

Review

Pyrolysis Process, Reactors, Products, and Applications: A Review

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Abstract: With the rapid growth of the global population, increasing per capita energy demands, and waste generation, the need for innovative strategies to mitigate greenhouse gas emissions and effective waste management has become paramount. Pyrolysis, a thermochemical conversion process, facilitates the transformation of diverse biomass feedstocks, including agricultural biomass, forestry waste, and other carbonaceous wastes, into valuable biofuels such as bio-oil, biochar, and producer gas. The article reviews the benefits of pyrolysis as an effective and scalable technique for biofuel production from waste biomass. The review describes the different types of pyrolysis processes, such as slow, intermediate, fast, and catalytic, focusing on the effects of process parameters like temperature, heating rate, and residence time on biofuel yields and properties. The review also highlights the configurations and operating principles of different reactors used for pyrolysis, such as fixed bed, fluidized bed, entrained flow, plasma system, and microwaves. The review examines the factors affecting reactor performance, including energy consumption and feedstock attributes while highlighting the necessity of optimizing these systems to improve sustainability and economic feasibility in pyrolysis processes. The diverse value-added applications of biochar, bio-oil, and producer gas obtained from biomass pyrolysis are also discussed.

Keywords: biochar; biomass; bio-oil; entrained flow reactor; fixed-bed reactor; fluidized-bed reactor; microwave reactor; plasma reactor; producer gas; pyrolysis

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1. Introduction

The accelerated growth of the global population and increasing energy consumption have placed significant pressure on traditional energy resources, primarily fossil fuels, leading to a rise in greenhouse gas emissions that intensifies environmental degradation and climate change [1]. Energy resources are under increasing pressure due to the growing world population, which is exacerbating the global energy crisis. Moreover, increased waste production requires integrating waste management into urban and energy development strategies to ensure long-term sustainability [2]. Thus, the diversification of energy sources has led to a renewed interest in utilizing biomass as an energy resource. Currently, the distribution of primary energy consumption in the world is supplemented by crude oil (54,564 terawatt-hours or TWh), coal (45,565 TWh), natural gas (40,102 TWh), hydropower (4240 TWh), wind (2325 TWh), solar (1642 TWh), and biofuels (1318 TWh) [3].

Biomass, encompassing agricultural, forestry, and other organic materials, holds significant potential for biofuel production [4]. It is essential to mention that various issues are associated with the accumulation of unprocessed biomass, such as soil and air pollution

due to the emission of greenhouse gases, specifically CH_4 , which is more potent than CO_2 . Moreover, untreated biomass can become a source of pests and diseases, posing a risk to public health and biodiversity. Biofuel production is increasing globally, but its contribution to total energy demand remains insignificant compared to other renewable energy sources such as wind, tidal, and solar. For example, biofuel production in North America increased from 38 TWh in 2000 to 514 TWh in 2023. Similarly, biofuel production in South and Central America reached 314 TWh in 2023 compared to 65 TWh in 2000 [5]. Biofuel production in Europe is currently 194 TWh, compared to 8 TWh in 2000. In the Asia Pacific, biofuel production increased from <1 TWh in 2000 to 262 TWh in 2023. However, biofuel production is a strategic component for achieving global climate goals. Therefore, it is essential to seek sustainable alternatives that reduce dependence on fossil fuels and mitigate their associated negative environmental impact.

Thermochemical conversion technologies, such as pyrolysis, are emerging as promising methods to transform biomass into high-value energy products, as they enable the conversion of organic waste into renewable energy sources while utilizing available resources [6]. These technologies allow the recovery and conversion of waste, contributing to reduced greenhouse gas emissions by using a renewable resource. Therefore, pyrolysis can be classified as slow, fast, intermediate, and catalytic, which are differentiated by the operating conditions implemented [7]. The adaptability of the pyrolysis process to a wide range of lignocellulosic biomass enables it to be versatile with different feedstock sources. Hence, different biomass types can produce different bioproduct profiles. For example, some feedstocks are better suited for bio-oil production, while others may be optimized for biochar production. This flexibility allows production to be adjusted according to specific applications [8].

Biochar produced through pyrolysis is a carbon-rich material that serves as an energy source and contributes to carbon sequestration, enabling stable carbon storage in the soil [9]. Bio-oil production through pyrolysis provides a renewable alternative to conventional liquid fuels, which can be refined and upgraded to meet the quality standards required for various energy applications [10]. At high temperatures, biomass and other organic materials dehydrate and break down into smaller molecules, releasing volatile components such as gases or vapors generated during the process. These volatile components condense rapidly to generate bio-oil. The bio-oil's quantity and quality depend on the rapid cooling of volatile vapors. Otherwise, non-condensable gases can be collected and used as fuel. Furthermore, the analysis and characterization of the products obtained from the pyrolysis process enable the quality of the bioproducts by examining their physical and chemical properties, including moisture content, calorific value, and chemical composition. Additionally, this characterization helps to enhance and optimize the process by identifying the optimal pyrolysis conditions that maximize the yield and quality of the products. It also helps to identify unwanted byproducts, such as tar, facilitating adjustments in the process. Product characterization is crucial for research and development, as it provides valuable data that can be used to innovate and enhance the production of biofuels and bioproducts [11].

Although pyrolysis shows significant potential for renewable energy production and waste reduction, its large-scale adoption faces several technical and economic challenges that must be addressed to ensure effective biomass conversion into valuable products and thus consolidate action to contribute substantially to the circular economy [12]. The commercial utility of most thermochemical biomass conversion processes is relatively limited by the high costs associated with pre-processing and post-processing technologies and competition with cheaper and commercial fossil fuels [13]. To improve biomass conversion efficiency into bioproducts, developing more effective and economical pretreatment techniques becomes relevant. On the other hand, several technical challenges must be con-

sidered, first related to the thermochemical conversion process to which pyrolysis belongs and then to the catalysts. Issues faced by the process include high energy consumption, interference from moisture and ash content in the biomass, the need to purify intermediate products, and fouling problems [6]. Catalysts also play a crucial role in optimizing the pyrolysis process, enhancing product quality, and increasing the economic viability of pyrolysis technology. Challenges include catalyst recovery and regeneration, the toxicity of specific catalysts, and the need to optimize operating conditions to maximize product yield and selectivity [14].

This article provides insight into the various types of pyrolysis, including slow, intermediate, fast, and catalytic, and their operating parameters. Understanding these parameters makes it possible to comprehend why the product properties differ according to the adoption of specific parameters. Similarly, a section outlines the types of reactors suitable for the pyrolysis process, including fixed-bed reactors, fluidized-bed reactors, entrained-flow reactors, plasma reactors, and microwave reactors. The review also examines the various applications of pyrolysis products, including bio-oil, biochar, and producer gas. It highlights their roles in energy production due to their potential as biofuels or the high value they can hold as bioproducts in other applications. The review aims to provide a holistic understanding of the state of pyrolysis technology.

2. Pyrolysis

2.1. Slow Pyrolysis

Pyrolysis is broadly categorized, depending on vapor residence time and heating rates. Slow pyrolysis primarily produces biochar and desired products and by-products, such as bio-oil and gases [15,16]. Slow pyrolysis promotes the formation of solid products, especially biochar, as lower temperatures allow for slower and more stable carbonaceous structures to form during biomass decomposition [17]. Slow pyrolysis conditions primarily include temperatures ranging from 300 °C to 500 °C, slow heating rates of 0.1–1 °C/s, and long vapor residence times between 10 and 100 min [1]. The composition of biofuel products varies according to process conditions, specifically temperature, heating rate, and vapor residence time [18]. When the heating rate is less than 10 °C/min, chemical bonds are broken, and the biomass structure is reorganized into a more stable matrix, inhibiting volatile matter generation [19]. The heating rate is a parameter to ensure uniform heat transfer within the biomass particles [20]. Table 1 summarizes some notable studies on the slow pyrolysis of different feedstocks under varied reaction conditions.

A study using wood and coconut shell waste as raw materials found that a shorter retention time, between 30 min and 45 min, limited biomass particle interaction and increased biochar production in slow pyrolysis [19]. The biochar yield decreases with an increase in pyrolysis temperature from 400 °C to 800 °C due to a higher biomass decomposition rate, resulting in less solid material. However, biochar produced at higher temperatures has a higher carbon content and a more stable structure, which gives it better physicochemical properties, such as higher thermal stability [21].

Table 1. Notable studies on the slow pyrolysis of different biomass under varied reaction conditions.

Feedstock	Process Conditions	Biochar Yield (wt%)	Calorific Value of Biochar (MJ/kg)	Bio-Oil Yield (wt%)	Calorific Value of Bio-Oil (MJ/kg)	Producer Gas Yield (wt%)	Reference
Coconut husk waste	• Temperature: 400–600 °C • Residence time: 30–60 min	41–29	21–24	-	-	-	Babu et al. [21]
Coffee silverskin	• Temperature: 280–500 °C • Residence time: 10 min	32–81	23–24	18–23	-	15–30	del Pozo et al. [22]
Cyanobacteria (<i>Arthrospira platensis</i>)	• Temperature: 600 °C • Heating rate: 10 °C/min	27	-	22	-	17–39	Chernova et al. [23]
Food waste	• Temperature: 300–600 °C • Residence time: 30–60 min • Heating rate: 5–20 °C/min	28–52	21–23	36	-	36	Patra et al. [12]
Grape pomace	• Temperature: 225–400 °C • Residence time: 10 min	54–94	23–24	6–15	-	7–25	del Pozo et al. [22]
<i>Madhuca longifolia</i> biomass	• Temperature: 350–600 °C • Heating rate: 20 °C/min	42–10	-	33–42	-	25–52	Thiru et al. [4]
Orange bagasse	• Temperature: 525 °C • Heating rate: 25 °C/min	33	27	28	22	31	Bhattacharjee and Biswas [24]
Palm empty fruit bunches	• Temperature: 460–740 °C • Heating rate: 10 °C/min • Residence time: 1 h	28	19	45	25	28	Ferreira et al. [25]
Wood waste	• Temperature: 400–800 °C • Residence time: 30–60 min	36–22	25–32	-	-	-	Babu et al. [21]

Another study examined the slow pyrolysis of a shrub (*Prosopis juliflora*) to assess the distribution of product yields, physicochemical characteristics, thermodynamics, and sustainability [26]. Increasing the process temperature from 300 °C to 600 °C decreased biochar yield but increased bio-oil and producer gas yields. Higher heating value and fixed carbon content of biochar improved with increasing pyrolysis temperature. The highest bio-oil yield was obtained at 500 °C, containing 36% phenolic and 23% aromatic compounds. As the temperature increased, H₂ and CH₄ yields in the producer gas varied in 7.2–20% and 1.9–2.6%, respectively.

A study by Vieira et al. [27] evaluated the effects of different heating rates (i.e., 5, 10, and 20 °C/min) on biochar and bio-oil yields. An increase in the heating rate affected the quantity of volatile matter released, influencing the final products. In addition, the optimal temperature to maximize biochar yield was 450 °C. At higher temperatures, the release of volatiles increases, which reduces the biochar yield while improving its thermal stability [28]. A longer contact time between the solid and gaseous phases, attributed to longer reaction time, allows for the repolymerization of tar vapors, thereby increasing the biochar yield [29]. Consequently, at reduced temperatures and controlled heating rates, the chemical bonds of the biomass are disassembled, reorganizing the matrix into a more stable configuration that prevents the generation of volatile vapors [20]. Another study reported that increasing the N₂ gas flow rate from 5 mL/min to 400 mL/min decreased the biochar yield from different feedstocks because the volatiles, as they were generated, were immediately pushed to the condenser by the high N₂ flow rate, resulting in rapid condensation and bio-oil production [29]. This rapid condensation of volatile vapors increased bio-oil yields and reduced secondary polymerization reactions, leading to lower biochar production.

2.2. Intermediate Pyrolysis

Intermediate pyrolysis is characterized by operating conditions that allow an optimal balance in producing bio-oil, biochar, and gases. The operating conditions of the process span a range of 400–600 °C, like those reported for slow pyrolysis, which facilitates efficient thermal decomposition of biomass without reaching high thermal intensities. The heating rate for intermediate pyrolysis is between 200 and 300 °C/min [30]. Some reports mention heating rates between 60 and 600 °C/min [31]. The vapor residence time for intermediate pyrolysis ranges from 10 s to 30 s [32].

Intermediate pyrolysis allows for a balanced production of bio-oil, biochar, and producer gas [33]. Regarding yields, intermediate pyrolysis offers a favorable balance with bio-oil production ranging between 35 wt% and 50 wt%, while biochar represents 25 wt% and 40 wt% [1]. The gases produced during this process constitute between 20 wt% and 30 wt%. A wide range of feedstocks can be handled using intermediate pyrolysis, and high-moisture residues and lignocellulosic materials that are challenging to process using other methods, such as fast pyrolysis, can be effectively processed [34]. Table 2 summarizes some notable studies on the intermediate pyrolysis of different feedstocks under varied reaction conditions.

Table 2. Notable studies on the intermediate pyrolysis of different biomass under varied reaction conditions.

Feedstock	Process Conditions	Biochar Yield (wt%)	Bio-Oil Yield (wt%)	Calorific Value of Bio-Oil (MJ/kg)	Producer Gas Yield (wt%)	Reference
<i>Acacia cincinnata</i> trunk	- Temperature: 500 °C - Heating rate: 25 °C/min - Biomass particle size: 0.5–1 mm	32	53	24	15	Ahmed et al. [35]
<i>Acacia cincinnata</i> phyllodes	- Temperature: 500 °C - Heating rate: 25 °C/min - Biomass particle size: 0.5–1 mm	35	45	31	20	Ahmed et al. [35]
<i>Acacia holosericea</i> phyllodes	- Temperature: 500 °C - Heating rate: 25 °C/min - Biomass particle size: 0.5–1 mm	39	41	28	20	Ahmed et al. [35]
<i>Aegle marmelos</i> de-oiled cake	- Temperature: 600 °C - Heating rate: 25 °C/min - Biomass particle size: 1.6 mm	24–27	42–55	41	32–35	Paramasivam et al. [36]
Microalgae (<i>Scenedesmus</i>)	- Temperature: 350–550 °C - Residence time: 10 min	-	15–40	-	-	Nyoni and Hlangothi [37]
Sawdust	- Temperature: 500 °C - Particle size: 0.5–0.6 mm	29	37	39	34	Tinwala et al. [38]
Woody biomass	- Temperature: 450 °C - Biomass particle size: 1.4 mm	29	44	-	28	Ochieng et al. [39]

According to Torri et al. [40], bio-oil samples generated by intermediate pyrolysis of *Eucalyptus* and *Picea abies* are mainly composed of phenolic compounds derived from the decomposition of lignin and ketones. The composition of bio-oil varies according to the type of biomass, indicating that the choice of raw material significantly influences the quality of the bio-oil. Phenolic compounds generated from intermediate pyrolysis have applications in producing phenolic resins, which can partially replace petroleum-derived phenols. Phenolic compounds, such as dimethoxyphenyls, can serve as markers to identify the origin of biomass in bio-oil, which is essential for characterizing and controlling the products' quality [40]. Additionally, the aqueous phase generated during intermediate pyrolysis offers a range of alternative uses. This byproduct, composed of a complex mixture of sugars, organic acids, phenols, and other water-soluble compounds, has the potential to produce biogas through anaerobic digestion and release chemicals; likewise, the aqueous phase can serve as a substrate for fermentation. However, the variability in its chemical composition depends on the raw material used and the process conditions. Hence, optimizing parameters helps maximize the quality and performance of products [34]. Integrating intermediate pyrolysis with anaerobic digestion and fermentation represents a strategic way to use available resources.

Temperature is key in producing bio-oil, biochar, and gas in intermediate pyrolysis. Bouaïk et al. [41] reported that the optimal temperature for bio-oil production is 450 °C. On the other hand, Ibrahim et al. [42] identified 600 °C as a temperature that can generate higher bio-oil yields, highlighting that higher temperatures produce more gas and less biochar. Bouaïk et al. [41] reported that a fast heating rate of 50 °C/min increases bio-oil yield. Ibrahim et al. [42] reported that a heating rate of up to 50 °C/min is typical in intermediate pyrolysis, and modifying it can affect the biomass decomposition rate, thereby influencing the yield of the products. Regarding the residence time, it was also reported that the optimal residence time is 15 min to maximize bio-oil production. Ibrahim et al. [42] reported a shorter residence time of 2 min as optimal for intermediate pyrolysis.

