.2024.119213.
43. Andrew, R.; Gokak, D.T.; Sharma, P.; Sharma, J.; Somkuwar, N.; Gupta, S. Practical achievements on biomass steam gasification in a rotary tubular coiled-downdraft reactor. *Procedia Environ. Sci.* **2016**, *35*, 818–825. https://doi.org/10.1016/j.proenv.2016.07.098.
44. Wang, L.; Zhou, T.; Hou, B.; Yang, H.; Hu, N.; Zhang, M. A comprehensive review of biomass gasification characteristics in fluidized bed reactors: Progress, challenges, and future directions. *Fluids* **2025**, *10*, 147. https://doi.org/10.3390/fluids10060147.
45. Rupesh, S.; Muraleedharan, C.; Arun, P. Influence of residence time on syngas composition in CaO enhanced air–steam gasification of biomass. *Environ. Dev. Sustain.* **2021**, *24*, 8363–8377. https://doi.org/10.1007/s10668-021-01787-1.
46. Begum, S.; Rasul, M.G.; Akbar, D.; Ramzan, N. Performance analysis of an integrated fixed bed gasifier model for different biomass feedstocks. *Energies* **2013**, *6*, 6508–6524. https://doi.org/10.3390/en6126508.
47. Kaneesamkandi, Z.; Rehman, A.U.; Usmani, Y.S.; Sayeed, A.; Alabi, H.S. Methodology for selecting an ideal thermal gasification technique for municipal solid waste using multi-criteria decision analysis. *Appl. Sci.* **2023**, *13*, 12675. https://doi.org/10.3390/app132312675.
48. Ongen, A.; Kurtulus Ozcan, H.; Ozbas, E.E. Gasification of biomass and treatment sludge in a fixed bed gasifier. *Int. J. Hydrogen Energy* **2016**, *41*, 8146–8153. https://doi.org/10.1016/j.ijhydene.2015.11.159.
49. Jothiprakash, G.; Balasubramaniam, P.; Sundaram, S.; Ramesh, D. Catalytic biomass gasification for syngas production: Recent progress in tar reduction and future perspectives. *Biomass* **2025**, *5*, 37. https://doi.org/10.3390/biomass5030037.

50. Mai, T.P.; Nguyen, D.Q. Gasification of Biomass. In *Gasification for Low-Grade Feedstock*; Basu, P., Ed.; IntechOpen: London, UK, 2020; pp. 1–13. https://doi.org/10.5772/intechopen.93954.
51. Basu, P. *Biomass Gasification, Pyrolysis and Torrefaction: Practical Design and Theory*, 4th ed.; Academic Press, Elsevier: Amsterdam, The Netherlands, 2022. https://doi.org/10.1016/C2020-0-01024-3.
52. IEA Bioenergy. Status Report on Thermal Gasification of Biomass and Waste 2021. IEA Bioenergy Task 33. 2022. Available online: https://www.ieabioenergy.com/wp-content/uploads/2022/03/Status-Report2021_final.pdf (accessed on 24 April 2025).
53. European Biogas Association. *Gasification. Diversification of Biomass Processing and Waste Utilization*; European Biogas Association: Brussels, Belgium, 2024. Available online: https://www.europeanbiogas.eu/wp-content/uploads/2024/12/EBA-Gasification_December-2024.pdf (accessed on 24 April 2025).
54. Arena, U.; Di Gregorio, F.; Zaccariello, L. Fluidized bed gasification of solid recovered fuels: Performance and syngas quality assessment. *Waste Manag.* **2019**, *84*, 151–162. https://doi.org/10.1016/j.wasman.2018.12.024.
55. Vargas-Salgado, C.; Hurtado-Pérez, E.; Alfonso-Solar, D.; Malmquist, A. Empirical design, construction, and experimental test of a small-scale bubbling fluidized bed reactor. *Sustainability* **2021**, *13*, 1061. https://doi.org/10.3390/su13031061.
56. Hu, Y.; Chen, Z. Thermochemical conversion of sewage sludge: Progress in pyrolysis and gasification. *Water* **2025**, *17*, 1833. https://doi.org/10.3390/w17121833.
57. Ewald, A.; Spliethoff, H.; Fendt, S. Entrained flow gasification of sewage sludge-performance parameters and the fate of phosphorus, potassium, sulfur, and heavy metals. *Energy Fuels* **2025**, *39*, 2616–2629. https://doi.org/10.1021/acs.energyfuels.4c05209.
58. Dammann, M.; Santo, U.; Boning, D.; Knoch, H.; Eberhard, M.; Kolb, T. Entrained flow gasification: Pilot-scale experimental, balancing and equilibrium data for model validation. *Fuel* **2025**, *382*, 132809. https://doi.org/10.1016/j.fuel.2024.132809.
59. Mower, G. Plasma Gasification: Revolutionizing Waste Management. Alliance for Innovation and Infrastructure. Policy Blog, Innovation and Technology, Energy. 2024. Available online: https://www.aii.org/plasma-gasification-revolutionizing-waste-management/ (accessed on 14 June 2025).
