

Review Article

Optimizing Waste for Energy: Exploring Municipal Solid Waste Variations on Torrefaction and Biochar Production

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Energy primarily comes from fossil fuels, which leads to environmental deterioration through increased carbon dioxide load and other greenhouse gases in the atmosphere. Renewable energy is a cheap alternative, and biomass, like municipal solid wastes (MSWs), can be suitably used for energy production. This paper reviews the impact of variations in MSW composition on its physical, chemical, and lignocellulosic properties. It further illustrates how these properties affect torrefaction products. It was observed that MSW can refer to either a combination of different waste types or independent wastes; hence, there is no standard composition of MSW. The variations in composition are responsible for fluctuating physical, chemical, and lignocellulosic properties. These properties, along with torrefaction process parameters, simultaneously affect the torrefied product, whereas lignocellulosic properties influence the biochar yield, and physical and chemical properties impact calorific value and ash content. Torrefying MSW containing low moisture content yields biochar with a high calorific value. Methods to improve the lignocellulosic properties of MSW have not been studied. Research is needed to assess the possibility of improving biochar yields in MSW by enhancing lignin percentages, possibly through blending MSW. A guide on the best blend combinations and ratios is required. Also, it is crucial to study optimal torrefaction process parameters.

1. Introduction

Our planet faces a constant rise in energy demand fueled by population growth, improved living standards, and industrial expansion [1]. Fossil fuels, primarily oil (33%), natural gas (21%), and coal (24%), still dominate the global energy mix, accounting for roughly 78.6% of energy consumption [2]. However, this reliance on fossil fuels has severe environmental consequences, particularly the increased emission of greenhouse gases, like carbon dioxide (CO₂), into the atmosphere,

contributing to climate change [3]. Although fossil fuels accounted for a staggering 84% of global energy demand in 2019 [4], a growing recognition of their finite nature and detrimental environmental impacts has spurred significant efforts toward transitioning to renewable energy sources [5].

Renewable energy offers a sustainable and cost-effective alternative to fossil fuels. It primarily relies on readily available, naturally abundant, and reusable resources for electricity generation. There is a diverse range of renewable energy sources available, including hydropower, solar, wind, geothermal, and

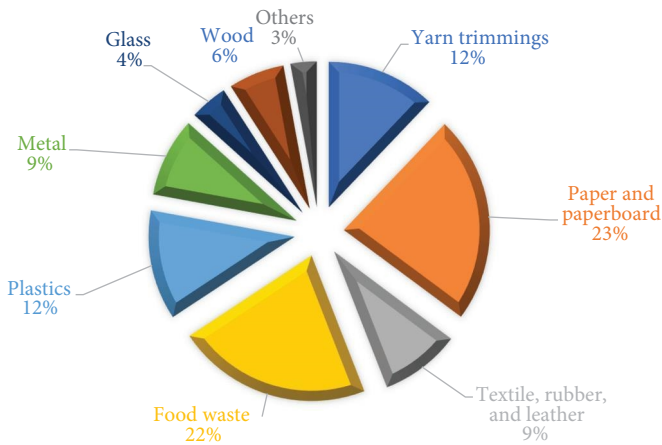


FIGURE 1: Characterization of municipal solid waste. Data source: EPA [13].

biomass [6]. Governments, prioritizing locally sourced renewable energy sources, consider factors like cost, availability, quality, and socioenvironmental implications when planning their energy mix [7]. Among renewable energy options, biomass ranks as the third largest contributor after wind and hydropower [4]. As defined by Mamvura and Danha [8], biomass refers to organic material derived from living plants or animals or those that have recently died. Compared to fossil fuels, biomass offers a significant environmental advantage as it produces less pollution and achieves near-zero CO₂ emissions throughout its lifecycle [9]. Primarily composed of hemicellulose, cellulose, and lignin, with minor amounts of other organic and inorganic components, biomass is a promising source for producing liquid biofuels, gaseous biofuels, and solid biofuels, making it a viable alternative to fossil fuels [10].