2.3. Fast Pyrolysis

Fast pyrolysis is a process that maximizes the production of liquids, mainly bio-oil, and minimizes the formation of biochar [19]. Fast pyrolysis occurs between 400 °C and 700 °C [1]. The vapor residence time varies between 1 s and 10 s but is typically less than 2 s [43]. The high heating rate in fast pyrolysis is generally more than 1000 °C/s. The high heating rate and short vapor residence time allow the biomass to quickly reach its decomposition temperature, releasing volatile products that can be rapidly quenched to produce bio-oil [44].

Fast pyrolysis minimizes secondary reactions that could degrade volatile products [9]. Controlled secondary reactions refer to chemical reactions that occur after the initial decomposition of biomass, during which the volatile products generated can undergo additional transformations. These secondary reactions can include the decomposition of vapors into simpler compounds, the formation of new compounds from the recombination of volatile products, and the oxidation of some of these products [39]. To ensure a low water content in the bio-oil, the feedstock should be dried until the water content is significantly reduced [45]. Table 3 summarizes some notable studies on the fast pyrolysis of different feedstocks under varied reaction conditions.

Table 3. Notable studies on the fast pyrolysis of different biomass under varied reaction conditions.

Feedstock	Process Conditions	Biochar Yield (wt%)	Calorific Value of Biochar (MJ/kg)	Bio-Oil Yield (wt%)	Calorific Value of Bio-Oil (MJ/kg)	Producer Gas Yield (wt%)	Reference
Algae (<i>Chlorella vulgaris</i>)	• Temperature: 450–550 °C • Residence time: 6.4 s	43	26–32	48	27–32	-	Sotoudehniakarani et al. [46]
Black spruce	• Temperature: 555 °C • Residence time: 129 s	39	-	25	-	37	Álvarez-Chávez et al. [47]
Citrus waste	• Temperature: 425–500 °C	33–27	26–28	55	-	12–24	Alvarez et al. [48]
Corn cob	• Temperature: 600 °C • Heating rate: 150 °C/s • Residence time: 10 min	33	-	43	-	24	Adelawon et al. [49]
Mahogany wood waste	• Temperature: 425–500 °C • Heating rate: 500 °C/s • Residence time: 1.5 s	34	-	70	30	10–38	Chukwuneke et al. [50]
Municipal solid waste	• Temperature: 500 °C • Residence time: 3 min	27	-	40	25	33	Hasan et al. [51]
Olive husk	• Temperature: 600 °C	10	-	60	-	30	Benamara et al. [52]
Olive wood	• Temperature: 600 °C	25	-	30	-	35	Benamara et al. [52]
Pinecone (<i>Pinus halepensis</i>)	• Temperature: 500–700 °C • Residence time: 25 min	18–32	24–27	-	-	-	Maaoui et al. [53]
Pinecone (<i>Pinus pinea</i>)	• Temperature: 500–700 °C • Residence time: 25 min	25–32	22–26	-	-	-	Maaoui et al. [53]

Fast pyrolysis can generate between 60 wt% and 75 wt% of liquid products, 15 wt% to 25 wt% of biochar, and 10 wt% to 20 wt% of non-condensable gaseous products [31,45]. Biomass particle size also impacts the yields of fast pyrolysis products. Biomass particles smaller than 2 mm tend to favor the production of bio-oil and gas, while particles with a size up to 10 mm increase the yield of biochar, considering a study carried out at 500 °C and a residence time of 3 min using waste biomass [51]. Hence, it becomes relevant to consider optimizing biomass particle size to maximize the efficiency of the fast pyrolysis process. Among other parameters of the fast pyrolysis process, the volume of fluidizing gas, such as nitrogen, affects both the temperature distribution and heat transfer in the reactor, which directly influences the yield of the products. A higher inert gas flow rate leads to a short vapor residence time. In addition, if the biomass feed rate is too fast, it may reduce biomass conversion, negatively affecting bio-oil yield, which may incur high energy requirements for preheating and system operation [54].

Several similarities and differences are observed by comparing studies on operating conditions that influence product yield in fast pyrolysis. However, it is worth noting that the effects of these conditions may vary depending on the type of biomass processed and the specific conditions. At temperatures above 600 °C, secondary cracking reactions become dominant, reducing bio-oil and biochar yield in favor of gaseous products. Furthermore, a shorter residence time of less than 1 s promotes rapid vapor removal, maximizing bio-oil yield. In comparison, longer times of more than 10 s result in higher conversion to gases and biochar. These patterns repeat with variations depending on the biomass and temperature range used, but optimizing these parameters allows for adjusting yields according to the needs of each process [55–57].

2.4. Catalytic Pyrolysis

Catalytic pyrolysis utilizes catalysts to enhance efficiency, increase bio-oil yields and fuel properties, and improve product quality by accelerating biomass processing [58]. Catalytic pyrolysis utilizes catalysts, including zeolites, noble metals, transition metals, or modified biochar, to facilitate specific chemical reactions and enhance the conversion of biomass into hydrocarbons, thereby reducing the formation of undesirable compounds such as acids, alcohols, and phenols [14,59]. The reaction rates for slow, intermediate, and fast pyrolysis processes can be accelerated by incorporating a catalyst, which improves the quality of the final products.

In situ catalytic pyrolysis involves mixing biomass directly with the catalyst inside the reactor for pyrolysis [60]. This process is carried out in a single reactor, which implies lower costs and a simpler configuration. However, problems like loss of catalyst effectiveness due to coke formation and difficulties deoxygenating biomass may exist. In situ catalytic pyrolysis also inhibits tar formation and focuses on generating liquid and gaseous products. On the other hand, in ex situ catalytic pyrolysis, the catalyst is first activated. Then the biomass is decomposed, where a heat carrier is used. In this case, biomass particles and the catalyst do not usually come into contact with each other within the pyrolysis reactor, which allows better control over the catalytic reactions and easy separation of spent catalysts. In addition, this configuration enables secondary cracking reactions to be stimulated under a longer vapor residence time. Thus, the production of biochar and gases is optimized [15,61].

Metal salt-based catalysts effectively break down lignin into its monomers, although they are not ideal for producing bio-oil. Metal oxide catalysts, such as CaO and Fe₂O₃, increase the production of phenolic compounds and promote reactions that improve selectivity toward desired products. Bentonite and activated carbon are economical options that can enhance deoxidation and aromatic hydrocarbon generation [59]. On the other hand, molecular sieve catalysts, including zeolites, are effective in producing aromatic

compounds due to their microporous structure and distribution of acid sites [62]. For example, HZSM-5 zeolite is known for its ability to increase bio-oil yield and its high selectivity toward aromatic hydrocarbons while reducing the formation of undesirable compounds like carboxylic acids and phenols [15]. As a low-cost catalyst, biochar facilitates chemical reactions through its functional groups, promotes vapor degradation, improves product distribution, reduces the formation of undesirable compounds, and encourages interaction with inorganic species to obtain final products of improved quality [59].

Biomass structure impacts the yield and quality of bio-oil and biochar produced through catalytic pyrolysis. The composition of cellulose, hemicellulose, and lignin varies depending on the type of biomass, and each is decomposed differently. The interactions between lignin and cellulose can produce heavier tar, and physical characteristics impact the yield and quality of bio-oil and biochar produced through catalytic pyrolysis [63]. A higher H/C ratio in the biomass tends to produce better quality bio-oil with a higher content of aromatic hydrocarbons and a lower amount of oxygenated compounds. Biomass with a high lignin content and larger particle size tends to generate biochar of higher quality and yield [64]. Lignin decomposes better at temperatures above 500 °C. It produces more stable carbon in the biochar. At the same time, the presence of cellulose and hemicellulose can decrease the quality of the biochar and increase the production of volatiles and bio-oil [60]. Table 4 summarizes some notable studies on the catalytic pyrolysis of different feedstocks under varied reaction conditions.

Table 4. Notable studies on the catalytic pyrolysis of different biomass under varied reaction conditions.

Feedstock	Process Conditions	Biochar Yield (wt%)	Bio-Oil Yield (wt%)	Producer Gas Yield (wt%)	Reference
Algae (<i>Laminaria japonica</i>) and polypropylene	• Temperature: 500 °C • Residence time: 1 h • Catalyst: Al-SBA-15	42	31	25	Lee et al. [65]
Algae (<i>Chlorella vulgaris</i>)	• Temperature: 500 °C • Catalyst: HZSM-5	26	53	22	Bhoi et al. [14]
Algae (<i>Cladophora glomerata</i>)	• Temperature: 500 °C • Catalyst: Biochar	35	30	35	Norouzi et al. [66]
Cyanobacteria	• Temperature: 550 °C • Residence time: 30 min • Heating rate: 10 °C/min • Catalyst: Mg/Al-LDO	24	36	39	Gao et al. [67]
Cyanobacteria (<i>Oscillatoria</i>)	• Temperature: 550 °C • Heating rate: 20 °C/min • Catalyst: TiO₂ and ZnO	43	33	27	Kawale and Kishore [68]
Seaweed (<i>Enteromorpha clathrata</i>)	• Temperature: 550 °C • Catalyst: ZSM-5	46	37	23	Wang et al. [63]
Seaweed (<i>Gracilaria gracilis</i>)	• Temperature: 500 °C • Residence time: 30 min • Catalyst: HMS	36	39	27	Norouzi et al. [69]

Abbreviations: Alumina-Santa Barbara Amorphous-15 (Al-SBA-15), Hydroxymethanesulfonate (HMS), Magnesium/alumina-layered double oxides (Mg/Al-LDO), Zeolite Socony Mobil-5 (ZSM-5).

Catalyst deactivation in pyrolysis processes presents a notable challenge influencing efficiency, product selectivity, and economic feasibility. Catalyst deactivation can arise from creating and accumulating coke on active sites and pores of the catalytic support material [70] and decreasing their surface area due to sintering. Contaminants in the

feedstock, such as sulfur, chlorine, or heavy metals, can bind irreversibly to the catalysts' active sites, resulting in fouling and poisoning. Catalytic, fragile, and less thermally stable supports can undergo structural degradation at high reaction temperatures [71]. However, various thermal and chemical methods can regenerate catalysts [72]. For instance, thermal regeneration involves the combustion of coke deposits in an oxidizing environment like air. Conversely, chemical regeneration utilizes solvents, water, acids, and other chemical agents to remove impurities and coke deposits from the catalyst surfaces. Regenerating catalysts also carries environmental consequences, both beneficial and detrimental. Reusing spent catalysts contributes to waste reduction and decreased raw material usage while enhancing efficiency in thermochemical biomass conversion processes [73]. Conversely, catalyst regeneration can emit CO₂, NO_x, SO_x, and other atmospheric pollutants. Spent catalysts or their washed solvents (as in the case of chemical regeneration) might contain heavy metals or toxic residues that could seep into the soil and groundwater if not properly managed and disposed of [74]. Additionally, regeneration processes tend to require a significant amount of energy.

3. Pyrolysis Reactors

Several commonly used configurations for pyrolysis reactors include fixed-bed, fluidized bed, entrained flow, plasma, and microwave reactors. Pyrolysis process parameters such as temperature, heating rate, residence time, and feedstock type require optimization to enhance the yield and quality of products (i.e., bio-oil, biochar, and gas). Nonetheless, improvements in reactor design, such as the incorporation of catalysts or integration with downstream upgrading systems, can enhance both the commercial viability and environmental performance of pyrolysis technologies [75]. Table 5 highlights the advantages and drawbacks of some widely used pyrolysis reactors.

Table 5. Advantages and disadvantages of some pyrolysis reactor configurations.

Reactor	Advantages	Limitations
Fixed bed	• Simple reactor design • Low cost to build and operate • Less maintenance • Suitable for small-scale applications • Easy recovery of heterogeneous catalysts	• Poor heat transfer • Non-uniform temperature distribution • Limited scalability options • Not suitable for continuous operations
Fluidized bed	• Superior heat and mass transfer • Uniform temperature distribution • Potential for scale-up and piloting • Suitable for continuous operations	• Complex operation • High particle attrition • Challenges in catalyst recovery • Requires regular maintenance
Entrained flow	• High throughput potential • Short residence time requirement • Suitable for gas-phase products	• Requires biomass with a small particle size • Energy-intensive operation • Requires gas cleanup and conditioning
Plasma	• Superior for degrading complex biomass due to high-temperature operations • Efficient tar cracking and reforming • Produces relatively clean gas product	• Extremely energy-intensive • High cost to build and operate • Requires reactor materials that are resistant to extremely high temperatures • Limited commercial use
Microwave	• Rapid and selective heating • Suitable for small-scale operations • Less resource and space-intensive due to compact design • Energy-efficient	• Uneven heating for larger feedstock concentrations • Limited scalability • High equipment cost • Requires more research and development

3.1. Fixed-Bed Reactor

A fixed-bed reactor is commonly used for small-scale pyrolysis processes, which convert biomass into biofuels and other valuable products. These are typically tubular, primarily available in different sizes, and made of stainless steel or Inconel. Solid catalysts are generally filled in this reactor. Feedstock is loaded into the reactor and transported by a carrier gas. Figure 1 illustrates the schematics of a typical fixed-bed reactor used for pyrolysis. A fixed bed reactor mainly consists of an electrical heat source, a holding cavity, a cleaning system, and a vapor cooling unit. This reactor includes firebricks, concrete, or steel, which keeps the feedstock stationary throughout the pyrolysis process [76]. These reactors have a wider temperature distribution and high carbon conversion efficiency, can process feedstock with higher ash content, melt ash, and provide gas with a low tar content.

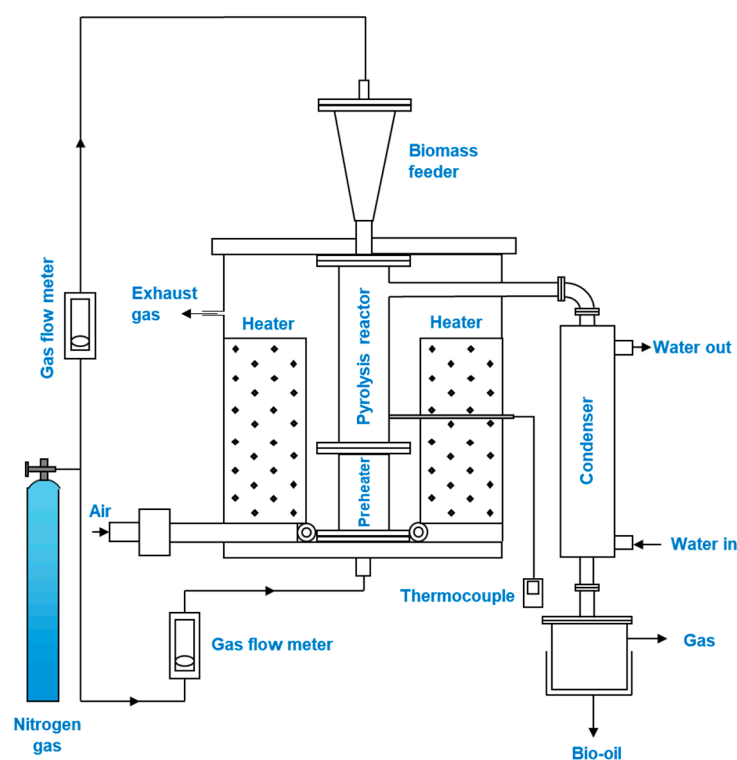


Figure 1. Schematic diagram of a fixed-bed reactor used for pyrolysis. (Adapted from Gholizadeh et al. [2]).