60. Kaushal, R.; Rohit; Dhaka, A.K. A comprehensive review of the application of plasma gasification technology in circumventing the medical waste in a post-COVID-19 scenario. *Biomass Convers. Biorefin.* **2024**, *14*, 1427–1442. https://doi.org/10.1007/s13399-022-02434-z.
61. Cai, X.; Wei, X.; Du, C. Thermal plasma treatment and coprocessing of sludge for utilization of energy and material. *Energy Fuel* **2020**, *34*, 7775–7805. https://doi.org/10.1021/acs.energyfuels.0c00572.
62. Gabbar, H.A.; Darda, S.A.; Damideh, V.; Hassen, I.; Aboughaly, M.; Lisi, D. Comparative study of atmospheric pressure DC, RF, and microwave thermal plasma torches for waste to energy applications. *Sustain. Energy Technol. Assess.* **2021**, *47*, 101447. https://doi.org/10.1016/j.seta.2021.101447.
63. Yaliwal, V.S.; Banapurmath, N.R.; Gireesh, N.M.; Tewari, P.G. Production and utilization of renewable and sustainable gaseous fuel for power generation applications: A review of literature. *Renew. Sustain. Energy Rev.* **2014**, *34*, 608–627. https://doi.org/10.1016/j.rser.2014.03.043.
64. Erdogan, A.A.; Yilmazoglu, M.Z. Plasma gasification of the medical waste. *Int. J. Hydrogen Energy* **2021**, *46*, 29108–29125. https://doi.org/10.1016/j.ijhydene.2020.12.069.
65. Tagliaferri, C.; Evangelisti, S.; Clift, R.; Lettieri, P.; Chapman, C.; Taylor, R. Life cycle assessment of conventional and advanced two-stage energy-from-waste technologies for methane production. *J. Clean. Prod.* **2016**, *129*, 144–158. https://doi.org/10.1016/j.jclepro.2016.04.092.
66. Materazzi, M.; Lettieri, P.; Mazzei, L.; Taylor, R.; Chapman, C. Thermodynamic modelling and evaluation of a two-stage thermal process for waste gasification. *Fuel* **2013**, *108*, 356–369. https://doi.org/10.1016/j.fuel.2013.02.037.
67. Tamošiūnas, A.; Milieška, M.; Gimžauskaitė, D.; Aikas, M.; Uscila, R.; Zakarauskas, K.; Fendt, S.; Bastek, S.; Spliethoff, H. Plasma gasification of medical plastic waste to syngas in a greenhouse gas (CO_2) Environment. *Sustainability* **2025**, *17*, 2040. https://doi.org/10.3390/su17052040.
68. Ellacuriaga, M.; Gil, M.V.; Gómez, X. Syngas fermentation: Cleaning of syngas as a critical stage in fermentation performance. *Fermentation* **2023**, *9*, 898. https://doi.org/10.3390/fermentation9100898.
69. Munir, M.T.; Mardon, I.; Al-Zuhair, S.; Shawabkeh, A.; Saqib, N.U. Plasma gasification of municipal solid waste for waste-to-value processing. *Renew. Sustain. Energy Rev.* **2019**, *116*, 109461. https://doi.org/10.1016/j.rser.2019.109461.
70. Zhang, Y.; Matsumura, Y. Recent advances in supercritical water gasification for hydrogen production from biomass. *Renew. Sustain. Energy Rev.* **2021**, *137*, 110489. https://doi.org/10.1016/j.rser.2020.110489.

71. Shahabuddin, M.; Tanvir Alam, M.; Krishna, B.B.; Bhaskar, T.; Perkins, G. A review on the production of renewable aviation fuels from the gasification of biomass and residual wastes. *Bioresour. Technol.* **2020**, *312*, 123596. https://doi.org/10.1016/j.biortech.2020.123596.
72. Wang, C.; Liu, Z.; He, M. A review on supercritical water gasification for CO_2 utilization and hydrogen production. *Int. J. Hydrogen Energ.* **2022**, *47*, 8012–8031. https://doi.org/10.1016/j.ijhydene.2022.01.091.
73. Du, X.; Lei, J.; Zhu, C.; Sima, J.; Sun, C.; Wang, J.; Song, K.; Huang, L.; Huang, Q.; Yan, J. Microwave-assisted gasification of plastics for tunable syngas production via bauxite residue-based catalytic oxygen carriers. *Chem. Eng. J.* **2025**, *510*, 161606. https://doi.org/10.1016/j.cej.2025.161606.
74. Arpia, A.A.; Nguyen, B.; Chen, W.H.; Dong, C.D.; Ok, Y.S. Microwave-assisted gasification of biomass for sustainable and energy-efficient biohydrogen and biosyngas production: A state-of-the-art review. *Chemosphere* **2022**, *287*, 132014. https://doi.org/10.1016/j.chemosphere.2021.132014.
75. Che, Y.; Yan, B.; Li, J.; Zhao, Z.; Gao, X.; Chen, G.; Cravotto, G.; Sun, Y.; Zhao, J. Microwave applied to the thermochemical conversion of biomass: A review. *Renew. Sustain. Energy Rev.* **2025**, *216*, 115674. https://doi.org/10.1016/j.rser.2025.115674.