Biomass can be derived from various sources, including wood, energy crops, forest and agricultural residues, and industrial and municipal solid waste (MSW) [11]. MSW, a significant contributor to the global waste stream, largely originates from discarded materials like leaves, paper, grass clippings, plastics, glass, metals, diapers, organic matter, and food residue [12]. The MSW can be composed of several materials, including noncarbonaceous and carbonaceous materials, as presented in Figure 1 [13, 14]. Lignocellulosic biomass, the primary component of plant cell walls, is mainly composed of cellulose, lignin, and hemicellulose. Due to variations in MSW processing methods, the percentages of cellulose, lignin, and hemicellulose can differ significantly across studies [15]. Studies by Farmanbordar et al. [16] report that the high cellulose content observed in most MSW compositions is likely attributed to the presence of wastepaper, wood, and garden waste. Conversely, MSW with a higher proportion of branches and barks often possesses higher lignin percentages, as noted by Schmitt et al. [17].

The composition of MSW, generated from production and consumption activities, creates a heterogeneous mixture with regional variations [18]. Waste generation, disposal, and management pose global challenges, with projections indicating a potential 70% increase in waste quantities by 2050 if current

trends continue [19]. Factors influencing waste quantity and quality include urbanization, weather conditions, and socioeconomic parameters like population, lifestyle, income per capita, and education level [19, 20]. To address the mounting waste management concerns, various waste-to-energy (WtE) technologies have been adopted to convert waste biomass into biofuels usable for heat and power generation, as well as in the transportation sector [21].

While directly using biomass-derived fuels for heat and power generation is possible, their high moisture content (MC), low energy density, inconsistent composition, and hydrophilic nature pose significant challenges [21]. These undesirable properties decrease the calorific value, lead to excessive smoke during combustion, and reduce combustion efficiency [5, 21, 22, 23]. To overcome these limitations and enhance the utility of biomass in various sectors, pretreatment is necessary for producing high-quality secondary energy resources [24].

Biomass treatment or conversion technologies can be categorized into physical, chemical, biological, and thermochemical processes [10, 21]. Thermochemical processes offer several advantages. Unlike biological processes, which rely on specific microorganisms for specific conversions, thermochemical processes are less time-consuming, requiring only minutes for biomass conversion, and can be applied to various feedstock types [22]. Thermochemical conversion techniques encompass torrefaction, liquefaction, pyrolysis, gasification, and combustion [4, 9, 22]. Physical technologies involve separation, pulverization, and pelletization, while transesterification is an example of chemical technology [21].

Among the thermochemical conversion technologies, torrefaction offers a promising approach for improving the quality of biomass for energy production. It involves slow heating (around 50°C/min) in a controlled atmosphere without oxygen at temperatures ranging from 200 to 300°C for 10–60 min [11, 25]. During this process, volatile components are released, leaving behind a dehydrated and carbonized solid fuel called torrefied biomass [24]. This torrefied biomass can be further processed for gasification and combustion or densified into briquettes or pellets for improved handling, transportation, and storage [23, 26].

The torrefaction process is influenced by two key factors: the composition and physical properties of the biomass feedstock and the operating conditions employed [11, 22]. Operating conditions include temperature, residence time (duration the biomass spends at the processing temperature), heating rate, reactor type, particle size of the biomass feedstock, and the surrounding atmosphere [22].

Torrefaction offers several advantages for improving the utilization of biomass for energy production. It significantly improves the calorific value, energy density, and carbon content of the biomass [1, 11, 27]. Additionally, it increases the carbon-to-oxygen ratio, a measure of the fuel's efficiency during combustion, and enhances the grindability of the biomass, making it easier to process [27]. Simultaneously, torrefaction reduces the MC, ash content, and atomic H/C ratio of the biomass [1, 11, 27]. These combined effects translate to

improved handling characteristics, easier transportation, and more efficient combustion processes with lower emissions [23, 26].

While various studies have explored the impact of torrefaction process parameters on the quality of biochar derived from different biomass types, there are knowledge gaps addressed by this review (Table 1). Existing reviews have primarily focused on the effects of process parameters on biochar quality, with some limitations. Fuad et al. [25] concentrated solely on microwave-assisted torrefaction, neglecting other torrefaction methods. Sukiran et al. [38] explored recent developments in torrefaction using oil palm waste as feedstock, and Olugbade and Ojo [27] discussed the operating mechanisms of various torrefaction processes, focusing on wet, dry, and ionic-liquid-assisted torrefaction for agro-residue. Abdulyekeen et al. [11] compared the effects of torrefaction parameters on biochar from MSW and other biomass types, but the impact of feedstock properties on the final biochar was not considered.