Fixed-bed reactors are extensively utilized both in homogeneous and in heterogeneous catalysis processes. A fixed-bed reactor can optimize pyrolysis process parameters, including temperature, heating rate, vapor residence time, influence of external transport resistance on product selectivity, and molar variations during the reaction. Fixed-bed reactors allow the feedstock to pass through a stationary or fixed bed of a solid catalyst or the reaction medium [77]. Biomass particles in the fixed-bed reactor system may not receive uniform heating due to the low heating rate. This occurs because of the reactor's poor heat transfer coefficient and improper mixing of feedstock particles within the reactor. Consequently, the particles near the heating element would heat up to a greater extent than those away from the heating source. The feedstock used in the reactor should be smaller to prevent uneven heating, as larger-sized feedstock encounters conduction [64]. In addition, fixed-bed reactors have drawbacks, such as longer reaction time requirements and low specific capacity. However, this reactor is cost-effective due to its batch format, simplicity in operation, easy clean-up, and low maintenance [78].

3.2. Fluidized Bed Reactor

A fluidized bed reactor is one in which the feedstock is suspended by a strong upward flow of fluid, primarily an inert gas. The inert gas flow is regulated to prevent the feedstock from drifting away from the reactor. A fluidized bed reactor is a bed filled with material where the rapid flow of fluid generates a mixture of particles and fluid that behaves like a liquid [79]. For the biomass particles to be effectively suspended in the reactor, they must be smaller, approaching a fine texture. A benefit of this type of reactor is its ability to transmit heat consistently, resulting in an evenly distributed reaction.

Figure 2 illustrates the schematics of a typical fluidized bed reactor used for pyrolysis. The reactor consists of solid particles, such as catalysts or biomass feedstock, suspended by the upward movement of a gas or liquid, resulting in their fluid-like behavior. This facilitates the optimal mixing of solid particles and fluids, ensuring a homogeneous temperature distribution and enhanced interaction between reactants and catalysts. These reactors are often operated continuously, with feedstock introduced and products extracted consistently, making them suitable for large-scale industrial applications.

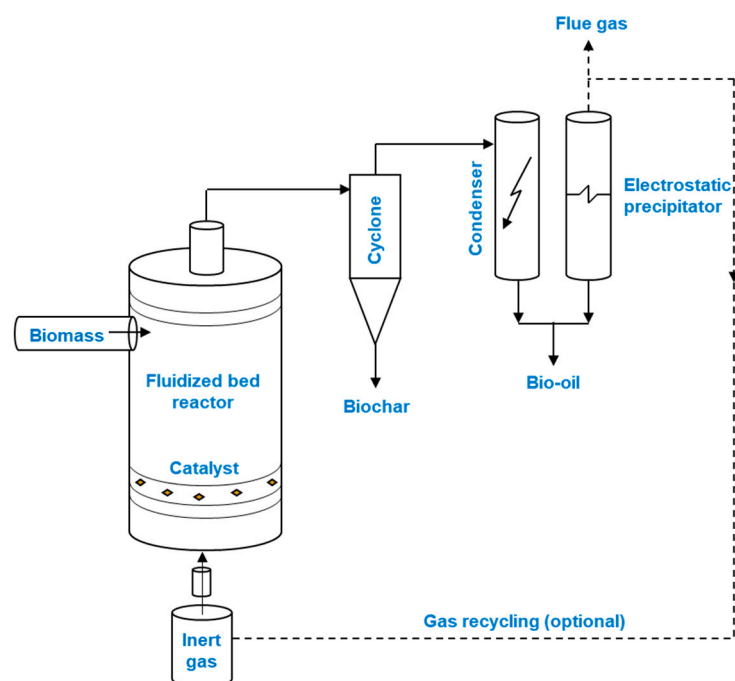


Figure 2. Schematic diagram of a fluidized bed reactor used for pyrolysis.

The fluidized bed reactor is preferred for rapid and flash pyrolysis processes. The reactor has several benefits, such as its user-friendly operation, efficient temperature regulation, superior heat transfer rates, and the capacity to be scaled up [80]. The feedstock in a fluidized bed reactor is generally pulverized into fine particles. The fluidized bed is created by positioning densely packed materials, such as sand, on a permeable plate known as a distributor within the reactor. The fluidization mechanism of a fluidized bed consists mainly of bed material and the fluidizing gas. The bed material is responsible for storing and transporting heat to the feedstock, the heat carrier. Conversely, the fluidizing gas facilitates the amalgamation of the packing material with the feedstock, improving heat transfer. A range of inert substances, including silica and alumina, is employed as packing materials, predominantly consisting of inert materials. In contrast, inert gases such as nitrogen and helium serve as fluidizing gases [81].

The pyrolysis operations in the fluidized-bed reactor exhibit elevated reaction rates due to enhanced heat transfer efficiency. The entire reactor medium can be uniformly heated

while the bed is in fluidized motion. The efficacy of pyrolysis is intricately associated with the biomass particle size and fluidization medium. Nonetheless, maintaining the fluidized-bed reactor, especially its control system, presents difficulties due to the complex architecture of the reactor system. To maintain solid particles in a fluidized state within the reactor, it is necessary to precisely control the velocity of the carrier gas, ensuring uniformity and stability [82]. To achieve this objective, it is essential to have a meticulously regulated gas compressor that can maintain a consistent carrier gas flow rate during continuous operation. Another crucial aspect is the inclusion of solid particles within the volatile substances discharged from the reactor. To create an effective separation system, performing precise basic calculations and implementing a proper control system is necessary. Another potential concern is the erosion of the reactor body caused by the fluidized particles, which might increase maintenance costs [83].

3.3. Entrained Flow Reactor

An entrained flow reactor, or a drop tube reactor, moves feedstock through a tube using the force of gravity [84]. Figure 3 illustrates the schematics of a typical entrained flow reactor used for pyrolysis. The reactor utilizes finely pulverized feedstock, which is fed into a high-temperature reactor where it is rapidly heated in an inert atmosphere to prevent oxidation. The reactor's architecture allows for a constant influx of feed material and gases, facilitating uniform and efficient thermal processing with brief residence times, typically ranging from seconds to a few minutes. This leads to the efficient transformation of solid substances into gaseous and liquid products, which can then be gathered and processed.

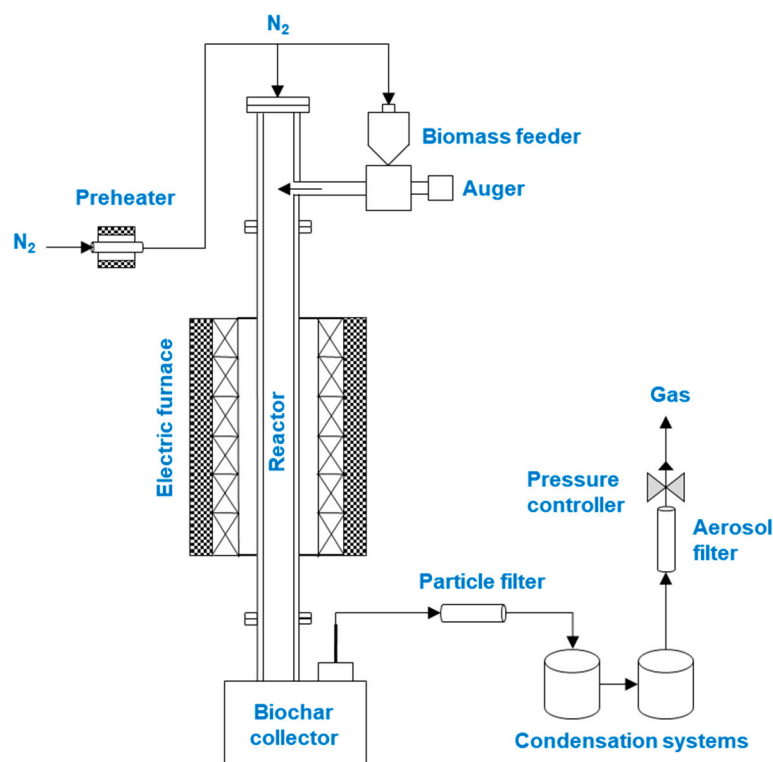


Figure 3. Schematic diagram of an entrained flow reactor used for pyrolysis.

In an entrained flow reactor, the feedstock is kept at a high temperature for heating in the furnace. Feedstock drying is necessary to achieve complete dehydration and prevent moisture consumption during evaporation. This is due to the rapid descent of feedstock under gravitational acceleration, which requires a fast reaction time. Furthermore, maintaining a high surface-to-volume ratio of feedstock is necessary to optimize heat absorption,

which can be achieved through fine grinding. The residence time of biomass in the reactor is generally short and is dictated by the distance it traverses within the reactor [85].

An entrained flow reactor has several key benefits, including its ability to accommodate various types of fuel, maintain a consistent temperature throughout, achieve high carbon conversion rates, facilitate easy scaling up, operate with short residence times, and minimize the presence of tar. Nevertheless, several disadvantages are associated with it, including the need for numerous oxidants, high plant operation and maintenance costs, a significant amount of heat required for the final gaseous product, and the necessity of recovering heat to increase efficiency [86].

3.4. Plasma Reactor

High-efficiency and rapid thermal degradation of robust solid waste is achieved in a plasma reactor by utilizing plasma's thermochemical capabilities. In plasma pyrolysis, carbonaceous materials are processed under limited oxygen to produce a solid and gaseous product at an elevated temperature [87]. Figure 4 illustrates the schematics of a typical plasma reactor used for pyrolysis. The reactor utilizes high-energy plasma to convert biomass and waste into valuable products. Gas plasma is formed by applying a strong electric field, creating a highly ionized state with high temperatures [88]. This tremendous heat breaks down complex organic molecules into gases, bio-oil, and biochar with negligible emissions. Plasma pyrolysis can remediate contaminated feedstocks and boost conversion efficiency due to its unique circumstances.

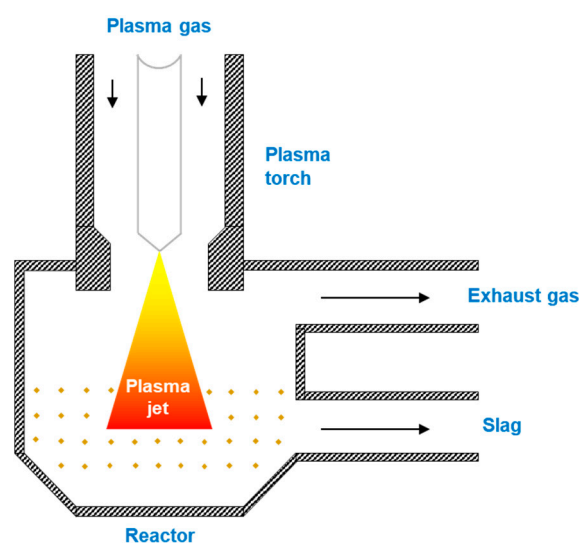


Figure 4. Schematic diagram of a plasma reactor used for pyrolysis.

Plasma pyrolysis is a rapid process that converts the waste material into lucrative end products in less than 1 s [8]. Elevated temperature results in a fast or flash pyrolysis reaction, in which a high voltage electric field creates hot plasma, which, upon injection, heats the feedstock and leads to volatile cracking and the formation of lighter hydrocarbons along with hydrogen. Plasma pyrolysis significantly advances sustainable waste treatment by eliminating tar production and reducing harmful substances, including dioxins and furans. The electrodes in the plasma chamber are supplied with electricity. Subsequently, the plasma carrier gas undergoes ionization, resulting in the generation of electrons. These electrons subsequently collide with atoms, resulting in the production of ions and the release of additional electrons. Researchers have studied and utilized high-power plasma torches that demonstrate exceptional performance and efficiency in generating plasma during plasma pyrolysis. The plasma arc temperature must exceed 2725 °C, as gas molecules

undergo ionization at this temperature [89]. The plasma density, which refers to the concentration of ionized gas within a given volume, is elevated in hot plasma. A high plasma density is also advantageous for attaining elevated temperatures [2].

Plasma technology is used to pyrolyze various waste materials, including plastics, agricultural waste, tires, and medical waste [90]. However, further development is necessary. The heat transfer system exhibited a high level of efficiency. Medical waste, a toxic substance, may be readily transformed into gaseous byproducts and biochar. These byproducts can then be used to generate energy by further combustion. Nevertheless, plasma pyrolysis reactors are limited due to high operating costs, the large amount of heat generated and released, and the high use of electric power. To address this issue, one possible solution is to recycle the gaseous byproducts released from the reactor outlet. Alternatively, another approach may involve combusting some products [91]. The efficient heat transmission mechanism and rapid attainment of the desired pyrolysis temperature make it suitable for large-scale applications.

3.5. Microwave Reactor

Microwave-assisted reactors can be operated in either a moving-bed or a fixed-bed configuration. They employ microwave radiation to heat the feedstock by exciting the water, sugar, and fat molecules. Microwave rays are a form of electromagnetic radiation with a frequency of 0.3–300 GHz or wavelengths between 1 and 300 mm [92]. These rays are generated by a magnetron and directed toward an enclosed chamber containing the feedstock. Figure 5 illustrates the schematics of a typical microwave reactor used for pyrolysis. Two commonly employed types of microwave ovens are single-mode ovens and multimode ovens. The feedstock must be centrally located in a single-mode microwave oven cavity. Microwaves are concentrated at the oven's base using microwave guides. The multimode oven is equipped with a microwave guide that uniformly disperses the waves in all directions, rendering the placement of the feedstock inconsequential. The radiation not absorbed by the feedstock will be dissipated into a water sink [93].

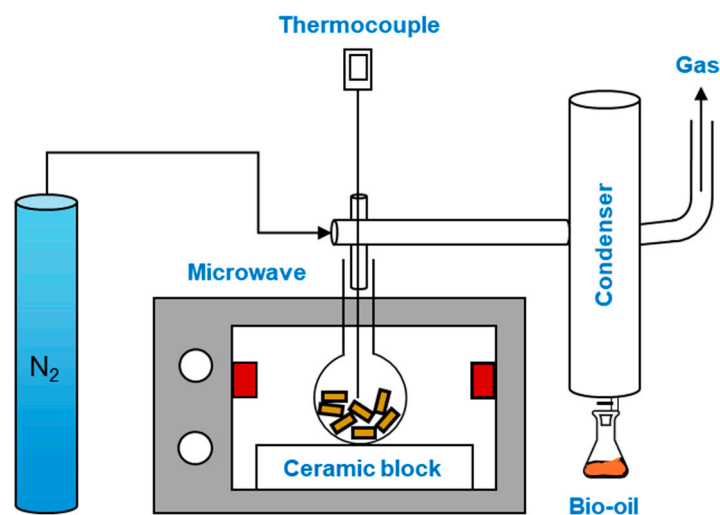


Figure 5. Schematic diagram of a microwave reactor used for pyrolysis.

Traditional pyrolysis is a well-established heating method widely adopted in several industrial settings. However, the heating process causes the uneven heating of the feedstock during pyrolysis. Microwave pyrolysis enables operation at temperatures as high as 1000 °C, with a rapid heating rate. This approach includes both slow and fast pyrolysis. Moreover, microwave heating enables electromagnetic waves to penetrate the feedstock

thoroughly, resulting in the thorough excitation of the molecules' interiors. Therefore, this heating method is more efficient than conventional pyrolysis [94].

The benefit of microwave-assisted heating is eliminating the necessity for pre-drying the feedstock. Water molecules in the feedstock function as an absorbent, facilitating the efficient penetration of microwaves and rapid heating of the fodder. Uneven heating can be addressed by employing microwaves to thermally activate the inside section of the feedstock by radiative waves. A fundamental limitation of microwave pyrolysis is the significant relationship between the feedstock's heating rate and the material's dielectric constant, affecting the penetration depth of microwave radiation [95].

The reactor's cost-effectiveness depends on heat consumption, operational duration, feedstock size, downtime, and process output. Pyrolysis is an endothermic process that requires heat, with energy demands increasing as the feedstock size enlarges. The traditional pyrolysis reactor utilizes heat transmission mechanisms such as conduction and convection, requiring a more significant energy input than the microwave heating reactor. Microwave pyrolysis results in a reduction in energy usage by more than 50% when compared to conventional heating methods [78]. Combining a mobile bed with a microwave enables greater efficiency than traditional pyrolysis. In addition, the physicochemical characteristics of the feedstock, including its moisture content, chemical composition, and particle size, are crucial factors in guaranteeing the efficiency of the reactor.