76. Ayuso-Díaz, I.; Perez-Gil, S.; Lopez, G.; Santamaria, L.; Antoñanzas-González, F.J. Progress on waste plastics gasification process: A review of operating conditions, reactors and catalysts for clean syngas production and tar abatement. *Int. J. Hydrogen Energy* **2025**, *148*, 150000. https://doi.org/10.1016/j.ijhydene.2025.06.190.
77. Arregi, A.; Lopez, G.; Amutio, M.; Bilbao, J. High-temperature steam gasification of plastic waste: Effect on syngas composition and hydrogen production. *J. Clean. Prod.* **2022**, *363*, 132635. https://doi.org/10.1016/j.jclepro.2022.132635.
78. Nipattummakul, N.; Ahmed, I.; Kerdsuwan, S.; Gupta, A.K. High temperature steam gasification of wastewater sludge. *Appl. Energy* **2010**, *87*, 3729–3734. https://doi.org/10.1016/j.apenergy.2010.07.001.
79. Lee, U.; Chung, J.N.; Ingley, H.A. High-temperature steam gasification of municipal solid waste, rubber, plastic and wood. *Energy Fuels* **2014**, *28*, 4573–4587. https://doi.org/10.1021/ef500713j.
80. Mungyeko Bisulandu, B.J.R.; Huchet, F. Rotary kiln process: An overview of physical mechanisms, models and applications. *Appl. Therm. Eng.* **2022**, *221*, 119637. https://doi.org/10.1016/j.applthermaleng.2022.119637.
81. Freda, C.; Catizzone, E.; Villone, A.; Cornacchia, G. Biomass gasification in rotary kiln integrated with a producer gas thermal cleaning unit: An experimental investigation. *Results Eng.* **2024**, *21*, 101763. https://doi.org/10.1016/j.rineng.2024.101763.
82. Shi, H.; Si, W.; Li, X. The concept, design and performance of a novel rotary kiln type air-staged biomass gasifier. *Energies* **2016**, *9*, 67. https://doi.org/10.3390/en9020067.
83. Abouemara, K.; Shahbaz, M.; Mckay, G.; Al-Ansari, T. The review of power generation from integrated biomass gasification and solid oxide fuel cells: Current status and future directions. *Fuel* **2024**, *360*, 130511. https://doi.org/10.1016/j.fuel.2023.130511.
84. Situmorang, Y.A.; Zhao, Z.; Yoshida, A.; Abudula, A.; Guan, G. Small-scale biomass gasification systems for power generation (<200 kW class): A review. *Renew. Sustain. Energy Rev.* **2020**, *117*, 109486. https://doi.org/10.1016/j.rser.2019.109486.
85. Courson, C.; Gallucci, K. 8—Gas cleaning for waste applications (syngas cleaning for catalytic synthetic natural gas synthesis). In *Substitute Natural Gas from Waste: Technical Assessment and Industrial Applications of Biochemical and Thermochemical Processes*; Materazzi, M., Foscolo, P.U., Eds.; Academic Press, Elsevier: Amsterdam, The Netherlands, 2019; pp. 161–220. https://doi.org/10.1016/B978-0-12-815554-7.00008-8.
86. Sikarwar, V.S.; Zhao, M.; Clough, P.; Yao, J.; Zhong, X.; Memon, M.Z.; Shah, S.; Anthony, E.J.; Fennell, P.S. An overview of advances in biomass gasification. *Energy Environ. Sci.* **2016**, *9*, 2939. https://doi.org/10.1039/c6ee00935b.
87. Valderrama Rios, M.L.; Gonzalez, A.M.; Lora, E.E.S.; Almazan del Olmo, O.A. Reduction of tar generated during biomass gasification: A review. *Biomass Bioenerg.* **2018**, *108*, 345–370. https://doi.org/10.1016/j.biombioe.2017.12.002.
88. Castagnoli, A.; Salem, A.M.; Desideri, U.; Pecorini, I. Environmental assessment of gasification and green hydrogen potential role in waste management decarbonization. *J. Clean. Prod.* **2024**, *482*, 144174. https://doi.org/10.1016/j.jclepro.2024.144174.
89. Yan, B.; Jia, X.; Li, J.; Li, Z.; Che, Y.; Zhou, Z.; Zhao, J.; Zhou, S.; Chen, G. In-situ elimination of biomass gasification tar based on the understanding of tar formation process: A review. *J. Energy Inst*. **2024**, *112*, 101477. https://doi.org/10.1016/j.joei.2023.101477.
90. Shahbaz, M.; AlNouss, A.; Ghiat, I.; Mckay, G.; Mackey, H.; Elkhalifa, S.; Al-Ansari, T. A comprehensive review of biomass based thermochemical conversion technologies integrated with CO_2 capture and utilisation within BECCS networks. *Resour. Conserv. Recycl.* **2021**, *17*, 105734. https://doi.org/10.1016/j.resconrec.2021.105734.