Given the significant variations in MSW composition based on demographics [39], this review analyzes the impact of these compositional variations on the physical, chemical, and lignocellulosic properties of the resulting torrefaction products. We further explored how these varying biomass properties influence the characteristics of the torrefied products. Additionally, we highlighted the suitability of different waste combinations classified as MSW for the torrefaction process.

To address the knowledge gaps in MSW torrefaction and provide a more comprehensive understanding of this technology, this review explored several critical questions. First, we investigated how variations in the composition of MSW (cellulose, lignin, hemicellulose, MC, etc.) impact the product yield and quality (energy density, calorific value, etc.) of torrefaction. Understanding this relationship allows researchers to predict torrefaction outcomes based on the specific composition of the MSW feedstock used. This knowledge is crucial for optimizing the torrefaction process for efficient biomass conversion from waste materials. Second, the review identified which specific MSW components (e.g., high cellulose content and presence of plastics) significantly influence the torrefaction process and the properties of the resulting biochar. By pinpointing these key components, researchers and practitioners can develop targeted strategies for optimizing the MSW composition or implementing pretreatment steps before torrefaction. This could involve source separation of waste streams or preprocessing techniques to enhance the suitability of the feedstock for the torrefaction process. Third, the review explored the optimal torrefaction process parameters (temperature, residence time, etc.) for different MSW compositions to achieve the desired product characteristics. By investigating this question, researchers can make recommendations for tailoring the torrefaction process to specific MSW feedstocks. This ensures efficient conversion and maximizes the quality of the resulting biochar for various applications, such as combustion or gasification.

By addressing these research questions, this review aims to provide valuable insights for researchers, practitioners, and policy-makers involved in developing and implementing

sustainable waste management solutions through biomass conversion technologies like torrefaction. This knowledge will contribute to advancements in waste management practices, promoting a circular economy and a more sustainable future for energy production. A circular economy focuses on reducing waste generation, maximizing resource recovery, and extending the lifespan of products and materials. By effectively utilizing MSW through torrefaction, we can divert waste from landfills, recover valuable energy resources, and contribute to a more sustainable waste management system. Furthermore, this review can inform the development of techno-economic models to assess the economic viability of MSW torrefaction at various scales. Additionally, it can guide life cycle assessments to evaluate the environmental impact of MSW torrefaction compared to traditional waste management practices.

2. Characterization of MSW

This section delves into the characterization of MSW with a specific focus on its lignocellulosic composition. Understanding this composition is crucial for optimizing torrefaction processes, a thermochemical treatment that enhances the fuel properties of biomass. MSW is not just trash; it holds potential as a source of lignocellulose, a valuable component in plant matter ideal for torrefaction, a thermochemical treatment that enhances fuel properties. To optimize torrefaction for MSW, understanding its lignocellulosic composition is crucial.

2.1. Lignocellulosic Composition of MSW. Biomass, as defined by Negi et al. [23], is the organic matter storing energy through photosynthesis. This renewable resource holds promise for electricity, fuel, heat, and various other products. Biomass can be either lignocellulosic or nonlignocellulosic [34]. Lignocellulose itself is a complex fibrous structure with a varied chemical makeup, as described by Silva et al. [7]. These chemicals can be categorized as structural organic macromolecules or low-weight compounds with physiological or protective functions.

Agricultural and forestry residues are prime examples of lignocellulosic feedstock suitable for torrefaction [21, 40, 41]. This includes materials from dedicated energy plantations and leftovers from various agricultural or forestry processing stages. Even products containing varying percentages of cellulose, hemicellulose, and lignin can be torrefied. However, these organic materials are naturally resistant to biodegradation [21, 42, 43]. The chemical makeup of lignocellulosic biomass varies depending on inherent factors like the plant species, its age, and even its position on the stem.

Khan et al. [39] classified lignocellulosic feedstocks into categories like woody biomass, agricultural biomass, and even organic MSW. While Schmitt et al. [17] focused on lignocellulose-rich urban waste, dividing it into yard waste, mixed waste paper, and general MSW. Khan et al. [39] categorized woody biomass as products derived from trees, such as bark, pine, and sawdust. Agricultural biomass included crop residues like husks, shells, and stalks. Plant biomass encompassed shrubs, leaves, and small plants. Algal biomass referred to cultivated algae and microalgae in bioreactors.

TABLE 1: Comparison of the current review with the previous review on torrefaction.