4. Pyrolysis Products and Applications

4.1. Biochar

Biochar is a solid product obtained from the pyrolysis of biomass. It is a carbonaceous material primarily composed of fixed carbon with a chemical and physical structure that makes it versatile for various applications. Its chemical composition mainly includes carbon, which can contain between 40% and 90%, depending on the raw material and production conditions [96], along with percentages of hydrogen, nitrogen, oxygen, and inorganic elements such as alkali and alkaline earth metals [59]. In addition, biochar has a variety of functional groups on its surface, such as hydroxyl, carboxyl, and other oxygenated groups.

The structure of biochar is predominantly amorphous, with microcrystalline carbon characteristics that provide it with significant porosity, making it suitable for applications in water purification and energy storage and as an additive in composite materials [96]. Covalent bonds, C–C bonds, C–H bonds, hydrogen bonds, and Van der Waals interactions, influence biochar's thermal stability, aromaticity, reactivity, and adsorptive properties [59]. Similarly, the atomic ratios of O/C and H/C indicate the degree of aromatization, energy density, and functional groups in biochar. The composition and structure of biochar vary depending on the biomass used and the pyrolysis conditions. The porosity and surface morphology of biochar can be influenced by pyrolysis conditions, such as temperature and residence time, affecting its mechanical and functional properties [96,97]. For example, before 600 °C, smaller aromatic rings are formed, and the release of substitutional groups is rapid. Beyond this temperature, the condensation of larger aromatic rings reduces the concentration of free radicals, suggesting a more complex and less reactive structure of biochar [98].

Figure 6 illustrates versatile applications of biochar. Biochar is highly valued for its capacity as a catalyst in pyrolysis, where it can promote the degradation of pyrolysis vapors, improve product distribution, and reduce the formation of undesirable compounds such as CO₂ while increasing hydrogen production [59]. Furthermore, biochar can be chemically modified to enhance its functionality, increasing its surface area and porosity, which optimizes its adsorption capacity for contaminants and nutrients, and improves

its reactivity in specific applications, such as the adsorption of heavy metals and organic pollutants [99].

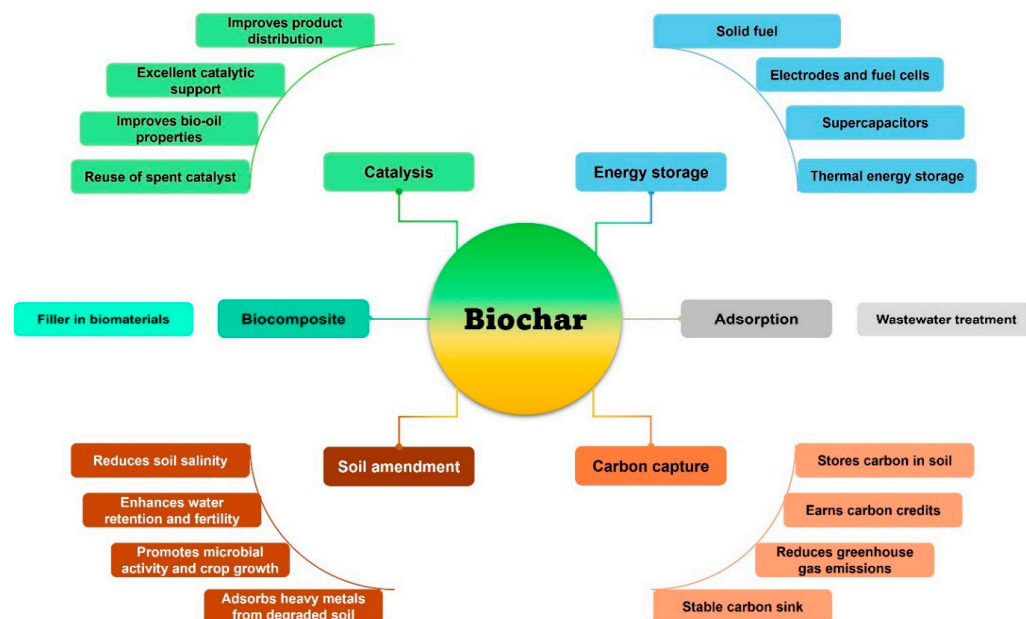


Figure 6. Diverse applications of biochar obtained from pyrolysis.

Biochar also offers several benefits in soil remediation. Thanks to its high surface area and porous structure, it has adsorption properties that allow it to capture potentially toxic elements from contaminated soils, thus reducing their bioavailability and mobility. Likewise, biochar improves soil quality by increasing fertility, improving water retention, and promoting microbial activity, which can lead to higher agricultural yields [99]. Biochar's porous structure attracts beneficial microorganisms, increasing soil biodiversity and crop yields. Its stable carbon sequestration reduces atmospheric CO₂, making it an eco-friendly soil supplement. Biochar filters heavy metals and pesticides from soil and water, benefiting the environment. Biochar with a high potassium content can improve the properties of soil deficient in potassium or where conventional fertilization is not sustainable or is expensive [100]. Biochar improves long-term soil bulk density, pH, and organic carbon [101]. It also enhances soil properties affected by water stress under drought conditions [102]. Moreover, biochar can help control soil pests by inhibiting the growth of fungal pathogens, resulting in healthier crops and fewer crop diseases.

Yadav et al. [103] stated that biochar can adjust the sodium/potassium ratio under salt stress conditions. This helps in osmotic adjustment and improves plant health [104]. The use of biochar as a source of potassium can serve as a more sustainable alternative to chemical fertilizers, contributing to the circular economy by recycling organic waste and reducing dependence on external inputs. Additionally, biochar can sequester carbon, thereby contributing to climate change mitigation. Its high stability as a carbonaceous material allows the carbon captured in its structure to be stored in the soil. When applied to the soil, biochar reduces greenhouse gas emissions because it acts as an effective carbon sink [103].

Other applications of biochar found are related to energy storage due to its unique electrochemical properties. In supercapacitors, biochar can be utilized as an electrode material due to its high surface area and porosity, which facilitates the adsorption of electrolyte ions and enhances the specific capacitance of the device. This hierarchical structure of micropores, mesopores, and macropores also makes it ideal for electrode materials for batteries and fuel cells, as it can store charge and facilitate electron transfer to

enhance performance [105]. On the other hand, biochar can be combined with materials such as carbon nanotubes or graphene to create hybrid energy storage systems, thus increasing the energy density and efficiency of the systems. In thermal energy storage, biochar can absorb and release heat, making it helpful in building material applications to regulate indoor temperatures and reduce energy consumption for heating and cooling. In biomass gasification processes, biochar is a byproduct that can store energy in a solid form, acting as fuel or being further processed [96]. Biochar has been investigated for use in hydrogen storage, where a dominant micropore structure and oxygen-rich functional groups are required for effective gas adsorption [105]. Biochar can also be used as a clean solid fuel for co-firing and/or co-gasification with coal to reduce the carbon emissions in heavy industries [106].

It was previously mentioned that biochar can capture toxic elements from contaminated soils and be applied to wastewater treatment. Its porous structure allows the capture of heavy metals, organic compounds, and nutrients through physical and chemical adsorption and complexation, ion exchange, and electrostatic attraction facilitated by the functional groups on its surface. In addition, biochar can improve water quality by providing a medium for the growth of microorganisms that break down contaminants [107,108]. Biochar is a stable material that can persist in soil for years, demonstrating its long-term carbon fixation benefits [103]. Therefore, raising future perspectives on studying the influence of biochar particle size on persistent free radical reactivity, its evaluation in potential impact on microorganisms in aquatic systems, and exploring large-scale production of biochar for wastewater treatment represents an advanced application by leveraging the catalytic properties of biochar, especially in remediation of water pollutants [109]. Persistent free radicals that can participate in various chemical reactions, such as the activation of oxidants in advanced oxidation processes, making them elements to improve the efficiency of biochar in energy and environmental applications [110], through the development of pilot-scale experiments, progress can be made towards practical applications while considering the reuse of spent biochar as a catalyst [109].

Lifecycle analysis of biochar use in soil validates its effectiveness as a carbon sink, aiding in long-term carbon storage and combating climate change. Since biochar is a thermally stable and fixed carbon-dense material generated from the carbonization of organic materials, it can resist microbial decay when mixed into soil, enabling it to remain for hundreds to thousands of years. For instance, Terra preta, also known as Amazonian Dark Earth, is a distinct kind of soil discovered in the Amazon Basin that is highly fertile and rich in carbon [111]. It is noted for its dark hue, elevated nutrient levels, and ability to hold nutrients effectively. Pre-Columbian societies in the Amazon created terra preta by deliberately or accidentally mixing charcoal, human waste, and other organic substances into the soil. Throughout its life span, when present in the soil, biochar mitigates greenhouse gas emissions by preserving organic carbon that would otherwise deteriorate and emit CO₂ [112]. Moreover, biochar has the potential to improve soil fertility, lower nitrous oxide emissions, and enhance water retention, thereby increasing its environmental advantages. Some recent lifecycle analysis studies have consistently indicated that the net carbon balance in biochar systems could be negative. This means more carbon is sequestered than released, particularly when derived from sustainable biomass and incorporated into regenerative farming practices [111–116].

A techno-economic analysis of pyrolysis is another crucial aspect to assess the scale-up feasibility, economic viability, and commercialization potential of transforming biomass into valuable biofuels [117]. Techno-economic analysis evaluated capital investments, operating expenses, return on investment, payback period, feedstock availability and cost, feedstock pretreatment and processing, product separation and purification cost, product

and byproduct yields, waste management and recycling, and market prices [118]. Key technical aspects include reactor design, process efficiency, energy integration, and the requirements for product upgrading. From an economic perspective, the profitability of pyrolysis systems is influenced by the scale of operation, feedstock costs, and revenue generated from co-products, such as biochar and bio-oil [119]. Techno-economic analysis also includes sensitivity analyses to assess how changes in input variables, like energy prices or carbon credits, affect the feasibility and scalability of pyrolysis [117,120]. This can also provide recommendations to identify cost drivers, optimize pyrolysis process parameters and reactor configurations, and evaluate the potential of competitively commercializing pyrolysis technologies.

4.2. Bio-Oil

Bio-oil, obtained through biomass pyrolysis, is a complex mixture containing a wide variety of organic compounds, which include more than 400 different chemical compounds grouped under the categories of alcohols, phenols, aldehydes, ketones, esters, ethers, hydrocarbons, and aromatics [36,40,45]. The composition of the source biomass influences bio-oil composition. This is a result of the thermal decomposition of biomass components, such as cellulose, hemicellulose, and lignin, which includes acids, alcohols, guaiacols, syringols, aldehydes, esters, ketones, phenols, furan, oxygenated aromatics, and sugars. The conditions of the pyrolysis process, particularly temperature, heating rate, reaction time, and catalyst used, influence the composition of the bio-oil [4]. Certain compounds, such as aldehydes, alcohols, and acids, are generated from the decomposition of cellulose and hemicellulose, while phenols, guaiacols, and syringols are obtained from the decomposition of lignin [121].

The percentage of hydrocarbons in the bio-oil decreases as the temperature rises from 400 °C to 700 °C. The carboxylic acid content remains relatively constant at 500 °C but shows variations at other temperatures [122]. Other significant factors affecting the quality and yield of bio-oil as a final product are related to the chemical composition of biomass. For example, agricultural residues, woody biomass, cattle manure, municipal solid waste, and plastics can produce bio-oil with varying chemical and physical profiles. Biomass with a high hemicellulose content can generate a bio-oil with a higher content of sugars and phenolic compounds [123]. In contrast, lignin-rich biomass can produce a bio-oil with more aromatic and phenolic compounds [124].

Figure 7 illustrates the diverse applications of bio-oil. Bio-oil, as a renewable energy source, appears promising. Bio-oil can replace fossil fuels in power, heating, and industry. Bio-oil can be converted into biodiesel or used to produce chemicals for polymers and pharmaceuticals. However, its acidity and volatility make it challenging to utilize. Bio-oil applications include its use as a liquid fuel, raw material for biochemicals, resins, adhesives, solvents, additives, biopolymers, and binders [121]. However, optimizing its properties requires improvement processes [125]. To be a viable substitute for fossil fuels, it must convert oxygenated compounds into aromatic hydrocarbons [126]. Bio-oil compounds have varied chemical structures, including both simple and complex compounds. Phenols have a benzene ring with hydroxyl groups, which confer chemical properties that can be utilized to produce various chemicals and materials. Acids and alcohols have applications in synthesizing biofuels and chemicals. However, bio-oil also contains a high percentage of moisture and ash. These properties can affect its behavior in specific applications, such as direct use as fuel, but this can be improved with the use of catalysts in the process, which help to optimize the quality of the product and its properties [125]. The pyrolysis process, implemented using the ZSM-5 catalyst, significantly improves the structure of the bio-oil by converting oxygenated compounds into less reactive and more desirable hydrocarbons,

such as aromatic and aliphatic hydrocarbons [127]. This is achieved through deoxygenation and catalytic cracking processes. Hence, the bio-oil produced has fewer acids and alcohols and a higher proportion of ketones, improving its calorific value.

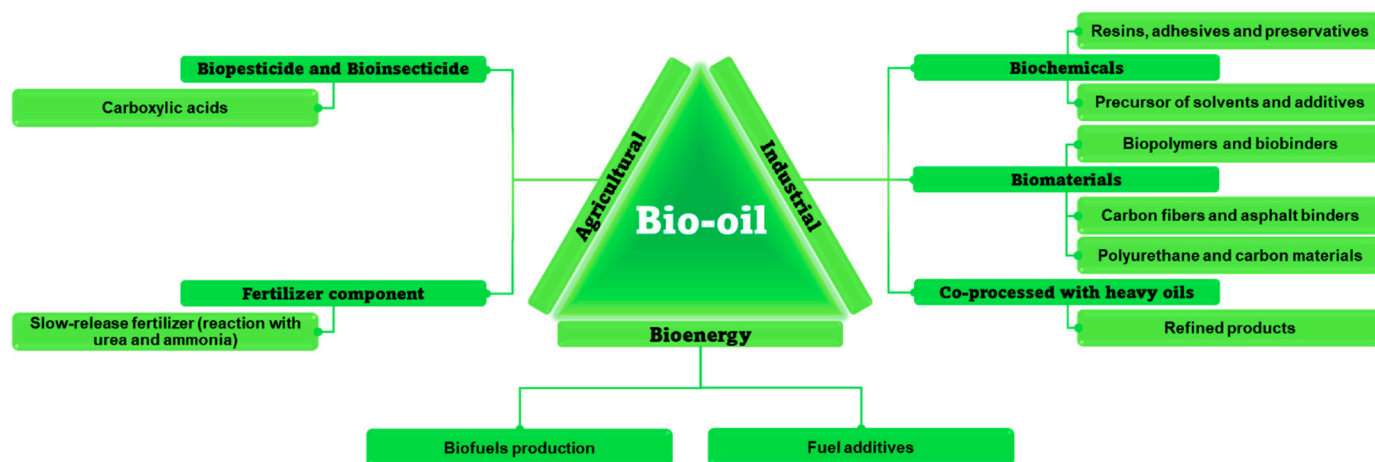


Figure 7. Diverse applications of bio-oil obtained from pyrolysis.

ZSM-5, CaO, red mud, dolomite, Ni/Al₂O₃, and Co- and Fe-based catalysts are commonly utilized for bio-oil upgrading [128]. As noted earlier, ZSM-5 is particularly effective at deoxygenating and aromatizing bio-oil. Its strong Brønsted acid sites and shape-selective micropores facilitate the breakdown of larger oxygenates into lighter, more stable hydrocarbons. Incorporating metals like Ni, Co, and Cu into ZSM-5 can enhance selectivity and minimize coke formation [129]. This modification also results in a higher yield of aromatic hydrocarbons, a decrease in the range of oxygenated compounds, and an improvement in thermal stability and energy density of bio-oil. Red mud, a byproduct of bauxite refining, is a low-cost base catalyst containing metal oxides such as Al, Fe, and Ti [130]. Red mud aids in the cracking and reforming of tar. However, it exhibits lower selectivity for aromatics compared to ZSM-5. Due to its potential for tar reforming, red mud can be used in gasification processes to lower tar production and enhance syngas output [131]. Conversely, CaO is a potent base catalyst for decarboxylation and CO₂ fixation. CaO interacts with CO₂ and acidic oxygenated compounds, reducing the acidity of bio-oil while increasing its hydrocarbon content and calorific value [132].