91. IEA Bioenergy. Valuable (by-)Products of Gasification. IEA Bioenergy Task 33. 2022. Available online: https://www.ieabioenergy.com/wp-content/uploads/2022/12/WS_Report-final1.pdf (accessed on 13 March 2025).

92. Saidi, M.; Gohari, M.H.; Ramezani, A.T. Hydrogen production from waste gasification followed by membrane filtration: A review. *Environ. Chem. Lett.* **2020**, *18*, 1529–1556. https://doi.org/10.1007/s10311-020-01030-9.
93. Macedo, M.S.; Soria, M.A.; Madeira, L.M. Process intensification for hydrogen production through glycerol steam reforming. *Renew. Sustain. Energy Rev.* **2021**, *146*, 111151. https://doi.org/10.1016/j.rser.2021.111151.
94. Maj, I.; Niesporek, K.; Płaza, P.; Maier, J.; Łój, P. Biomass ash: A review of chemical compositions and management trends. *Sustainability* **2025**, *17*, 4925. https://doi.org/10.3390/su17114925.
95. Puri, L.; Hu, Y.; Naterer, G. Critical review of the role of ash content and composition in biomass pyrolysis. *Front. Fuels* **2024**, *2*, 1378361. https://doi.org/10.3389/ffuel.2024.1378361.
96. Vlăduț, N.V.; Atanasov, A.; Ungureanu, N.; Ivașcu, L.V.; Cioca, L.I.; Matei, G.; Boruz, S.; Cerempei, V.; Țîței, V.; Żelaziński, T.; et al. Trends in the development of conservative / ecological agriculture in the context of current climate change—A review. *INMATEH Agric. Eng.* **2024**, *74*, 980–1032. https://doi.org/10.35633/inmateh-74-86.
97. Shen, Y.; Yoshikawa, K. Recent progresses in catalytic tar elimination during biomass gasification or pyrolysis—A review. *Renew. Sustain. Energy Rev.* **2013**, *21*, 371–392. https://doi.org/10.1016/j.rser.2012.12.062.
98. de Lasa, H.; Torres Brauer, N.; Rojas Chaves, F.; Serrano Rosales, B. Biomass-derived tar conversion via catalytic post-gasification in circulating fluidized beds: A review. *Catalysts* **2025**, *15*, 611. https://doi.org/10.3390/catal15070611.
99. Santana, H.E.P.; Jesus, M.; Santos, J.; Rodrigues, A.C.; Pires, P.; Ruzene, D.S.; Silva, I.P.; Silva, D.P. Lignocellulosic biomass gasification: Perspectives, challenges, and methods for tar elimination. *Sustainability* **2025**, *17*, 1888. https://doi.org/10.3390/su17051888.
100. Anis, S.; Zainal, Z.A. Tar reduction in biomass producer gas via mechanical, catalytic and thermal methods: A review. *Renew. Sustain. Energy Rev.* **2011**, *15*, 2355–2377. https://doi.org/10.1016/j.rser.2011.02.018.
101. Loweski Feliz, M.; Abdelouahed, L.; Taouk, B. Comparative and descriptive study of biomass gasification simulations using Aspen Plus. *Energies* **2024**, *17*, 4443. https://doi.org/10.3390/en17174443.
102. Wu, S.; Wang, Q.; Ryota, I. Study on the effects of tar reforming and steam gasification of Keyaki Bark in Saitama Prefecture. *Sustainability* **2025**, *17*, 2215. https://doi.org/10.3390/su17052215.
103. Iturbides, R.D.; Haza, U.J.; Polaert, I. Recent technological innovations on continuous microwave assisted biomass pyrolysis and perspectives for industrial scale applications. *Bioresour. Technol. Rep.* **2022**, *19*, 101202. https://doi.org/10.1016/j.biteb.2022.101202.
104. Okebalama, C.B.; Marschner, B. Reapplication of biochar, sewage waste water, and NPK fertilizers afects soil fertility, aggregate stability, and carbon and nitrogen in dry-stable aggregates of semi-arid soil. *Sci. Total Environ.* **2023**, *866*, 161203. https://doi.org/10.1016/j.scitotenv.2022.161203.
105. Talwar, P.; Agudelo, M.A.; Nanda, S. Pyrolysis process, reactors, products, and applications: A review. *Energies* **2025**, *18*, 2979. https://doi.org/10.3390/en18112979.
106. Ifran, M.F.; Mirara, F. Biochar application in improving soil health and sustainability. *Bull. Biol. All. Sci. Res.* **2024**, *9*, 81. https://doi.org/10.54112/bbasr.v2024i1.81.
107. Zhu, S.; Liang, P.; Yang, L.; Wei, B.; Han, S.; Wu, M.; He, X.; Zeng, W.; He, Z.; Xiao, J.; et al. Effects of biochar-based fertilizers on Fenlong-Ridging soil physical properties, nutrient activation, enzyme activity, bacterial diversity, and sugarcane yield. *Agronomy* **2025**, *15*, 1594. https://doi.org/10.3390/agronomy15071594.
108. Oni, B.A.; Oziegbe, O.; Olawole, O.O. Significance of biochar application to the environment and economy. *Ann. Agric. Sci.* **2019**, *64*, 222–236. https://doi.org/10.1016/j.aoas.2019.12.006.