Study	Characterization of MSW	Overview of waste-to-energy technologies	Overview of torrefaction	Factors influencing torrefaction	Impact of lignocellulosic composition	Effects of torrefaction on biomass properties	Optimization of torrefaction performance	Potential applications of torrefied biomass or torrefied MSW	Challenges, research directions, future perspective
Tumuluru et al. [28]	X	X	✓	✓	X	✓	X	✓	X
Nhuchhen et al. [29]	X	✓	✓	✓	✓	✓	X	✓	X
Chen et al. [30]	X	X	✓	X	X	✓	X	✓	✓
Bach and Skreiberg [31]	X	X	✓	X	X	✓	X	X	✓
Ribeiro et al. [5]	X	X	✓	✓	X	✓	X	X	✓
Barskov et al. [32]	X	X	✓	✓	✓	✓	X	X	X
Ariff et al. [25]	X	X	✓	✓	✓	✓	X	X	✓
Mamvura and Danha [8]	X	X	✓	✓	X	X	X	✓	X
He et al. [33]	X	X	✓	✓	X	X	X	✓	✓
Olugbade and Ojo [27]	X	X	✓	✓	X	✓	X	✓	✓
Ong et al. [3]	X	X	✓	✓	X	✓	X	X	✓
Sarker et al. [24]	X	X	✓	X	X	✓	X	✓	✓
Adeleke et al. [34]	X	X	✓	✓	X	X	X	X	✓
Devaraja et al. [35]	X	X	✓	✓	X	✓	X	✓	✓
Waheed et al. [36]	X	X	✓	✓	X	✓	X	✓	X
Ivanovski et al. [37]	X	X	✓	X	X	X	X	✓	✓
This review	✓	✓	✓	✓	✓	✓	X	✓	✓

TABLE 2: Municipal solid waste composition (%) from various literature.

Food/ organic waste	Plastic (hard plastic)	Paper and carton (packaging)	Glass	Fabric/ textiles	Metals	Ashes	Yard waste	Stones and debris	Water bottles	Polyethene (soft plastic)	Others	Ref
69.4	18.1	6	2.4	2.8	1.2	—	—	—	—	—	2.1	[49]
92.66	3.72	1.62	0.68	0.50	0.16	—	—	—	—	—	0.66	[50]
67	7	11	4	6	1	4	—	—	—	—	—	[51]
37.8	7.8	6.7	0.7	1.3	0.8	—	33.6	8.6	—	—	2.7	[52]
57	13	9	4	—	4	—	—	—	—	—	—	[53]
71.4	7.8	2.7	1.5*	1.3	1.5*	—	—	8.6	—	—	6.7	[54]
90.85	0.35	1.6	1.10	0.65	0.15	—	—	—	1.40	2.95	1.0	[55]
92.1	1.8	1.3	0.6	0.5	0.1	—	—	—	—	3.0	0.6	[46]
62	12	11	6	1	1	—	—	—	1**	—	6	[56]
70	5	5	—	—	3	—	—	—	—	—	—	[57]
49.8	5.1	5.4	—	0.5	—	—	—	—	13**	24.2***	13.4	[58]
37.8	7.6	6.0	0.8	1.2	0.6	—	10.1	2.2#	—	33.7***	—	[12]
77.2	9.5	8.3	1.3	—	0.3	—	—	—	—	—	3.4	[59]
67	7	11	4	6	1	4	—	—	—	—	—	[51]
67	8	6	1	—	1	—	—	—	—	—	17	[60]
57	13	9	4	—	4	—	—	—	—	—	13	[61]

* Glass and metals were combined, ** rubber and leather, *** garden, and # wood.

Finally, organic MSW included biodegradable waste like food scraps, coffee grounds, fruit peels, paper, and even biogas digestate. In the study by Schmitt et al. [17], yard waste comprised a mix of hardwoods and softwoods with branches, bark, and needles collected for composting. Mixed waste paper was the lowest grade mixed paper waste collected for recycling, while their MSW category included food scraps like banana peels, cereals, coffee grounds, canned goods, and hygiene products destined for landfills.

Cellulosic biomass can come from various sources, including forests (forest residues and woody biomass), agriculture (crop residues and perennial energy grasses), and even MSW. MSW offers a particularly attractive option because it avoids competition between food production and energy needs, and it is widely available globally [3, 23]. MSW primarily consists of biodegradable organic materials like food waste, paper, plant materials, leather, wood, and textiles, alongside some synthetic materials like plastics and rubber. Food and plant-derived waste make up a significant portion of landfill waste, including garden trimmings and yard waste [44, 45, 46, 47, 48].