Esterification is another bio-oil upgrading process that converts fatty acids into esters, decreasing acid value, viscosity, and water content while increasing the calorific value of bio-oil [133]. Hydrogenation is another upgrading technique, which reduces the oxygen content, acidity, and corrosiveness from bio-oil and improves its thermal stability [134]. Steam reforming converts bio-oil into synthesis gas to produce fuels and chemicals [135]. Other techniques include emulsification, which facilitates mixing bio-oil with fossil fuels, and distillation, which separates the components according to their boiling points [136]. Extraction with supercritical fluids and membrane separation are advanced methods that extract and separate specific compounds from bio-oil [137]. This improves bio-oil properties with a composition adjusted to the particular use needs. Likewise, catalytic cracking focuses on the breakdown of large molecules in the presence of a catalyst to produce fuels and light chemicals. In contrast, liquid–liquid extraction focuses on separating specific compounds from bio-oil using solvents [138].

Once the improved bio-oil is obtained, it can be used directly in boilers or emulsified with conventional fuels, such as diesel, for injection into internal combustion engines, thereby reducing polluting emissions, including nitrogen oxide (NO_x) and sulfur oxide (SO_x) [139]. Moreover, the improved bio-oil can be used in producing chemical products,

acting as a precursor for solvents, additives, and other compounds used in various industries, and can thus be co-processed with heavy oils in catalytic cracking units to produce refined products. Its use in creating bio-binders that replace petroleum-derived binders is also being explored. Bio-oil can also produce bio-polyol, polyurethane foams, resins, platform chemicals, and other industrial bioproducts [140,141]. Bio-oil can also be upgraded to create materials with high strength and density, which can be used to make carbon fibers and bio-binders for asphalt [142]. Likewise, bio-oil can be used to create biopolymers, which can be applied in various industries, including construction and automotive, as well as in packaging materials, cosmetics, and personal care products [123].

The carboxylic acids present in the aqueous phase of bio-oil can be extracted for use in agriculture as a precursor for biopesticides, bioinsecticides, and plant growth promoters [143]. Furthermore, bio-oil can be an additive for preparing slow-release fertilizers for agricultural applications, especially by reacting with ammonia and urea [144]. This combination generates a product with enhanced fuel stability, improved physical and chemical properties, higher density, and calorific value, while mitigating other unfavorable properties such as corrosiveness and susceptibility to aging [110]. Another bio-oil option is that obtained from polystyrene pyrolysis. Although not derived from organic sources such as biomass, it can be used as an additive in fuels, for example, in heavy fuel oil, thereby improving its fluidity and reducing the need for additional heat during pumping. Furthermore, its composition, rich in hydrocarbons, makes it useful in fuel mixtures and as a chemical industry solvent [141].

4.3. Producer Gas

The non-condensable gas generated during biomass pyrolysis is known as producer gas. This is a complex mixture of different permanent gases resulting from the thermal decomposition of biomass, the composition of which is determined by the biomass properties and pyrolysis process parameters, including temperature, residence time, heating rate, and catalysts [145]. The yield of gas products increases with the rise in pyrolysis temperature [146]. The main components of producer gas include CO, H₂, CH₄, ethane, ethylene, acetylene, and propane [147,148]. Temperatures below 500 °C result in a decrease in gas yield. However, above 500 °C, gas yields increase [149]. Similarly, at higher temperatures and with the addition of catalysts, the generation of gases rich in H₂ is favored, while at low temperatures, CO and CO₂ predominate. The release of carbonyl and carboxyl functional groups generates CO₂. The breaking of C–O bonds releases CO, and breaking C–H bonds and aromatics generates H₂, respectively. Additionally, the accelerated depolymerization of biomass lignin produces CH₄. The gases produced can create heat during pyrolysis [150].

Figure 8 illustrates the applications of producer gas obtained from pyrolysis. Producer gas is useful for heating, electricity generation, metal smelting, and chemical manufacturing. Producer gases create electricity and thermal energy efficiently in combined heat and power systems. They also feed on synthetic fuels, such as methanol and hydrogen, which support the development of green energy. Producer gases have a lower energy density than natural gas.

Producer gas can be processed by Fischer–Tropsch synthesis to convert it into liquid hydrocarbons, green diesel, paraffins and olefins, heavy alcohols, or raw materials to produce platform chemicals [151]. This process seeks to increase the production of light olefins while minimizing selectivity towards CH₄ and limiting the production of excess CO₂ [152]. On the other hand, H₂ production can be maximized by catalytic pyrolysis followed by steam reforming to improve yields and reduce the formation of other gases such as CH₄ and CO. Catalysts, especially those based on nickel, cobalt, and iron as well as those supported by biochar, enhance H₂ production, facilitating the conversion of heavy

compounds and tar into lighter gases. Furthermore, nickel, cerium, or calcium oxide catalyzes steam reforming to maximize H_2 production [153]. The implementation and selection of suitable catalysts can enhance reaction efficiency and facilitate the conversion of organic compounds into useful gases, thereby increasing H_2 yield [152].

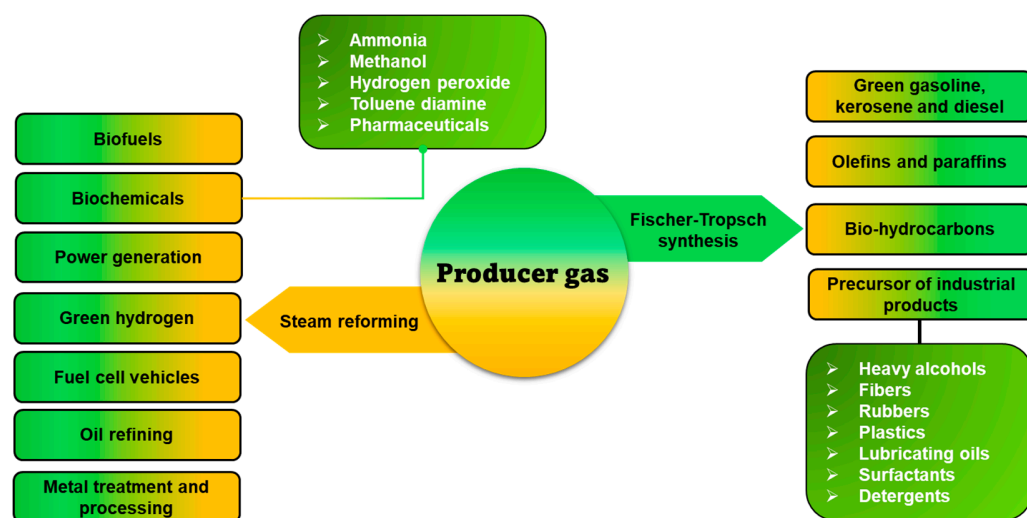


Figure 8. Diverse applications of producer gas obtained from pyrolysis.

Syngas is the most common precursor for Fischer–Tropsch synthesis, where iron, cobalt, and molybdenum are the most commonly used catalysts. Their selection depends on the H_2/CO ratio. Iron is preferred for syngas with a low H_2/CO ratio, while cobalt is more effective when a higher ratio is required [154]. Another technique to consider is the addition of promoters to catalysts, such as potassium, which can increase the olefin-to-paraffin ratio and improve selectivity toward long-chain hydrocarbons [151].

Fischer–Tropsch synthesis enables the production of a diverse range of second-generation biofuels, offering various applications focusing on sustainability and reducing dependence on fossil fuels [155]. These biofuels can be converted into liquid fuels, such as gasoline, diesel, and kerosene, for use in internal combustion engines, such as synthetic fuels in diesel engines [156,157]. In both the aviation and maritime sectors, these biofuels can be implemented, thereby reducing the carbon footprint of both sectors. Likewise, Fischer–Tropsch biofuels can be blended with gasoline and petroleum to reduce the carbon footprint and improve fuel properties, such as enhancing cetane indices [155]. Moreover, in addition to their use in transportation, hydrocarbons obtained by the Fischer–Tropsch process can be utilized in the production of chemicals and industrial materials, including fibers, rubbers, plastics, lubricating oils, surfactants, and detergents, thereby expanding their applicability in the chemical industry [158].

Hydrogen’s ability to store energy makes it ideal for integrating intermittent renewable sources, such as solar and wind, into the electrical grid [159–161]. The applications of hydrogen include its use as fuel in fuel cell vehicles. Hydrogen-rich gas can be used in fuel cells and direct combustion processes in power generation. Hydrogen-rich gas is used as a reagent in producing chemicals such as ammonia and methanol, essential in manufacturing fertilizers and other industrial compounds. Among other chemicals, hydrogen helps produce hydrogen peroxide, toluene diamine, and pharmaceuticals, and can treat and process metals [162]. In the food industry, it is used to hydrogenate fats and oils. In oil refining, hydrogen is incorporated into hydroprocessing and desulfurization processes, improving fuel quality [163]. Hydrogen can also be incorporated into advanced

energy systems, such as syngas production, improving power generation efficiency through integrated combined gasification cycles and high-temperature fuel cells.

It is important to note that the purification and conditioning of producer gas (generated from pyrolysis), synthesis gas or syngas (generated from gasification), and biogas (generated from anaerobic digestion) are vital processes for making them suitable for downstream uses such as Fischer–Tropsch synthesis, methanol production, or power generation. Typically, producer gas and syngas have impurities like tar, particulate matter, sulfur compounds, ammonia, and CO₂, leading to equipment damage, catalyst poisoning, and a compromise in process efficiency [164]. The purification and conditioning of syngas for practical applications involve various technical difficulties due to the intricate mix of contaminants and the requirement for accurate gas composition [165]. Efficient purification involves several stages to eliminate these impurities, including filtration, scrubbing, and chemical absorption. After cleaning, producer gas or syngas must be conditioned to satisfy the specific needs of downstream processes. This usually entails modifying the H₂/CO ratio through water–gas shift reaction and eliminating excess CO₂ to improve fuel quality or synthesis efficiency. Removal of CO₂ from producer gas or syngas becomes essential to improve their heating value and avoid catalyst deactivation during biomass-to-gas or gas-to-liquid processing. Membrane separation, amine scrubbing, and pressure swing adsorption methods are frequently employed for CO₂ removal from producer gas, syngas, or biogas [166]. These conditioning procedures ensure that the producer gas or syngas adheres to the purity and composition requirements necessary for effective and clean use in industrial and energy applications. However, these procedures are energy-intensive and need careful management to balance performance, cost, and environmental impact.

5. Conclusions

Pyrolysis is crucial in pursuing sustainable energy solutions and efficient waste management. Pyrolysis offers a dual benefit by transforming diverse feedstocks, including agricultural waste, forestry residues, and plastic waste, into beneficial biofuels and biochar, thereby mitigating environmental impacts. Pyrolysis adaptability enables it to process various biomass types, making it suitable for areas with diverse agricultural practices. The process can be customized by adjusting the temperature, residence time, and particle size to optimize the yield of bio-oil, biochar, and producer gas.

Pyrolysis reactors, such as entrained flow, plasma, fluidized bed, and fixed bed reactors, all present distinct advantages and disadvantages for waste treatment and biomass conversion. Entrained flow reactors offer superior scalability and carbon conversion efficiency, albeit at the expense of substantial energy and oxidant requirements. Plasma reactors facilitate swift processing and reduced tar generation, although they exhibit elevated electrical demand. Fluidized bed reactors offer effective temperature regulation and mixing, whereas fixed bed reactors are dependable and economical but struggle with processing durations and efficiency. Understanding these attributes is crucial for improving pyrolysis processes and promoting sustainable waste management strategies.

Biochar, bio-oil, and producer gases derived from biomass pyrolysis have various applications in energy generation, environmental restoration, and materials research. Biochar enhances soil quality, absorbs pollutants, and sequesters carbon. Bio-oil is a sustainable fuel and chemical precursor, with potential for further improvement using catalysts. Producer gas is suitable for fuel and chemical synthesis. These products promote sustainability, a circular economy, and the shift from fossil fuels.

Pyrolysis has promising potential, driven by a growing demand for effective waste management and sustainable energy solutions. Enhancements in reactor design, process optimization, and catalyst development, and incorporation of machine learning could

improve process efficiency, scalability, and decision making. Integrating carbon capture techniques and biochar application in agriculture can establish pyrolysis as a key player in carbon-negative systems. Its combination with renewable energy sources and decentralized systems can support rural areas. Furthermore, the production of fuel-grade bio-oil, specialty chemicals, and engineered biochar could increase the economic viability of pyrolysis. The growing demand for sustainable solutions and carbon credit markets positions pyrolysis as a key biorefinery technique to convert biomass into solid, liquid, and gaseous biofuels.

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References

1. Jha, S.; Nanda, S.; Acharya, B.; Dalai, A.K. A review of thermochemical conversion of waste biomass to biofuels. *Energies* **2022**, *15*, 6352. [CrossRef]
2. Gholizadeh, M.; Li, C.; Zhang, S.; Wang, Y.; Niu, S.; Li, Y.; Hu, X. Progress of the development of reactors for pyrolysis of municipal waste. *Sustain. Energy Fuels* **2020**, *4*, 5885–5915. [CrossRef]
3. Our World in Data. Global Direct Primary Energy Consumption. Available online: <https://ourworldindata.org/grapher/global-primary-energy> (accessed on 31 May 2025).
4. Thiru, S.; Kola, R.; Thimmaraju, M.K.; Dhanalakshmi, C.S.; Sharma, V.; Sakthi, P.; Maguluri, L.P.; Ranganathan, L.; Lalvani, J.I. An analytical characterization study on biofuel obtained from pyrolysis of Madhuca longifolia residues. *Sci. Rep.* **2024**, *14*, 14745. [CrossRef]
5. Our World in Data. Biofuel Energy Production, 2023. Available online: <https://ourworldindata.org/grapher/biofuel-production> (accessed on 31 May 2025).
6. Poornima, S.; Manikandan, S.; Prakash, R.; Deena, S.R.; Subbaiya, R.; Karmegam, N.; Kim, W.; Govarthanan, M. Biofuel and biochemical production through biomass transformation using advanced thermochemical and biochemical processes—A review. *Fuel* **2024**, *372*, 132204. [CrossRef]
7. Nanda, S.; Berruti, F. A technical review of bioenergy and resource recovery from municipal solid waste. *J. Hazard. Mater.* **2021**, *403*, 123970. [CrossRef]
8. Fahmy, T.Y.; Fahmy, Y.; Mobarak, F.; El-Sakhawy, M.; Abou-Zeid, R.E. Biomass pyrolysis: Past, present, and future. *Environ. Dev. Sustain.* **2020**, *22*, 17–32. [CrossRef]
9. Patra, B.R.; Mukherjee, A.; Nanda, S.; Dalai, A.K. Biochar production, activation and adsorptive applications: A review. *Environ. Chem. Lett.* **2021**, *19*, 2237–2259. [CrossRef]
10. Gogoi, D.; Kumar, M.; Lakshmi, Y.G. A comprehensive review on “pyrolysis” for energy recovery. *BioEnergy Res.* **2023**, *16*, 1417–1437. [CrossRef]
11. Joshi, N.C.; Sinha, S.; Bhatnagar, P.; Nath, Y.; Negi, B.; Kumar, V.; Gururani, P. A concise review on waste biomass valorization through thermochemical conversion. *Curr. Res. Microb. Sci.* **2024**, *6*, 100237. [CrossRef]
12. Patra, B.R.; Nanda, S.; Dalai, A.K.; Meda, V. Slow pyrolysis of agro-food wastes and physicochemical characterization of biofuel products. *Chemosphere* **2021**, *285*, 131431. [CrossRef]
13. Wang, S.; Wan, Z.; Han, Y.; Jiao, Y.; Li, Z.; Fu, P.; Li, N.; Zhang, A.; Yi, W. A review on lignin waste valorization by catalytic pyrolysis: Catalyst, reaction system, and industrial symbiosis mode. *J. Environ. Chem. Eng.* **2023**, *11*, 109113. [CrossRef]
14. Bhoi, P.R.; Ouedraogo, A.S.; Soloiu, V.; Quirino, R. Recent advances on catalysts for improving hydrocarbon compounds in bio-oil of biomass catalytic pyrolysis. *Renew. Sustain. Energy Rev.* **2022**, *121*, 109676. [CrossRef]