109. Van Zwieten, L.; Kimber, S.; Morris, S.; Chan, K.; Downie, A.; Rust, J.; Joseph, S.; Cowie, A. Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility. *Plant Soil* **2010**, *327*, 235–246. https://doi.org/10.1007/s11104-009-0050-x.
110. Jatav, H.S.; Rajput, V.D.; Minkina, T.; Singh, S.K.; Chejara, S.; Gorovtsov, A.; Barakhov, A.; Bauer, T.; Sushkova, S.; Mandzhieva, S.; et al. Sustainable approach and safe use of biochar and its possible consequences. *Sustainability* **2021**, *13*, 10362. https://doi.org/10.3390/su131810362.
111. Hossain, M.K.; Strezov, V.; Chan, K.Y.; Nelson, P. Agronomic properties of wastewater sludge biochar and bioavailability of metals in production of cherry tomato (*Lycopersicon esculentum*). *Chemosphere* **2010**, *78*, 1167–1171. https://doi.org/10.1016/j.chemosphere.2010.01.009.
112. Raza, M.A.S.; Ibrahim, M.A.; Ditta, A.; Iqbal, R.; Aslam, M.U.; Muhammad, F.; Ali, S.; Çiğ, F.; Ali, B.; Muhammad Ikram, R. Exploring the recuperative potential of brassinosteroids and nano-biochar on growth, physiology, and yield of wheat under drought stress. *Sci. Rep.* **2023**, *13*, 15015. https://doi.org/10.1038/s41598-023-42007-2.

113. Edeh, I.G.; Mašek, O.; Buss, W. A meta-analysis on biochar's effects on soil water properties—New insights and future research challenges. *Sci. Total Environ.* **2020**, *714*, 136857. https://doi.org/10.1016/j.scitotenv.2020.136857.
114. Razzaghi, F.; Obour, P.B.; Arthur, E. Does biochar improve soil water retention? A systematic review and meta-analysis. *Geoderma* **2020**, *361*, 114055. https://doi.org/10.1016/j.geoderma.2019.114055.
115. Bilias, F.; Kalderis, D.; Richardson, C.; Barbayiannis, N.; Gasparatos, D. Biochar application as a soil potassium management strategy: A review. *Sci. Total Environ.* **2023**, *858*, 159782. https://doi.org/10.1016/j.scitotenv.2022.159782.
116. Chi, W.; Nan, Q.; Liu, Y.; Dong, D.; Qin, Y.; Li, S.; Wu, W. Stress resistance enhancing with biochar application and promotion on crop growth. *Biochar* **2024**, *6*, 43. https://doi.org/10.1007/s42773-024-00336-z.
117. Jatuwong, K.; Aiduang, W.; Kiatsiriroat, T.; Kamopas, W.; Lumyong, S. A review of biochar from biomass and its interaction with microbes: Enhancing soil quality and crop yield in *Brassica* cultivation. *Life* **2025**, *15*, 284. https://doi.org/10.3390/life15020284.
118. Perra, M.; Bacchetta, G.; Muntoni, A.; De Gioannis, G.; Castangia, I.; Rajha, H.N.; Manca, M.L.; Manconi, M. An outlook on modern and sustainable approaches to the management of grape pomace by integrating green processes, biotechnologies and advanced biomedical approaches. *J. Funct. Foods* **2022**, *98*, 105276. https://doi.org/10.1016/j.jff.2022.105276.
119. Lyu, H.; Zhang, H.; Chu, M.; Zhang, C.; Tang, J.; Chang, S.X.; Mašek, O.; Ok, Y.S. Biochar affects greenhouse gas emissions in various environments: A critical review. *Land. Degrad. Dev.* **2022**, *33*, 3327–3342. https://doi.org/10.1002/ldr.4405.
120. Korai, S.K.; Korai, P.K.; Jaffar, M.A.; Qasim, M.; Younas, M.U.; Shabaan, M.; Zulfiqar, U.; Wang, X.; Artyszak, A. Leveraging biochar amendments to enhance food security and plant resilience under climate change. *Plants* **2025**, *14*, 1984. https://doi.org/10.3390/plants14131984.
121. Dai, W.; Bao, Z.; Meng, J.; Chen, T.; Liang, X. Biochar makes soil organic carbon more labile, but its carbon sequestration potential remains large in an alternate wetting and drying paddy ecosystem. *Agronomy* **2025**, *15*, 1547. https://doi.org/10.3390/agronomy15071547.
122. Gorovtsov, A.V.; Minkina, T.M.; Mandzhieva, S.S.; Perelomov, L.V.; Soja, G.; Zamulina, I.V.; Rajput, V.D.; Sushkova, S.N.; Mohan, D.; Yao, J. The mechanisms of biochar interactions with microorganisms in soil. *Environ. Geochem. Health.* **2020**, *42*, 2495–2518. https://doi.org/10.1007/s10653-019-00412-5.