Table 2 summarizes the composition of MSW from various studies. MSW is typically classified into organic waste, plastic, paper, glass, textiles, metals, ash, and others. While some authors separate organic waste from garden waste [12, 52, 58] and plastics into hard and soft plastics [46, 55], many group leather and textiles together. Additionally, Christensen et al. [58] and Pathak et al. [56] combine leather and textiles with rubber, while Mboowa et al. [12] exclude wood from organic waste, and Joshi et al. [54] combine glass and metals, unlike other authors who separate organic waste from garden waste. MSW can also be classified based on its thermal degradation characteristics, according to Hoang et al. [62]. This system categorizes waste into food scraps, lignocellulosic materials, plastics, other combustibles, and incombustible materials. Notably, lignocellulosic

materials like paper, cardboard, wood, and textiles were grouped together due to their pyrolysis behavior, which closely resembles that of woody biomass. This highlights the potential of MSW as a viable source of lignocellulose for torrefaction.

Furthermore, the proportions of these various components within MSW can vary significantly depending on factors like collection methods, geographical location, and socioeconomic status of the population generating the waste [63]. For instance, high-income countries tend to generate more paper waste due to higher consumption levels, while low-income countries might have a higher proportion of food scraps. Understanding this variation is crucial for predicting the overall lignocellulosic content of MSW in a specific region and optimizing torrefaction processes accordingly.

Table 3 takes a closer look at the heart of the matter: the lignocellulosic composition of individual components found in MSW. A clear trend emerges in which cellulose content generally outweighs hemicellulose and lignin content across most waste streams. This is significant because cellulose boasts a high concentration of carbon, making it a valuable contributor to the overall energy potential of biomass [63]. Wastes with higher cellulose content are likely to decompose more significantly during torrefaction, leading to a lower yield of solid residue and a greater production of volatile and gaseous products [65]. Interestingly, some researchers like Sukiran et al. [38] propose that wastes with higher lignin content might be more suitable for torrefaction due to the possibility of a higher solid yield after the process. Lignocellulose, the key component targeted for torrefaction in MSW, is a complex structure composed of three main elements: cellulose, hemicellulose, and lignin.

2.1.1. Cellulose. Cellulose, as described by Acharya et al. [63], is a linear chain of D-glucose units linked by beta-1,4

TABLE 3: The lignocellulosic composition (%) of various biomass and MSW samples.

Waste sample	Cellulose	Hemicellulose	Lignin	Extractives/others	Ash	Ref
MSW (newspaper, kraft paper, high-grade paper, other paper, mixed/low-grade paper, compostable/soiled paper, leaves and grass, food waste, and other organics)	51.2	11.9	15.2	—	—	[17]
Lignocellulosic MSW (office paper, newspaper, cardboard)	70.1	12.0	14.2	—	6.0	[64]
MSW	27.8 ± 0.1	15.45 ± 0.07	17.17 ± 0.05	17.1 ± 0.3	—	[15]
Organic MSW (starchy kitchen, garden, food wastes, paper, and newspaper)	27.5 ± 1.3	9.3 ± 0.6	41.1 ± 3.2	16.1 ± 1.0	3.2 ± 0.9	[16]
Leaves and grass	15.3–42.6	10.2–29.7	7.6–43.8	—	—	[17, 65, 66, 67]
Food waste	55.4	7.2	11.4	—	—	[17]
Waste paper	35.62–48.5	9.0–14.2	16.9–23.9	1.4–4.85	1.4	[16, 17, 68]
Garden waste	46.1–51.6	11.2–16.5	27.7–39.7	3.5–19.57	1.0	[16, 66, 67, 68]
Cassava rhizome	44.41	25.18	25.26	—	—	[41]
Coconut husk	26.27	26.00	43.34	—	—	[41]
Rice husk	28.50–41.6	25.49–32	12.5–25.68	—	—	[41, 68]
Corn cobs	37.27–45	35–36.32	15–23.35	—	—	[41, 68]
Groundnut shells	49	21	19	—	—	[68]
Reed canary grass	42.6	29.7	7.6	—	—	[68]
Wheat straw	41.3	30.8	7.7	—	—	[65]
Willow	49.3	14.1	20.0	—	—	[65]
Bagasse	23.03	18.81	11.23	—	—	[69]

glycosidic bonds. This structure creates crystalline microfibrils that are highly ordered and compact. These crystalline regions are responsible for cellulose's strength and resistance to enzymatic breakdown [43, 62]. However, cellulose also contains amorphous regions that are more readily hydrolyzed. The ratio of crystalline to amorphous cellulose can impact the overall digestibility of lignocellulosic biomass [38].