15. Lee, X.J.; Ong, H.C.; Gan, Y.Y.; Chen, W.H.; Mahlia, T.M. State of art review on conventional and advanced pyrolysis of macroalgae and microalgae for biochar, bio-oil and bio-syngas production. *Energy Convers. Manag.* **2020**, *210*, 112707. [\[CrossRef\]](#)
16. Aboelela, D.; Saleh, H.; Attia, A.M.; Elhenawy, Y.; Majazi, T.; Bassyouni, M. Production and characterization of bio-oil from camelthorn plant using slow pyrolysis. *J. Therm. Anal. Calorim.* **2024**, *149*, 10633–10645. [\[CrossRef\]](#)
17. Boer, F.D.; Pignolet, L.; Valette, J.; Candelier, K.; Commandré, J.M.; Fournier, M.; Thévenon, M.F. Efficacy of slow pyrolysis liquid from sugarcane bagasse for wood protection and its leaching properties. *Eur. J. Wood Wood Prod.* **2024**, *82*, 1665–1683. [\[CrossRef\]](#)
18. Mlonka-Medrała, A.; Evangelopoulos, P.; Sieradzka, M.; Zajemska, M.; Magdziarz, A. Pyrolysis of agricultural waste biomass towards production of gas fuel and high-quality char: Experimental and numerical investigations. *Fuel* **2021**, *296*, 120611. [\[CrossRef\]](#)
19. Nanda, S.; Dalai, A.K.; Berruti, F.; Kozinski, J.A. Biochar as an exceptional bioresource for energy, agronomy, carbon sequestration, activated carbon and specialty materials. *Waste Biomass Valorization* **2016**, *7*, 201–235. [\[CrossRef\]](#)
20. Safdari, M.S.; Amini, E.; Weise, D.R.; Fletcher, T.H. Heating rate and temperature effects on pyrolysis products from live wildland fuels. *Fuel* **2019**, *242*, 295–304. [\[CrossRef\]](#)
21. Babu, K.K.B.S.; Nataraj, M.; Tayappa, M.; Vyas, Y.; Mishra, R.K.; Acharya, B. Production of biochar from waste biomass using slow pyrolysis: Studies of the effect of pyrolysis temperature and holding time on biochar yield and properties. *Mater. Sci. Energy Technol.* **2024**, *7*, 318–334.
22. del Pozo, C.; Rego, F.; Yang, Y.; Puy, N.; Bartrolí, J.; Fàbregas, E.; Bridgwater, A.V. Converting coffee silverskin to value-added products by a slow pyrolysis-based biorefinery process. *Fuel Process. Technol.* **2021**, *214*, 106708. [\[CrossRef\]](#)
23. Chernova, N.I.; Grigorenko, A.V.; Kiseleva, S.V.; Larina, O.M.; Kumar, V.; Vlaskin, M.S. Comparative evaluation of pyrolysis and hydrothermal liquefaction for obtaining biofuel from a sustainable consortium of microalgae *Arthrospira platensis* with heterotrophic bacteria. *Processes* **2022**, *10*, 2202. [\[CrossRef\]](#)
24. Bhattacharjee, N.; Biswas, A.B. Pyrolysis of orange bagasse: Comparative study and parametric influence on the product yield and their characterization. *J. Environ. Chem. Eng.* **2019**, *7*, 102903. [\[CrossRef\]](#)
25. Ferreira, M.F.; Oliveira, B.F.; Pinheiro, W.B.; Correa, N.F.; França, L.F.; Ribeiro, N.F. Generation of biofuels by slow pyrolysis of palm empty fruit bunches: Optimization of process variables and characterization of physical–chemical products. *Biomass Bioenergy* **2020**, *140*, 105707. [\[CrossRef\]](#)
26. Baghel, P.; Sakhiya, A.K.; Kaushal, P. Influence of temperature on slow pyrolysis of *Prosopis juliflora*: An experimental and thermodynamic approach. *Renew. Energy* **2022**, *185*, 538–551. [\[CrossRef\]](#)
27. Vieira, F.R.; Luna, C.M.R.; Arce, G.L.A.F.; Ávila, I. Optimization of slow pyrolysis process parameters using a fixed bed reactor for biochar yield from rice husk. *Biomass Bioenergy* **2020**, *132*, 105412. [\[CrossRef\]](#)
28. Greco, G.; Di Stasi, C.; Rego, F.; González, B.; Manyà, J.J. Effects of slow-pyrolysis conditions on the products yields and properties and on exergy efficiency: A comprehensive assessment for wheat straw. *Appl. Energy* **2020**, *279*, 115842. [\[CrossRef\]](#)
29. Babinszki, B.; Sebestyén, Z.; Jakab, E.; Kóhalmi, L.; Bozi, J.; Várhegyi, G.; Wang, L.; Skreiberg, Ø.; Czégény, Z. Effect of slow pyrolysis conditions on biocarbon yield and properties: Characterization of the volatiles. *Bioresour. Technol.* **2021**, *338*, 125567. [\[CrossRef\]](#)
30. Jerzak, W.; Reinmüller, M.; Magdziarz, A. Estimation of the heat required for intermediate pyrolysis of biomass. *Clean Technol. Environ. Policy* **2022**, *24*, 3061–3075. [\[CrossRef\]](#)
31. Pahnla, M.; Koskela, A.; Sulasalmi, P.; Fabritius, T. A review of pyrolysis technologies and the effect of process parameters on biocarbon properties. *Energies* **2023**, *16*, 6936. [\[CrossRef\]](#)
32. Mohammed, I.Y.; Abakr, Y.A.; Kazi, F.K.; Yusuf, S.; Alshareef, I.; Chin, S.A. Pyrolysis of Napier grass in a fixed bed reactor: Effect of operating conditions on product yields and characteristics. *BioResources* **2015**, *10*, 6457–6478. [\[CrossRef\]](#)
33. Kumar, V.K.; Hallad, S.C.; Panwar, N.L. Thermogravimetric pyrolysis investigation of pistachio shell for its potential of thermal properties, kinetics and thermodynamics. *Discov. Energy* **2024**, *4*, 7. [\[CrossRef\]](#)
34. Kazawadi, D.; Ntalikwa, J.; Kombe, G. A review of intermediate pyrolysis as a technology of biomass conversion for coproduction of biooil and adsorption biochar. *J. Renew. Energy* **2021**, *2021*, 533780. [\[CrossRef\]](#)
35. Ahmed, A.; Bakar, M.S.; Azad, A.K.; Sukri, R.S.; Phusunti, N. Intermediate pyrolysis of *Acacia cincinnata* and *Acacia holosericea* species for bio-oil and biochar production. *Energy Convers. Manag.* **2018**, *176*, 393–408. [\[CrossRef\]](#)
36. Paramasivam, B.; Kasimani, R.; Rajamohan, S. Characterization of pyrolysis bio-oil derived from intermediate pyrolysis of *Aegle marmelos* de-oiled cake: Study on performance and emission characteristics of C.I. engine fueled with *Aegle marmelos* pyrolysis oil-blends. *Environ. Sci. Pollut. Res.* **2018**, *25*, 33806–33819. [\[CrossRef\]](#)
37. Nyoni, B.; Hlangothi, S. Intermediate pyrolysis of *Scenedesmus* microalgae in a rotary kiln pyrolyser: Effect of temperature on bio-oil yields and composition. *Biomass Convers. Biorefin.* **2024**, *14*, 12155–12165. [\[CrossRef\]](#)
38. Tinwala, F.; Mohanty, P.; Parmar, S.; Patel, A.; Pant, K.K. Intermediate pyrolysis of agro-industrial biomasses in bench-scale pyrolyser: Product yields and its characterization. *Bioresour. Technol.* **2015**, *188*, 258–264. [\[CrossRef\]](#)

39. Ochieng, R.; Cerón, A.L.; Konist, A.; Sarker, S. Experimental and modeling studies of intermediate pyrolysis of wood in a laboratory-scale continuous feed retort reactor. *Bioresour. Technol. Rep.* **2023**, *24*, 101650. [\[CrossRef\]](#)
40. Torri, I.D.; Paasikallio, V.; Faccini, C.S.; Huff, R.; Caramão, E.B.; Sacon, V.; Oasmaa, A.; Zini, C.A. Bio-oil production of softwood and hardwood forest industry residues through fast and intermediate pyrolysis and its chromatographic characterization. *Bioresour. Technol.* **2016**, *200*, 680–690. [\[CrossRef\]](#)
41. Bouaik, H.; Tabal, A.; Barakat, A.; El Harfi, K.; Aboulkas, A. Optimal parameters and structural composition of bio-oil and biochar from intermediate pyrolysis of red algal biomass. *C. R. Chim.* **2021**, *24*, 85–99. [\[CrossRef\]](#)
42. Ibrahim, M.D.; Abakr, Y.A.; Gan, S.; Lee, L.Y.; Thangalazhy-Gopakumar, S. Intermediate pyrolysis of Bambara groundnut shell (BGS) in various inert gases (N₂, CO₂, and N₂/CO₂). *Energies* **2022**, *15*, 8421. [\[CrossRef\]](#)
43. Fardhyanti, D.S.; Megawati Chafidz, A.; Prasatiawan, H.; Raharjo, P.T.; Habibah, U.; Abasaeed, A.E. Production of bio-oil from sugarcane bagasse by fast pyrolysis and removal of phenolic compounds. *Biomass Convers. Biorefin.* **2024**, *14*, 217–227. [\[CrossRef\]](#)
44. SriBala, G.; Carstensen, H.H.; Van Geem, K.M.; Marin, G.B. Measuring biomass fast pyrolysis kinetics: State of the art. *Wiley Interdiscip. Rev. Energy Environ.* **2019**, *8*, e326. [\[CrossRef\]](#)
45. Aboelela, D.; Saleh, H.; Attia, A.M.; Elhenawy, Y.; Majozi, T.; Bassyouni, M. Recent advances in biomass pyrolysis processes for bioenergy production: Optimization of operating conditions. *Sustainability* **2023**, *15*, 1238. [\[CrossRef\]](#)
46. Sotoudehniakarani, F.; Alayat, A.; McDonald, A.G. Characterization and comparison of pyrolysis products from fast pyrolysis of commercial *Chlorella vulgaris* and cultivated microalgae. *J. Anal. Appl. Pyrolysis* **2019**, *139*, 258–273. [\[CrossRef\]](#)
47. Álvarez-Chávez, B.J.; Godbout, S.; Le Roux, É.; Palacios, J.H.; Raghavan, V. Bio-oil yield and quality enhancement through fast pyrolysis and fractional condensation concepts. *Biofuel Res. J.* **2019**, *6*, 1054–1064. [\[CrossRef\]](#)
48. Alvarez, J.; Hooshdaran, B.; Cortazar, M.; Amutio, M.; Lopez, G.; Freire, F.B.; Haghshenasfard, M.; Hosseini, S.H.; Olazar, M. Valorization of citrus wastes by fast pyrolysis in a conical spouted bed reactor. *Fuel* **2018**, *224*, 111–120. [\[CrossRef\]](#)
49. Adelawon, B.O.; Latinwo, G.K.; Eboibi, B.E.; Agbede, O.O.; Agarry, S.E. Comparison of the slow, fast, and flash pyrolysis of recycled maize-cob biomass waste, Box-Benhen process optimization and characterization studies for the thermal fast pyrolysis production of bioenergy. *Chem. Eng. Commun.* **2022**, *209*, 1246–1276. [\[CrossRef\]](#)
50. Chukwunke, J.L.; Ewulonu, M.C.; Chukwujike, I.C.; Okolie, P.C. Physico-chemical analysis of pyrolyzed bio-oil from *Swietenia macrophylla* (mahogany) wood. *Heliyon* **2019**, *5*, e01790. [\[CrossRef\]](#)
51. Hasan, M.M.; Rasul, M.G.; Jahirul, M.I.; Khan, M.M.K. Fast pyrolysis of municipal green waste in an auger reactor: Effects of residence time and particle size on the yield and characteristics of produced oil. *Energies* **2024**, *17*, 2914. [\[CrossRef\]](#)
52. Benamara, I.; Amara, S.; Tabet, F. Modelling and simulation of fast pyrolysis of pomace from three-phase olive mill targeting optimal yields of pyrolysis products. *Biofuels* **2024**, *15*, 349–361. [\[CrossRef\]](#)
53. Maaoui, A.; Trabelsi, A.B.; Abdallah, A.B.; Chaghtmi, R.; Lopez, G.; Cortazar, M.; Olazar, M. Assessment of pine wood biomass wastes valorization by pyrolysis with focus on fast pyrolysis biochar production. *J. Energy Inst.* **2023**, *108*, 101242. [\[CrossRef\]](#)
54. Li, P.; Shi, X.; Wang, X.; Song, J.; Fang, S.; Bai, J.; Zhang, G.; Chang, C.; Pang, S. Bio-oil from biomass fast pyrolysis: Yields, related properties and energy consumption analysis of the pyrolysis system. *J. Clean. Prod.* **2021**, *328*, 129613. [\[CrossRef\]](#)
55. Inayat, A.; Ahmed, A.; Tariq, R.; Waris, A.; Jamil, F.; Ahmed, S.F.; Ghenai, C.; Park, Y.K. Techno-economical evaluation of bio-oil production via biomass fast pyrolysis process: A review. *Front. Energy Res.* **2022**, *9*, 2021. [\[CrossRef\]](#)
56. Makepa, D.C.; Chihobo, C.H.; Musademba, D. Advances in sustainable biofuel production from fast pyrolysis of lignocellulosic biomass. *Biofuels* **2023**, *14*, 529–550. [\[CrossRef\]](#)
57. Karkach, B.; Tahiri, M.; Haibi, A.; Bouya, M.; Kifani-Sahban, F. Review on fast pyrolysis of biomass for biofuel production from date palm. *Appl. Sci.* **2023**, *13*, 10463. [\[CrossRef\]](#)
58. Chen, W.; Tao, X.; Shi, X.; Guo, W.; Wang, Y.; Liu, B.; Yang, H. Insight into catalytic effects of alkali metal salts addition on bamboo and cellulose pyrolysis. *npj Mater. Sustain.* **2024**, *2*, 25. [\[CrossRef\]](#)
59. Kang, K.; Nanda, S.; Hu, Y. Current trends in biochar application for catalytic conversion of biomass to biofuels. *Catal. Today* **2022**, *404*, 3–18. [\[CrossRef\]](#)
60. Zhong, N.; Ren, X.; Cheng, L.; Yamamoto, M.; Leskinen, T.; Lommi, J.; Zhu, H.; Granstrom, T.; Saddler, J.; Bi, X. Microwave-assisted catalytic pyrolysis of commercial residual lignin with in-situ catalysts to produce homogenous bio-oil and high-yield biochar with enriched pores. *Energy Convers. Manag.* **2022**, *295*, 117620. [\[CrossRef\]](#)
61. Kanattukara, B.V.; Singh, G.; Sarkar, P.; Chopra, A.; Singh, D.; Mondal, S.; Kapur, G.S.; Ramakumar, S.S. Catalyst-mediated pyrolysis of waste plastics: Tuning yield, composition, and nature of pyrolysis oil. *Environ. Sci. Pollut. Res.* **2023**, *30*, 64994–65010. [\[CrossRef\]](#)
62. Wang, Y.; Akbarzadeh, A.; Chong, L.; Du, J.; Tahir, N.; Awasthi, M.K. Catalytic pyrolysis of lignocellulosic biomass for bio-oil production: A review. *Chemosphere* **2022**, *297*, 134181. [\[CrossRef\]](#)
63. Wang, S.; Cao, B.; Liu, X.; Xu, L.; Hu, Y.; Afonaa-Mensah, S.; Abomohra, A.E.; He, Z.; Wang, Q.; Xu, S. A comparative study on the quality of bio-oil derived from green macroalga *Enteromorpha clathrata* over metal modified ZSM-5 catalysts. *Bioresour. Technol.* **2018**, *256*, 446–455. [\[CrossRef\]](#) [\[PubMed\]](#)