123. Joseph, S.; Cowie, A.L.; Van Zwieten, L.; Bolan, N.; Budai, A.; Buss, W.; Cayuela, M.L.; Graber, E.R.; Ippolito, J.A.; Kuzyakov, Y. How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar. *GCB Bioenergy* **2021**, *13*, 1731–1764. https://doi.org/10.1111/gcbb.12885.
124. Brtnicky, M.; Datta, R.; Holatko, J.; Bielska, L.; Gusiatin, Z.M.; Kucerik, J.; Hammerschmiedt, T.; Danish, S.; Radziemska, M.; Mravcova, L.; et al. A critical review of the possible adverse effects of biochar in the soil environment. *Sci. Total Environ.* **2021**, *796*, 148756. https://doi.org/10.1016/j.scitotenv.2021.148756.
125. Pathy, A.; Ray, J.; Paramasivan, B. Biochar amendments and its impact on soil biota for sustainable agriculture. *Biochar* **2020**, *2*, 287–305. https://doi.org/10.1007/s42773-020-00063-1.
126. Allohverdi, T.; Mohanty, A.K.; Roy, P.; Misra, M. A review on current status of biochar uses in agriculture. *Molecules* **2021**, *26*, 5584. https://doi.org/10.3390/molecules26185584.
127. Novak, J.M.; Busscher, W.J.; Watts, D.W.; Laird, D.A.; Ahmedna, M.A.; Niandou, M.A. Short-term CO_2 mineralization after additions of biochar and switchgrass to a typic Kandiudult. *Geoderma* **2010**, *154*, 281–288. https://doi.org/10.1016/j.geoderma.2009.10.014.
128. Dittmann, M.T.; Baki, C.; Tereanova, M.; Amelchanka, S.L.; Subois, S.; Wiget, A.; Leiber, F.; Krause, H.M.; Baumann, S. The effect of biochar supplementation on feed utilization, milk production and methane emission in lactating dairy cows. *Anim. Feed. Sci. Technol.* **2024**, *318*, 116127. https://doi.org/10.1016/j.anifeedsci.2024.116127.
129. Lind, V.; Sismaz, O.; Demirtas, A.; Sudagidan, M.; Weldon, S.; Budai, A.; O'Toole, A.; Moladinovic, D.D.; Jorgensen, G.M. Biochar effect on sheep feed intake, growth rate and ruminant in vitro and in vivo methane production. *Animal* **2024**, *18*, 101195. https://doi.org/10.1016/j.animal.2024.101195.
130. Nair, P.S.N.; Menon, P. S.; Suresh, S.; Sreekanth, A.J.; Sivasabari, K.; Adithya, K.S.; Anuranj, P.R.; Nayana, K.; Parvathy, S.; Chakraborty, S.; et al. Beneficial impacts of biochar as a potential feed additive in animal husbandry. *J. Exp. Biol. Agric. Sci.* **2023**, *11*, 479–499. https://doi.org/10.18006/2023.11(3).479.499.
131. Miroshnichenko, D.; Zhylina, M.; Shmeltser, K. Modern use of biochar in various technologies and industries. a review. *Chem. Chem. Technol.* **2024**, *18*, 232–243. https://doi.org/10.23939/chcht18.02.232.

132. Ravindiran, G.; Rajamanickam, S.; Janardhan, G.; Hayder, G.; Alagumalai, A.; Mahian, O.; Lam, S.S.; Sonne, C. Production and modifications of biochar to engineered materials and its application for environmental sustainability: A review. *Biochar* **2024**, *6*, 62. https://doi.org/10.1007/s42773-024-00350-1.
133. Enaime, G.; Baçaoui, A.; Yaacoubi, A.; Lübken, M. Biochar for wastewater treatment—Conversion technologies and applications. *Appl. Sci.* **2020**, *10*, 3492. https://doi.org/10.3390/app10103492.
134. Mohanty, S.K.; Boehm, A.B. *Escherichia coli* removal in biochar-augmented biofilter: Effect of infiltration rate, initial bacterial concentration, biochar particle size, and presence of compost. *Environ. Sci. Technol.* **2014**, *48*, 11535–11542.
135. Runtti, H.; Tuomikoski, S.; Kangas, T.; Lassi, U.; Kuokkanena, T.; Rämö, J. Chemically activated carbon residue from biomass gasification as a sorbent for iron(II), copper(II) and nickel(II) ions. *J. Water Process. Eng.* **2014**, *4*, 12–24. https://doi.org/10.1016/j.jwpe.2014.08.009.
136. Shakya, A.; Agarwal, T. Removal of Cr(VI) from water using pineapple peel derived biochars: Adsorption potential and reusability assessment. *J. Mol. Liq.* **2019**, *293*, 111497. https://doi.org/10.1016/j.molliq.2019.111497.
137. Afshar, M.; Mofatteh, S. Biochar for a sustainable future: Environmentally friendly production and diverse applications. *Results Eng.* **2024**, *23*, 102433. https://doi.org/10.1016/j.rineng.2024.102433.
138. Yang, X.; Han, D.; Zhao, Y.; Li, R.; Wu, Y. Environmental evaluation of a distributed-centralized biomass pyrolysis system: A case study in Shandong. China. *Sci. Total Environ.* **2020**, *716*, 136915. https://doi.org/10.1016/j.scitotenv.2020.136915.