2.1.2. Hemicellulose. Hemicellulose, unlike cellulose, consists of shorter, branched chains of various sugars [43, 62]. The primary sugars include xylose, mannose, and arabinose, but other sugars can also be present depending on the plant source [63]. Hemicellulose acts as a bridge, connecting cellulose microfibrils with lignin. Compared to cellulose, hemicellulose is more susceptible to degradation due to its less complex structure [43].

2.1.3. Lignin. Lignin is an amorphous biopolymer with a complex structure. It is composed of various phenylpropanoid units, with the specific type depending on the plant species [38]. Lignin acts as a "glue," binding cellulose and hemicellulose together, providing structural rigidity to the plant cell wall [63]. This complex structure also makes lignin highly resistant to degradation, hindering the accessibility of enzymes and other agents to cellulose and hemicellulose [43, 62].

As shown in Table 3, the proportions of cellulose, hemicellulose, and lignin vary across different components of MSW. This variation likely reflects the diverse nature of the waste stream. Importantly, the overall lignocellulosic content of MSW falls within a similar range as that of individual waste components like leaves, food waste, paper, and

garden trimmings, all of which are considered suitable feedstocks for torrefaction. Therefore, based on their lignocellulosic composition, MSW holds promise as a viable source for torrefaction, regardless of its specific composition. The dominant type of waste within the MSW mix might also significantly influence the overall lignocellulosic content. Further research is needed to explore this aspect in more detail.

2.2. Physiochemical Analysis. Understanding the properties of MSW is crucial for optimizing the torrefaction process. Two key analyses, proximate and ultimate analyses, provide valuable insights into the composition and energy potential of the waste stream.

2.2.1. Proximate Analysis. Proximate analysis is a crucial tool for understanding how MSW behaves during torrefaction. This analysis focuses on four key components that significantly influence the process. MC plays a vital role. High MC necessitates additional energy input for drying the waste before torrefaction, reducing overall efficiency. Fortunately, most MSW compositions typically have an MC below 20%, with the exception of food waste rich in organics [70]. Pre-treatment strategies like drying or mechanical sorting to remove food waste with high MC can be employed to optimize the process [38].

Another key component is volatile matter (VM). VM represents the portion of the biomass that readily decomposes and releases gases during heating. A high VM content indicates a material that ignites easily, potentially making it a good candidate for torrefaction. However, excessively high VM content could lead to a lower yield of the desired product, biochar [31]. Finding the optimal balance between VM

TABLE 4: The proximate analysis, ultimate analysis, and higher heating values results of various biomass and MSW compositions before torrefaction.

Sample	Proximate analysis				Ultimate analysis						HHV (MJ/kg)	Ref
	MC	VM (%)	Ash (%)	FC (%)	C (%)	H (%)	O (%)	N (%)	S (%)	Cl (%)		
MSW (biodegradables, textile, nylon plastic bags, paper, PET bottles)	3.3	79.7	9.1	7.2	63.6	8.1	27.1	0.4	0.11	—	15.978	[20]
MSW (food waste, saw dust)	—	68.54	20.42	11.04	40.56	5.62	28.01	3.66	0.27	1.46	17.525	[74]
Organic, papers, plastics, textiles, glass, ashes, metals	—	—	—	—	56.20	5.42	35.49	2.42	0.31	0.05	—	[51]
MSW (paper, sawdust, yard wastes, plastics)	5.51	76.23	3.39	14.87	44.48	5.67	49.83	—	—	—	16.42	[75]
MSW (biodegradable, nylon plastic bags, textile, PET bottles, and paper)	3.3	79.7	9.1	7.2	63.6	8.19	27.0	0.4	0.1	—	15.978	[76]
Food waste	11.95	81.00	3.28	3.77	44.61	7.34	44.16	3.48	0.40	—	19.67	[77]
Food waste (vegetables, grains, and meats)	79	18.7	2.3	—	47.57	6.76	36.19	2.61	0.01	0.88	19.52	[70]
Municipal lignocellulosic waste (mango tree, <i>ficus</i> , <i>cambuí</i> , <i>avocado</i> , <i>angico</i> , <i>pombeiro</i>)	10	77.61	4.49	17.61	44.91	7.25	47.84	0.64	—	—	19.32	[78]
MSW (food and yard waste, papers, plastics, polyethylene, water bottles, textiles, glass, metals, and others)	8.69	73.30	13.65	3.22	—	—	—	—	—	—	19.26	[55]
Rice husk	—	62.83	9.57	27.60	45.87	5.87	38.00	0.56	0.14	—	18.78	
Coconut husk	—	61.78	7.70	31.52	49.03	5.37	38.36	0.41	0.13	—	19.33	[41]
Cassava rhizome	—	71.92	4.95	23.13	45.14	5.82	43.12	0.84	0.13	—	18.04	
Corncob	—	76.04	2.01	21.95	46.74	6.04	44.23	0.84	0.15	—	18.80	