64. Pattnaik, F.; Patra, B.R.; Okolie, J.A.; Nanda, S.; Dalai, A.K.; Naik, S. A review of thermocatalytic conversion of biogenic wastes into crude biofuels and biochemical precursors. *Fuel* **2022**, *320*, 123857. [\[CrossRef\]](#)
65. Lee, H.W.; Choi, S.J.; Park, S.H.; Jeon, J.K.; Jung, S.C.; Kim, S.C.; Park, Y.K. Pyrolysis and co-pyrolysis of *Laminaria japonica* and polypropylene over mesoporous Al-SBA-15 catalyst. *Nanoscale Res. Lett.* **2014**, *9*, 376. [\[CrossRef\]](#)
66. Norouzi, O.; Jafarian, S.; Safari, F.; Tavasoli, A.; Nejati, B. Promotion of hydrogen-rich gas and phenolic-rich bio-oil production from green macroalgae *Cladophora glomerata* via pyrolysis over its bio-char. *Bioresour. Technol.* **2016**, *219*, 643–651. [\[CrossRef\]](#)
67. Gao, L.; Sun, J.; Xu, W.; Xiao, G. Catalytic pyrolysis of natural algae over Mg-Al layered double oxides/ZSM-5 (MgAl-LDO/ZSM-5) for producing bio-oil with low nitrogen content. *Bioresour. Technol.* **2017**, *225*, 293–298. [\[CrossRef\]](#)
68. Kawale, H.D.; Kishore, N. Production of hydrocarbons from a green algae (*Oscillatoria*) with exploration of its fuel characteristics over different reaction atmospheres. *Energy* **2019**, *178*, 344–355. [\[CrossRef\]](#)
69. Norouzi, O.; Tavasoli, A.; Jafarian, S.; Esmailpour, S. Catalytic upgrading of bio-products derived from pyrolysis of red macroalgae *Gracilaria gracilis* with a promising novel micro/mesoporous catalyst. *Bioresour. Technol.* **2017**, *243*, 1–8. [\[CrossRef\]](#)
70. Lin, F.; Xu, M.; Ramasamy, K.K.; Li, Z.; Klinger, J.L.; Schaidle, J.A.; Wang, H. Catalyst deactivation and its mitigation during catalytic conversions of biomass. *ACS Catal.* **2022**, *12*, 13555–13599. [\[CrossRef\]](#)
71. Grams, J.; Ruppert, A.M. Catalyst stability—Bottleneck of efficient catalytic pyrolysis. *Catalysts* **2021**, *11*, 265. [\[CrossRef\]](#)
72. Hatta, A.H.; Jalil, A.A.; Hassan, N.S.; Hamid, M.Y.S.; Bahari, M.B.; Aziz, M.A.; Alhassan, M.; Ibrahim, N.; Jusoh, N.W.C.; Hairom, N.H.H. A comprehensive review on the advancements in catalyst regeneration strategies for enhanced reactivity in CO methanation. *Mater. Today Chem.* **2023**, *33*, 101743. [\[CrossRef\]](#)
73. Wang, Y.; Wu, J.J. Thermochemical conversion of biomass: Potential future prospects. *Renew. Sustain. Energy Rev.* **2023**, *187*, 113754. [\[CrossRef\]](#)
74. Marafi, M.; Stanislaus, A. Spent catalyst waste management: A review: Part I—Developments in hydroprocessing catalyst waste reduction and use. *Resour. Conserv. Recycl.* **2008**, *52*, 859–873. [\[CrossRef\]](#)
75. Raza, M.; Inayat, A.; Ahmed, A.; Jamil, F.; Ghenai, C.; Naqvi, S.R.; Shanableh, A.; Ayoub, M.; Waris, A.; Park, Y.-K. Progress of the pyrolyzer reactors and advanced technologies for biomass pyrolysis processing. *Sustainability* **2021**, *13*, 11061. [\[CrossRef\]](#)
76. Ore, O.T.; Adebisi, F.M. A review on current trends and prospects in the pyrolysis of heavy oils. *J. Pet. Explor. Prod.* **2021**, *11*, 1521–1530. [\[CrossRef\]](#)
77. Brahma, S.; Nath, B.; Basumatary, B.; Das, B.; Saikia, P.; Patir, K.; Basumatar, S. Biodiesel production from mixed oils: A sustainable approach towards industrial biofuel production. *Chem. Eng. J. Adv.* **2022**, *10*, 100284. [\[CrossRef\]](#)
78. Mong, G.R.; Chong, C.T.; Chong, W.W.; Ng, J.H.; Ong, H.C.; Ashokkumar, V.; Tran, M.V.; Karmakar, S.; Goh, B.H.; Yasin, M.F. Progress and challenges in sustainable pyrolysis technology: Reactors, feedstocks and products. *Fuel* **2022**, *324*, 124777. [\[CrossRef\]](#)
79. Feng, X.; Jiang, L.; Li, D.; Tian, S.; Zhu, X.; Wang, H.; He, C.; Li, K. Progress and key challenges in catalytic combustion of lean methane. *J. Energy Chem.* **2022**, *75*, 173–215. [\[CrossRef\]](#)
80. Wang, J.; Ku, X.; Lin, J.; Yang, S. Impact of the reactor structure on biomass pyrolysis in fluidized-bed reactors: A course-grained CFD–DEM study. *Energy Fuels* **2021**, *35*, 10035–10050. [\[CrossRef\]](#)
81. Pienihakkinen, E.; Lindfors, C.; Ohra-aho, T.; Lehtonen, J.; Granström, T.; Yamamoto, M.; Oasmaa, A. Fast pyrolysis of hydrolysis lignin in fluidized bed reactors. *Energy Fuels* **2021**, *35*, 14758–14769. [\[CrossRef\]](#)
82. Zapater, D.; Kulkarni, S.R.; Wery, F.; Cui, M.; Herguido, J.; Menendez, M.; Heynderickx, G.J.; Van Geem, K.M.; Gascon, J.; Castano, P. Multifunctional fluidized bed reactors for process intensification. *Prog. Energy Combust. Sci.* **2024**, *105*, 101176. [\[CrossRef\]](#)
83. Amjad, U.E.; Ishaq, M.; Rehman, H.U.; Ahmad, N.; Sherin, L.; Hussain, M.; Mustafa, M. Diesel and gasoline like fuel production with minimum styrene content from catalytic pyrolysis of polystyrene. *Environ. Prog. Sustain. Energy* **2021**, *40*, e13493. [\[CrossRef\]](#)
84. Bieniek, A.; Sieradzka, M.; Jerzak, W.; Magdziarz, A. Fast pyrolysis of agricultural biomass in drop tube reactor for bio-oil production: Numerical calculations. *J. Anal. Appl. Pyrolysis* **2023**, *176*, 106241. [\[CrossRef\]](#)
85. Hameed, Z.; Aslam, M.; Khan, Z.; Maqsood, K.; Atabani, A.E.; Ghauri, M.; Khurram, M.S.; Rehan, M.; Nizami, A.S. Gasification of municipal solid waste blends with biomass for energy production and resources recovery: Current status, hybrid technologies and innovative prospects. *Renew. Sustain. Energy Rev.* **2021**, *136*, 110375. [\[CrossRef\]](#)
86. Ramani, B.; Anjum, A.; Bramer, E.; Dierkes, W.; Blume, A.; Brem, G. Flash pyrolysis of waste tires in an entrained flow reactor—An experimental study. *Polymers* **2024**, *16*, 1746. [\[CrossRef\]](#)
87. Tang, L.; Huang, H.; Hao, H.; Zhao, K. Development of plasma pyrolysis/gasification systems for energy efficient and environmentally sound waste disposal. *J. Electrostat.* **2013**, *71*, 839–847. [\[CrossRef\]](#)
88. Li, Z.; Lin, Q.; Li, M.; Cao, J.; Liu, F.; Pan, H.; Wang, Z.; Kawi, S. Recent advances in process and catalyst for CO₂ reforming of methane. *Renew. Sustain. Energy Rev.* **2020**, *134*, 110312. [\[CrossRef\]](#)
89. Li, T.; Rehmet, C.; Cheng, Y.; Jin, Y.; Cheng, Y. Experimental comparison of methane pyrolysis in thermal plasma. *Plasma Chem. Plasma Proc.* **2017**, *37*, 1033–1049. [\[CrossRef\]](#)

90. Lim, M.T.; Tan, E.S.; Chai, Y.H.; Chin, B.L.; Juwono, F.H.; Hisham, D.H.; Anuar, M.A. Pilot-scale flue gas pyrolysis system for organic and plastic wastes with improved liquid properties in a non-thermal plasma reactor. *J. Anal. Appl. Pyrolysis* **2023**, *173*, 106062. [\[CrossRef\]](#)
91. Bhatt, K.P.; Patel, S.; Upadhyay, D.S.; Patel, R.N. Production of hydrogen-rich fuel gas from waste plastics using continuous plasma pyrolysis reactor. *J. Environ. Manag.* **2024**, *356*, 120446. [\[CrossRef\]](#)
92. Putra, P.H.M.; Rozali, S.; Patah, M.F.A.; Idris, A. A review of microwave pyrolysis as a sustainable plastic waste management technique. *J. Environ. Manag.* **2022**, *303*, 132204. [\[CrossRef\]](#)
93. Ke, L.; Zhou, N.; Wu, Q.; Zeng, Y.; Tian, X.; Zhang, J.; Fan, L.; Ruan, R.; Wang, Y. Microwave catalytic pyrolysis of biomass: A review focusing on absorbents and catalysts. *npj Mater. Sustain.* **2024**, *2*, 24. [\[CrossRef\]](#)
94. Jahirul, M.I.; Rasul, M.G.; Schaller, D.; Khan, M.M.; Hasan, M.M.; Hazrat, M.A. Transport fuel from waste plastics pyrolysis—A review on technologies, challenges and opportunities. *Energy Convers. Manag.* **2022**, *258*, 115451. [\[CrossRef\]](#)
95. 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.
96. Mishra, R.K.; Mohanty, K. A review of the next-generation biochar production from waste biomass for material applications. *Sci. Total Environ.* **2023**, *904*, 167171. [\[CrossRef\]](#)
97. Shen, C.; Song, Z.; Qiu, Z.; Gao, R. Effects of pyrolysis temperature on drinking water treatment residual biochar properties and organophosphorus pesticides adsorption. *Chem. Pap.* **2024**, *78*, 5289–5299. [\[CrossRef\]](#)
98. Chen, D.; Xu, J.; Ling, P.; Fang, Z.; Ren, Q.; Xu, K.; Jiang, L.; Wang, Y.; Su, S.; Hu, S.; et al. Formation and evolution mechanism of persistent free radicals in biochar during biomass pyrolysis: Insights from biochar's element composition and chemical structure. *Fuel* **2024**, *357*, 129910. [\[CrossRef\]](#)
99. Wu, Y.; Yan, Y.; Wang, Z.; Tan, Z.; Zhou, T. Biochar application for the remediation of soil contaminated with potentially toxic elements: Current situation and challenges. *J. Environ. Manag.* **2024**, *351*, 119775. [\[CrossRef\]](#) [\[PubMed\]](#)
100. Biliyas, 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. [\[CrossRef\]](#)
101. Jiang, Y.; Li, T.; Xu, X.; Sun, J.; Pan, G.; Cheng, K. A global assessment of the long-term effects of biochar application on crop yield. *Curr. Res. Environ. Sustain.* **2024**, *7*, 100247. [\[CrossRef\]](#)
102. Kumar, A.; Bhattacharya, T.; Shaikh, W.A.; Roy, A. Sustainable soil management under drought stress through biochar application: Immobilizing arsenic, ameliorating soil quality, and augmenting plant growth. *Environ. Res.* **2024**, *259*, 119531. [\[CrossRef\]](#)
103. Yadav, A.; Yadav, P.; Bojjagani, S.; Srivastava, J.K.; Raj, A. Investigation of the speciation and environmental risk of heavy metals in biochar produced from textile sludge waste by pyrolysis at different temperatures. *Chemosphere* **2024**, *360*, 142454. [\[CrossRef\]](#) [\[PubMed\]](#)
104. 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. [\[CrossRef\]](#)
105. Rawat, S.; Wang, C.T.; Lay, C.H.; Hotha, S.; Bhaskar, T. Sustainable biochar for advanced electrochemical/energy storage applications. *J. Energy Storage* **2023**, *63*, 107115. [\[CrossRef\]](#)
106. Sarker, T.R.; Ethen, D.Z.; Nanda, S. Decarbonization of metallurgy and steelmaking industries using biochar: A review. *Chem. Eng. Technol.* **2024**, *47*, e202400217. [\[CrossRef\]](#)
107. Gupta, M.; Savla, N.; Pandit, C.; Pandit, S.; Gupta, P.K.; Pant, M.; Khilari, S.; Kumar, Y.; Agarwal, D.; Nair, R.R.; et al. Use of biomass-derived biochar in wastewater treatment and power production: A promising solution for a sustainable environment. *Sci. Total Environ.* **2022**, *825*, 153892. [\[CrossRef\]](#)
108. Wang, X.; Guo, Z.; Hu, Z.; Zhang, J. Recent advances in biochar application for water and wastewater treatment: A review. *PeerJ* **2020**, *8*, e9164. [\[CrossRef\]](#)
109. Liu, X.; Chen, Z.; Lu, S.; Shi, X.; Qu, F.; Cheng, D.; Wei, W.; Shon, H.K.; Ni, B.J. Persistent free radicals on biochar for its catalytic capability: A review. *Water Res.* **2024**, *250*, 120999. [\[CrossRef\]](#)
110. Chen, H.; Xu, H.; Zhu, H.; Yan, S.; Zhang, S.; Zhang, H.; Guo, X.; Hu, X.; Gao, W. A review on bioslurry fuels derived from bio-oil and biochar: Preparation, fuel properties and application. *Fuel* **2024**, *355*, 129283. [\[CrossRef\]](#)
111. Neina, D.; Agyarko-Mintah, E. The Terra Preta Model soil for sustainable sedentary yam production in West Africa. *Heliyon* **2023**, *9*, e15896. [\[CrossRef\]](#)
112. Shoudho, K.N.; Khan, T.H.; Ara, U.R.; Khan, M.R.; Shawon, Z.B.Z.; Hoque, M.E. Biochar in global carbon cycle: Towards sustainable development goals. *Curr. Res. Green Sustain. Chem.* **2024**, *8*, 100409. [\[CrossRef\]](#)
113. Alhashimi, H.A.; Aktas, C.B. Life cycle environmental and economic performance of biochar compared with activated carbon: A meta-analysis. *Resour. Conserv. Recycl.* **2017**, *118*, 13–26. [\[CrossRef\]](#)
114. Hamedani, S.R.; Kuppens, T.; Malina, R.; Bocci, E.; Colantoni, A.; Villarini, M. Life cycle assessment and environmental valuation of biochar production: Two case studies in Belgium. *Energies* **2019**, *12*, 2166. [\[CrossRef\]](#)