139. Yrjälä, K.; Ramakrishnan, M.; Salo, E. Agricultural waste streams as resource in circular economy for biochar production towards carbon neutrality. *Curr. Opin. Environ. Sci. Health* **2022**, *26*, 100339. https://doi.org/10.1016/j.coesh.2022.100339.
140. Rehman, A.; Nawaz, S.; Alghamdi, H.A.; Alrumman, S.; Yan, W.; Nawaz, M.Z. Effects of manure-based biochar on uptake of nutrients and water holding capacity of different types of soils. *Case Stud. Chem. Environ. Eng.* **2020**, *2*, 100036. https://doi.org/10.1016/j.cscee.2020.100036.
141. Zhang, Q.; Xiao, J.; Xue, J.; Zhang, L. Quantifying the effects of biochar application on greenhouse gas emissions from agricultural soils: A global meta-analysis. *Sustainability* **2020**, *12*, 3436. https://doi.org/10.3390/su12083436.
142. Sharma, A.; Chhabra, V. A review on the applications of biochar in agricultural farms: A low carbon emission technology. *J. Adv. Biol. Biotechnol.* **2024**, *27*, 118181. https://doi.org/10.9734/jabb/2024/v27i71009.
143. Kaushik, A.; Priyadharshini, P.; Manimegalai, S.; Palaniselvam, V.; Parthiban, K.T. Biochar production from plant residues: A sustainable approach for carbon sequestration and soil fertility improvement. *Arch. Curr. Res. Int.* **2024**, *24*, 1–13. https://doi.org/10.9734/acri/2024/v24i9864.
144. Borchard, N.; Schirrmann, M.; Cayuela, M.L.; Kammann, C.; Wrage-Mönnig, N.; Estavillo, J.M.; Fuertes-Mendizábal, T.; Sigua, G.; Spokas, K.; Ippolito, J.A.; et al. Biochar, soil and land-use interactions that reduce nitrate leaching and N_2O emissions: A meta-analysis. *Sci. Total Environ.* **2019**, *651*, 2354–2364. https://doi.org/10.1016/j.scitotenv.2018.10.060.
145. Mosa, A.; Mansour, M.M.; Soliman, E.; El-Ghamry, A.; Alfy, M.E.; Kenawy, A.M.E. Biochar as a soil amendment for restraining greenhouse gases emission and improving soil carbon sink: Current situation and ways forward. *Sustainability* **2023**, *15*, 1206. https://doi.org/10.3390/su15021206.
146. Wang, J.; Zhang, M.; Xiong, Z.; Liu, P.; Pan, G. Effects of biochar addition on N_2O and CO_2 emissions from two paddy soils. *Biol. Fertil. Soils* **2011**, *47*, 887–896. https://doi.org/10.1007/s00374-011-0595-8.
147. Mukherjee, A.; Lal, R.; Zimmerman, A.R. Effects of biochar and other amendments on the physical properties and greenhouse gas emissions of an artificially degraded soil. *Sci. Total Environ.* **2014**, *487*, 26–36. https://doi.org/10.1016/j.scitotenv.2014.03.141.
148. Kuzyakov, Y.; Bogomolova, I.; Glaser, B. Biochar stability in soil: Decomposition during eight years and transformation as assessed by compound-specific 14C analysis. *Soil. Biol. Biochem.* **2014**, *70*, 229–236. https://doi.org/10.1016/j. soilbio.2013.12.021.
149. Kalu, S.; Kulmala, L.; Zrim, J.; Peltokangas, K.; Tammeorg, P.; Rasa, K.; Kitzler, B.; Pihlatie, M.; Karhu, K. Potential of biochar to reduce greenhouse gas emissions and increase nitrogen use efficiency in boreal arable soils in the long-term. *Front. Environ. Sci.* **2022**, *10*, 914766. https://doi.org/10.3389/fenvs.2022.914766.
150. Abideen, Z.; Koyro, H.; Huchzermeyer, B.; Bilquees, G.; Khan, M.A. Impact of a biochar or a biochar-compost mixture on water relation, nutrient uptake and photosynthesis of Phragmites karka. *Pedosphere* **2020**, *30*, 466–477. https://doi.org/10.1016/S1002-0160(17)60362-X.
151. Adejumo, S.A.; Arowo, D.O.; Ogundiran, M.B.; Srivastava, P. Biochar in combination with compost reduced Pb uptake and enhanced the growth of maize in lead (Pb)-contaminated soil exposed to drought stress. *J. Crop Sci. Biotechnol.* **2020**, *23*, 273–288. https://doi.org/10.1007/s12892-020-00035-8.
152. Linville, J.L.; Shen, Y.; Ignacio-de Leon, P.A.; Schoene, R.P.; Urgun-Demirtas, M. In situ biogas upgrading during anaerobic digestion of food waste amended with walnut shell biochar at bench scale. *Waste Manag. Res.* **2017**, *35*, 669–679.