content and biochar yield is crucial for maximizing the benefits of torrefaction for a specific MSW composition.

Fixed carbon (FC) is the remaining solid material after the VM is driven off during torrefaction. It contributes to the final yield of biochar, a valuable product with potential applications in soil amendment, wastewater treatment, and even carbon sequestration. MSW with a higher proportion of woody components generally exhibits a higher FC content [31]. Understanding the FC content allows researchers to predict the biochar yield and tailor the torrefaction process to maximize it.

The final component analyzed is ash content. Ash is the inorganic material remaining after complete combustion [71]. Lower ash content translates to less residual waste after the biomass is used as fuel and reduces the need for disposal of postcombustion residues [72]. Additionally, high ash content can negatively impact the quality of biochar by reducing its surface area and porosity, thereby hindering its effectiveness in applications like soil amendment [73].

2.2.2. Ultimate Analysis. In addition to proximate analysis, ultimate analysis provides valuable insights into the elemental makeup of MSW, shedding light on how these elements influence the torrefaction process. Unlike proximate analysis, which focuses on overall fractions like VM and FC, ultimate analysis delves deeper, identifying the specific elements present in the waste stream [8]. These elements include carbon (C), hydrogen (H), nitrogen (N), oxygen (O), and sulfur (S).

Each of these elements plays a distinct role in influencing the torrefaction process and the properties of the final product.

Carbon (C) emerges as the champion of energy potential. It is the primary contributor to the heating value of biomass [38]. As evident in Table 4, carbon is consistently the dominant element in most MSW samples, highlighting its promise as a source of renewable energy. However, the presence of oxygen can act as a deterrent, slightly reducing the overall heating value [79, 80]. Fortunately, torrefaction offers a solution. By driving off some of the oxygen while concentrating the carbon content, torrefaction effectively increases the energy density of the final product [8].

While present in MSW, hydrogen (H) plays a less significant role in terms of heating value compared to carbon [38]. However, its influence should not be entirely disregarded. Hydrogen content can impact the overall efficiency of the torrefaction process itself. The potential downside of nitrogen (N) lies in its contribution to the formation of nitrogen oxides (NO_x) during the combustion of the torrefied product [8]. Fortunately, optimizing torrefaction conditions, particularly temperature can help minimize NO_x formation. Interestingly, the nitrogen content in the biochar might even prove beneficial for certain agricultural applications.

Just like carbon, the influence of oxygen (O) depends on its relative quantity within the specific MSW composition [75, 78]. A higher oxygen content can slightly reduce the overall heating value of the biomass [31]. Similar to carbon, torrefaction offers a solution by helping to reduce the oxygen

content, thereby increasing the energy density of the biochar [8]. Typically present in low concentrations within MSW, sulfur (S) can contribute to air pollution issues like SO_x formation during combustion [8]. While generally not a major concern due to its low concentration, excessively high sulfur levels might necessitate additional flue gas cleaning steps after the combustion of the torrefied MSW.

Understanding the interplay between these elements is crucial for optimizing torrefaction conditions and predicting the properties of the final product. For instance, a higher carbon content with lower oxygen content suggests a potentially higher energy output from the torrefied MSW. By employing ultimate analysis alongside proximate analysis, researchers and engineers gain a comprehensive understanding of the MSW composition, allowing them to tailor the torrefaction process for maximum efficiency and desired product characteristics.