115. Sahoo, K.; Upadhyay, A.; Runge, T.; Bergman, R.; Puettmann, M.; Bilek, E. Life-cycle assessment and techno-economic analysis of biochar produced from forest residues using portable systems. *Int. J. Life Cycle Assess.* **2021**, *26*, 189–213. [\[CrossRef\]](#)
116. Osman, A.I.; Farghali, M.; Rashwan, A.K. Life cycle assessment of biochar as a green sorbent for soil remediation. *Curr. Opin. Green Sustain. Chem.* **2024**, *46*, 100882. [\[CrossRef\]](#)
117. Okolie, J.A.; Tabat, M.E.; Gunes, B.; Epelle, E.I.; Mukherjee, A.; Nanda, S.; Dalai, A.K. A techno-economic assessment of biomethane and bioethanol production from crude glycerol through integrated hydrothermal gasification, syngas fermentation and biomethanation. *Energy Convers. Manag. X* **2021**, *12*, 100131. [\[CrossRef\]](#)
118. Okolie, J.A.; Nanda, S.; Dalai, A.K.; Kozinski, J.A. Techno-economic evaluation and sensitivity analysis of a conceptual design for supercritical water gasification of soybean straw to produce hydrogen. *Bioresour. Technol.* **2021**, *331*, 125005. [\[CrossRef\]](#)
119. Mohanty, A.; Ajmera, S.; Chinnam, S.; Kumar, V.; Mishra, R.K.; Acharya, B. Pyrolysis of waste oils for biofuel production: An economic and life cycle assessment. *Fuel Commun.* **2024**, *18*, 100108. [\[CrossRef\]](#)
120. Alherbawi, M.; Parthasarathy, P.; Elkhailifa, S.; Al-Ansari, T.; McKay, G. Techno-economic and environmental analyses of the pyrolysis of food waste to produce bio-products. *Heliyon* **2024**, *10*, e27713. [\[CrossRef\]](#)
121. Dai, L.; Wang, Y.; Liu, Y.; Ruan, R.; He, C.; Yu, Z.; Jiang, L.; Zeng, Z.; Tian, X. Integrated process of lignocellulosic biomass torrefaction and pyrolysis for upgrading bio-oil production: A state-of-the-art review. *Renew. Sustain. Energy Rev.* **2019**, *107*, 20–36. [\[CrossRef\]](#)
122. Qing, M.; Long, Y.; Liu, L.; Yi, Y.; Li, W.; He, R.; Yin, Y.; Tian, H.; He, J.; Cheng, S.; et al. Pyrolysis of the food waste collected from catering and households under different temperatures: Assessing the evolution of char structure and bio-oil composition. *J. Anal. Appl. Pyrolysis* **2022**, *164*, 105543. [\[CrossRef\]](#)
123. Qamar, O.A.; Jamil, F.; Hussain, M.; Ala'a, H.; Inayat, A.; Waris, A.; Akhter, P.; Park, Y.K. Feasibility-to-applications of value-added products from biomass: Current trends, challenges, and prospects. *Chem. Eng. J.* **2023**, *454*, 140240. [\[CrossRef\]](#)
124. Panwar, N.L.; Paul, A.S. An overview of recent development in bio-oil upgrading and separation techniques. *Environ. Eng. Res.* **2021**, *26*, 200382. [\[CrossRef\]](#)
125. Xiong, Z.; Syed-Hassan, S.S.; Xu, J.; Wang, Y.; Hu, S.; Su, S.; Zhang, S.; Xiang, J. Evolution of coke structures during the pyrolysis of bio-oil at various temperatures and heating rates. *J. Anal. Appl. Pyrolysis* **2018**, *134*, 336–342. [\[CrossRef\]](#)
126. Dada, K.T.; Sheehan, M.; Murugavelh, S.; Antunes, E. A review on catalytic pyrolysis for high-quality bio-oil production from biomass. *Biomass Convers. Biorefin.* **2021**, *13*, 2595–2614. [\[CrossRef\]](#)
127. Liu, R.; Rahman, M.M.; Sarker, M.; Chai, M.; Li, C.; Cai, J. A review on the catalytic pyrolysis of biomass for the bio-oil production with ZSM-5: Focus on structure. *Fuel Process. Technol.* **2020**, *199*, 106301.
128. Zhao, X.; Wei, L.; Cheng, S.; Julson, J. Review of heterogeneous catalysts for catalytically upgrading vegetable oils into hydrocarbon biofuels. *Catalysts* **2017**, *7*, 83. [\[CrossRef\]](#)
129. Rjeily, M.A.; Gennequin, C.; Pron, H.; Abi-Aad, E.; Randrianalisoa, J.H. Pyrolysis-catalytic upgrading of bio-oil and pyrolysis-catalytic steam reforming of biogas: A review. *Environ. Chem. Lett.* **2021**, *19*, 2825–2872. [\[CrossRef\]](#)
130. Chen, Z.; Wang, D.; Yang, H.; Zhang, Y.; Li, Y.; Li, C.; Yu, J.; Gao, S. Novel application of red mud as disposal catalyst for pyrolysis and gasification of coal. *Carbon Resour. Convers.* **2021**, *4*, 10–18. [\[CrossRef\]](#)
131. Xu, G.X.; Nanda, S.; Guo, J.J.; Song, Y.Q.; Kozinski, J.A.; Dalai, A.K.; Fang, Z. Red mud supported Ni-Cu bimetallic material for hydrothermal production of hydrogen from biomass. *Ind. Crops Prod.* **2024**, *212*, 118370. [\[CrossRef\]](#)
132. An, X.; Tang, C.; Liu, J.; Song, X.; Huang, C. Catalytic pyrolysis of biomass using desulfurization ash: Enhanced bio-oil yields and reaction pathway modulation. *Energy* **2025**, *330*, 136817. [\[CrossRef\]](#)
133. Lu, J.; Guo, S.; Fu, Y.; Chang, J. Catalytic upgrading of bio-oil by simultaneous esterification and alkylation with azeotropic water removal. *Fuel Process. Technol.* **2017**, *161*, 193–198. [\[CrossRef\]](#)
134. Park, Y.K.; Ha, J.M.; Oh, S.; Lee, J. Bio-oil upgrading through hydrogen transfer reactions in supercritical solvents. *Chem. Eng. J.* **2021**, *404*, 126527. [\[CrossRef\]](#)
135. Shao, S.; Zhang, P.; Li, X.; Yu, Y. Steam reforming of the simulated aqueous fraction of bio-oil based on pre-reforming with dolomite. *Fuel* **2023**, *344*, 128116. [\[CrossRef\]](#)
136. Lin, B.J.; Chen, W.H.; Budzianowski, W.M.; Hsieh, C.T.; Lin, P.H. Emulsification analysis of bio-oil and diesel under various combinations of emulsifiers. *Appl. Energy* **2016**, *178*, 746–757. [\[CrossRef\]](#)
137. Drugkar, K.; Rathod, W.; Sharma, T.; Sharma, A.; Joshi, J.; Pareek, V.K.; Ledwani, L.; Diwekar, U. Advanced separation strategies for up-gradation of bio-oil into value-added chemicals: A comprehensive review. *Sep. Purif. Technol.* **2022**, *283*, 120149. [\[CrossRef\]](#)
138. Lachos-Perez, D.; Martins-Vieira, J.C.; Missau, J.; Anshu, K.; Siakpebru, O.K.; Thengane, S.K.; Morais, A.R.; Tanabe, E.H.; Bertuol, D.A. Review on biomass pyrolysis with a focus on bio-oil upgrading techniques. *Analytica* **2023**, *4*, 182–205. [\[CrossRef\]](#)
139. Gupta, S.; Mondal, P.; Borugadda, V.B.; Dalai, A.K. Advances in upgradation of pyrolysis bio-oil and biochar towards improvement in bio-refinery economics: A comprehensive review. *Environ. Technol. Innov.* **2021**, *21*, 101276. [\[CrossRef\]](#)

140. Li, H.; Mahmood, N.; Ma, Z.; Zhu, M.; Wang, J.; Zheng, J.; Yuan, Z.; Wei, Q.; Xu, C.C. Preparation and characterization of bio-polyol and bio-based flexible polyurethane foams from fast pyrolysis of wheat straw. *Ind. Crops Prod.* **2017**, *103*, 64–72. [\[CrossRef\]](#)
141. Palmay, P.; Puente, C.; Haro, C.; Bruno, J.C.; Coronas, A. Bio oil as cutter stock in fuel oil blends for industrial applications. *Energies* **2023**, *16*, 1485. [\[CrossRef\]](#)
142. Zhang, Z.; Fang, Y.; Yang, J.; Li, X. A comprehensive review of bio-oil, bio-binder and bio-asphalt materials: Their source, composition, preparation and performance. *J. Traffic Transp. Eng. (Engl. Ed.)* **2022**, *9*, 151–166. [\[CrossRef\]](#)
143. Abd-Elnabi, A.D.; El-sawy, E.A.F.; El-Adawy, E.M. Insecticidal effects of the fast pyrolysis bio-oil against *Spodoptera littoralis* and *Aphis gossypii* insect pests. *J. Asia-Pac. Entomol.* **2024**, *27*, 102237. [\[CrossRef\]](#)
144. Yang, Q.; Liu, P.; Dong, S.; Zhang, J.; Zhao, B. Combined application of organic and inorganic fertilizers mitigates ammonia and nitrous oxide emissions in a maize field. *Nutr. Cycl. Agroecol.* **2020**, *117*, 13–27. [\[CrossRef\]](#)
145. Yek, P.N.; Chan, Y.H.; Foong, S.Y.; Mahari, W.A.; Chen, X.; Liew, R.K.; Ma, N.L.; Tsang, Y.F.; Sonne, C.; Cheng, Y.W.; et al. Co-processing plastics waste and biomass by pyrolysis-gasification: A review. *Environ. Chem. Lett.* **2024**, *22*, 171–188. [\[CrossRef\]](#)
146. Zadeh, Z.E.; Abdulkhani, A.; Aboelazayem, O.; Saha, B. Recent insights into lignocellulosic biomass pyrolysis: A critical review on pretreatment, characterization, and products upgrading. *Processes* **2020**, *8*, 799. [\[CrossRef\]](#)
147. Zhang, Y.; Liang, Y.; Li, S.; Yuan, Y.; Zhang, D.; Wu, Y.; Xie, H.; Brindhadevi, K.; Pugazhendhi, A.; Xia, C. A review of biomass pyrolysis gas: Forming mechanisms, influencing parameters, and product application upgrades. *Fuel* **2023**, *347*, 128461. [\[CrossRef\]](#)
148. Afraz, M.; Muhammad, F.; Nisar, J.; Shah, A.; Munir, S.; Ali, G.; Ahmad, A. Production of value-added products from biomass waste by pyrolysis: An updated review. *Waste Manag. Bull.* **2024**, *1*, 30–40. [\[CrossRef\]](#)
149. Xia, C.; Cai, L.; Zhang, H.; Zuo, L.; Shi, S.Q.; Lam, S.S. A review on the modeling and validation of biomass pyrolysis with a focus on product yield and composition. *Biofuel Res. J.* **2021**, *8*, 1296–1315. [\[CrossRef\]](#)
150. Rajpoot, L.; Tagade, A.; Deshpande, G.; Verma, K.; Geed, S.R.; Patle, D.S.; Sawarkar, A.N. An overview of pyrolysis of de-oiled cakes for the production of biochar, bio-oil, and pyro-gas: Current status, challenges, and future perspective. *Bioresour. Technol. Rep.* **2022**, *19*, 101205. [\[CrossRef\]](#)
151. Bayat, F.; Pirbazari, S.M.; Shojaei, N.; Kiani, S.; Tavasoli, A. Green catalyst innovation: Enhanced Fischer-Tropsch synthesis using potassium-promoted cobalt catalysts supported on pyrolyzed peanut shells and *Cladophora glomerata* modified biochars. *Fuel Process. Technol.* **2024**, *258*, 108094. [\[CrossRef\]](#)
152. Yousefian, F.; Babatabar, M.A.; Eshaghi, M.; Poor, S.M.; Tavasoli, A. Pyrolysis of rice husk, coconut shell, and *Cladophora glomerata* algae and application of the produced biochars as support for cobalt catalyst in Fischer-Tropsch synthesis. *Fuel Process. Technol.* **2023**, *247*, 107818. [\[CrossRef\]](#)
153. Nguyen-Thi, T.X.; Nguyen, P.Q.; Tran, V.D.; Ağbulut, Ü.; Nguyen, L.H.; Balasubramanian, D.; Tarelko, W.; Bandh, S.A.; Pham, N.D. Recent advances in hydrogen production from biomass waste with a focus on pyrolysis and gasification. *Int. J. Hydrogen Energy* **2024**, *54*, 127–160. [\[CrossRef\]](#)
154. Martinelli, M.; Gnanamani, M.K.; LeViness, S.; Jacobs, G.; Shafer, W.D. An overview of Fischer-Tropsch Synthesis: XtL processes, catalysts and reactors. *Appl. Catal. A Gen.* **2020**, *608*, 117740. [\[CrossRef\]](#)
155. dos Santos, R.G.; Alencar, A.C. Biomass-derived syngas production via gasification process and its catalytic conversion into fuels by Fischer Tropsch synthesis: A review. *Int. J. Hydrogen Energy* **2020**, *45*, 18114–18132. [\[CrossRef\]](#)
156. de Oliveira, D.C.; Lora, E.E.; Venturini, O.J.; Maya, D.M.; Garcia-Pérez, M. Gas cleaning systems for integrating biomass gasification with Fischer-Tropsch synthesis—A review of impurity removal processes and their sequences. *Renew. Sustain. Energy Rev.* **2023**, *172*, 113047. [\[CrossRef\]](#)
157. Jenčík, J.; Hönig, V.; Obergruber, M.; Hájek, J.; Vráblík, A.; Černý, R.; Schlehöfer, D.; Herink, T. Advanced biofuels based on Fischer-Tropsch synthesis for applications in diesel engines. *Materials* **2021**, *14*, 3077. [\[CrossRef\]](#)
158. Chen, Y.; Wei, J.; Duyar, M.S.; Ordonsky, V.V.; Khodakov, A.Y.; Liu, J. Carbon-based catalysts for Fischer-Tropsch synthesis. *Chem. Soc. Rev.* **2011**, *50*, 2337–2366. [\[CrossRef\]](#)
159. Aziz, M.; Darmawan, A.; Juangsa, F.B. Hydrogen production from biomasses and wastes: A technological review. *Int. J. Hydrogen Energy* **2021**, *46*, 33756–33781. [\[CrossRef\]](#)
160. Foong, S.Y.; Chan, Y.H.; Cheah, W.Y.; Kamaludin, N.H.; Ibrahim, T.N.; Sonne, C.; Peng, W.; Show, P.L.; Lam, S.S. Progress in waste valorization using advanced pyrolysis techniques for hydrogen and gaseous fuel production. *Bioresour. Technol.* **2021**, *320*, 124299. [\[CrossRef\]](#)
161. Vuppaladadiyam, A.K.; Vuppaladadiyam, S.S.; Awasthi, A.; Sahoo, A.; Rehman, S.; Pant, K.K.; Murugavelh, S.; Huang, Q.; Anthony, E.; Fennel, P.; et al. Biomass pyrolysis: A review on recent advancements and green hydrogen production. *Bioresour. Technol.* **2022**, *364*, 128087. [\[CrossRef\]](#)
162. Yuan, T.; Zhao, J.N.; Bao, N.R. Hydrogen applications: Advances in the field of medical therapy. *Med. Gas. Res.* **2022**, *12*, 99–107. [\[CrossRef\]](#)

163. Bezergianni, S.; Dimitriadis, A.; Kikhtyanin, O.; Kubička, D. Refinery co-processing of renewable feeds. *Prog. Energy Combust. Sci.* **2018**, *68*, 29–64. [[CrossRef](#)]
164. Singh, S.V.; Ming, Z.; Fennell, P.S.; Shah, N.; Anthony, E.J. Progress in biofuel production from gasification. *Prog. Energy Combust. Sci.* **2017**, *61*, 189–248.
165. Mondal, P.; Dang, G.S.; Garg, M.O. Syngas production through gasification and cleanup for downstream applications—Recent developments. *Fuel Process. Technol.* **2011**, *92*, 1395–1410. [[CrossRef](#)]
166. Oreggioni, G.D.; Brandani, S.; Luberti, M.; Baykan, Y.; Friedrich, D.; Ahn, H. CO₂ capture from syngas by an adsorption process at a biomass gasification CHP plant: Its comparison with amine-based CO₂ capture. *Int. J. Greenh. Gas Control* **2015**, *35*, 71–81. [[CrossRef](#)]

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