153. Qu, Y.; Qu, J.; Yan, W.; Yue, T.; Zhang, Q.; Yi, W.; Liu, X.; Sun, Y. Influence of biochar on physico-chemical, microbial community and maturity during biogas residue aerobic composting process. *Fermentation* **2022**, *8*, 623. https://doi.org/10.3390/fermentation8110623.
154. Xu, J.; Wang, X.; Sun, J.; Zhang, W.; Huang, R.; Chen, Y. Effects of recycled biochar addition on methane production performance in anaerobic fermentation of pig and cow manure. *Fermentation* **2025**, *11*, 372. https://doi.org/10.3390/fermentation11070372.
155. Cara, I.G.; Țopa, D.; Puiu, I.; Jităreanu, G. Biochar a promising strategy for pesticide-contaminated soils. *Agriculture* **2022**, *12*, 1579. https://doi.org/10.3390/agriculture12101579.
156. Paula, R.; Carvalho, J.; Júnior, A.; Fagundes, F.; de Lima, R.; Lima, E.; Oliveira, C.; de Oliveira, M.; Bezerra, A.; Ferreira, O.; et al. Analysis of biochar-cement composites by SEM/EDS: Interfacial interactions and effects on mechanical strength. *C J. Carbon. Res.* **2025**, *11*, 45. https://doi.org/10.3390/c11030045.
157. Gupta, S.; Hua, H.W.; Low, C.Y. Use of biochar as carbon sequestering additive in cement mortar. *Cem. Concr. Compos.* **2018**, *87*, 110–129. https://doi.org/10.1016/j.cemconcomp.2017.12.009.
158. Mensah, R.A.; Shanmugam, V.; Narayanan, S.; Razavi, N.; Ulfberg, A.; Blanksvärd, T.; Sayahi, F.; Simonsson, P.; Reinke, B.; Försth, M.; et al. Biochar-added cementitious materials—A review on mechanical, thermal, and environmental properties. *Sustainability* **2021**, *13*, 9336. https://doi.org/10.3390/su13169336.
159. Legan, M.; Gotvajn, A.Z.; Zupan, K. Potential of biochar use in building materials. *J. Environ. Manag.* **2022**, *309*, 114704. https://doi.org/10.1016/j.jenvman.2022.114704.
160. Raja, P.; Murugan, V.; Ravichandran, S.; Behera, L.; Mensah, R.A.; Mani, S.; Kasi, A.K.; Balasubramanian, K.B.N.; Sas, G.; Vahabi, H.; et al. A review of sustainable bio-based insulation materials for energy-efficient buildings. *Macromol. Mater. Eng.* **2023**, *308*, 2300086. https://doi.org/10.1002/mame.202300086.
161. Antal, M.J.; Grønli, M. The art, science, and technology of charcoal production. *Ind. Eng. Chem. Res.* **2003**, *42*, 1619–1640. https://doi.org/10.1021/ie0207919.
162. Cantrell, K.B.; Hunt, P.G.; Uchimiya, M.; Novak, J.M.; Ro, K.S. Impact of pyrolysis temperature and manure source on physicochemical characteristics of biochar. *Bioresour. Technol.* **2012**, *107*, 419–428. https://doi.org/10.1016/j.biortech.2011.11.084.
163. Méndez, A.; Gómez, A.; Paz-Ferreiro, J.; Gascó, G. Effects of sewage sludge biochar on plant metal availability after application to a Mediterranean soil. *Chemosphere* **2013**, *89*, 1354–1359. https://doi.org/10.1016/j.chemosphere.2012.05.092.
164. Brewer, C.E.; Schmidt-Rohr, K.; Satrio, J.A.; Brown, R.C. Characterization of biochar from fast pyrolysis and gasification systems. *Environ. Prog. Sustain. Energy* **2009**, *28*, 386–396. https://doi.org/10.1002/ep.10378.
165. Bosmans, A.; Vanderreydt, I.; Geysen, D.; Helsen, L. The crucial role of waste-to-energy technologies in enhanced landfill mining: A technology review. *J. Clean. Prod.* **2013**, *55*, 10–23. https://doi.org/10.1016/j.jclepro.2012.05.032.
166. European Biogas Association. *Biogases Towards 2040 and Beyond*; European Biogas Association: Brussels, Belgium, 2024. Available online: https://www.europeanbiogas.eu/wp-content/uploads/2024/04/Biogases-towards-2040-and-beyond_final.pdf (accessed on 24 April 2025).
167. European Confederation of Waste-to-Energy Plants—CEWEP. Waste-to-Energy Plants in Europe in 2022. 2024. Available online: https://www.cewep.eu/waste-to-energy-plants-in-europe-in-2022/ (accessed on 13 June 2025).
168. Statista. Installed Capacity of Municipal Waste Energy in Europe from 2010 to 2024. 2025. Available online: https://www.statista.com/statistics/1122054/europe-waste-to-energy-capacity/ (accessed on 13 March 2025).
169. Uddin, M.N. A comprehensive exploration of biomass gasification technologies advancing United Nations sustainable development goals: Part II. *John. Matthey Technol. Rev.* **2025**, *69*, 13–23. https://doi.org/10.1595/205651325X17252884203333.