2.2.3. Calorific Value. Calorific value refers to the amount of heat released during the complete combustion of a fuel. It is recorded as a higher heating value (HHV) if it includes the latent heat of vaporization of water and a lower heating value (LHV) or net calorific value if it excludes it [8]. The HHV of MSW typically ranges from 13.0 to 20.0 MJ/kg, which is generally lower than that of coal [31]. This can be attributed to the higher oxygen content in biomass compared to coal. Torrefaction offers a promising approach to improve the calorific value of MSW, making it a more viable substitute for coal or enabling co-firing with coal. Interestingly, MSW compositions with food waste tend to have a higher HHV compared to those without it. Conversely, studies suggest that the presence of plastics in MSW can lower the HHV, with the exception of Mboowa et al. [55]. This highlights the importance of understanding the specific composition of the waste stream to predict its energy potential.

2.3. Lignocellulosic Composition and Biomass Properties. The composition of lignocellulose, a complex carbohydrate structure found in plant cell walls, significantly influences the properties of biomass used in WtE processes. This section explores the relationship between lignocellulose content and key biomass properties analyzed through proximate and ultimate analyses. Understanding the interplay between lignocellulose composition and biomass properties is crucial for optimizing torrefaction processes. While studies suggest some general trends, the specific influence of lignocellulose content can be complex and requires a holistic approach. Further research is needed to untangle these relationships and guide the selection and processing of biomass feedstocks for optimal energy production.

2.3.1. Influence of Lignocellulosic Composition on Proximate Analysis. Studies, like one by Nakason et al. [41], suggest a positive correlation between lignin content and FC content. Their research found higher FC percentages in materials with higher lignin content (e.g., coconut husks vs. corn cobs). FC translates to the final yield of biochar, a valuable product from torrefaction. Conversely, the holocellulose content (cellulose and hemicellulose) appears to influence

VM content. Nakason et al. [41] observed an increase in VM with increasing holocellulose content (corn cobs vs. rice husks). VM represents the portion of biomass that readily decomposes and releases gases during heating, potentially making it a good candidate for torrefaction.

The relationship between lignocellulose content and ash content seems less straightforward. Nakason et al. [41] observed that rice husks, with the lowest lignocellulose content, had the highest ash content. This suggests that factors beyond lignocellulose, such as inorganic material content, can significantly impact ash content. However, Yuan et al. [64] reported conflicting results. Their study showed high lignocellulosic content (96.3%) alongside high ash content (20.42%). This discrepancy highlights the importance of considering the specific type of biomass and the methodology used for analysis. Nakason et al. [41] employed the NREL/TP-510-42618 standard analysis method, while Yuan et al. [64] utilized a fiber analyzer.

2.3.2. Influence of Lignocellulose Content on Ultimate Analysis. The influence of lignocellulose content on ultimate analysis (elemental composition) appears even more intricate. Nakason et al. [41] observed that corn cobs, with the highest holocellulose content, had higher percentages of hydrogen, nitrogen, sulfur, and oxygen compared to coconut husks with lower holocellulose content. However, Yuan et al. [64] reported differing results, suggesting minimal influence of holocellulose content on ultimate analysis. These contrasting findings warrant further investigation. The type of biomass, pretreatment methods, and analytical techniques employed can all influence the observed relationships.

3. WtE Technologies

The ever-increasing volume and complex composition of MSW pose significant challenges for modern waste management systems. WtE technologies have emerged as a promising solution, offering a way to convert waste into usable energy forms like electricity, heat, or fuels [61]. This not only reduces our reliance on traditional energy sources like wood but also promotes a more sustainable waste management approach by diverting waste from landfills [55]. However, selecting the most appropriate WtE technology for a developing country requires careful consideration of several factors. WtE technologies can be classified based on thermochemical, physical, chemical, biological, or biochemical processes, as depicted in Figure 2 [29, 81]. Farooq et al. [82] proposed a framework that considers six key aspects to guide policymakers in this process: environmental performance, waste characteristics, cost considerations, conversion efficiency and complexity, skilled workforce, and geographical location. Several WtE technologies exist, each with its own advantages and limitations [83]. Here, we explore some of the most common methods and compared with torrefaction as the key player (Table 5).

3.1. Biochemical Conversion Technologies. Biomass holds immense potential as a renewable resource, but unlocking its value requires innovative conversion technologies.

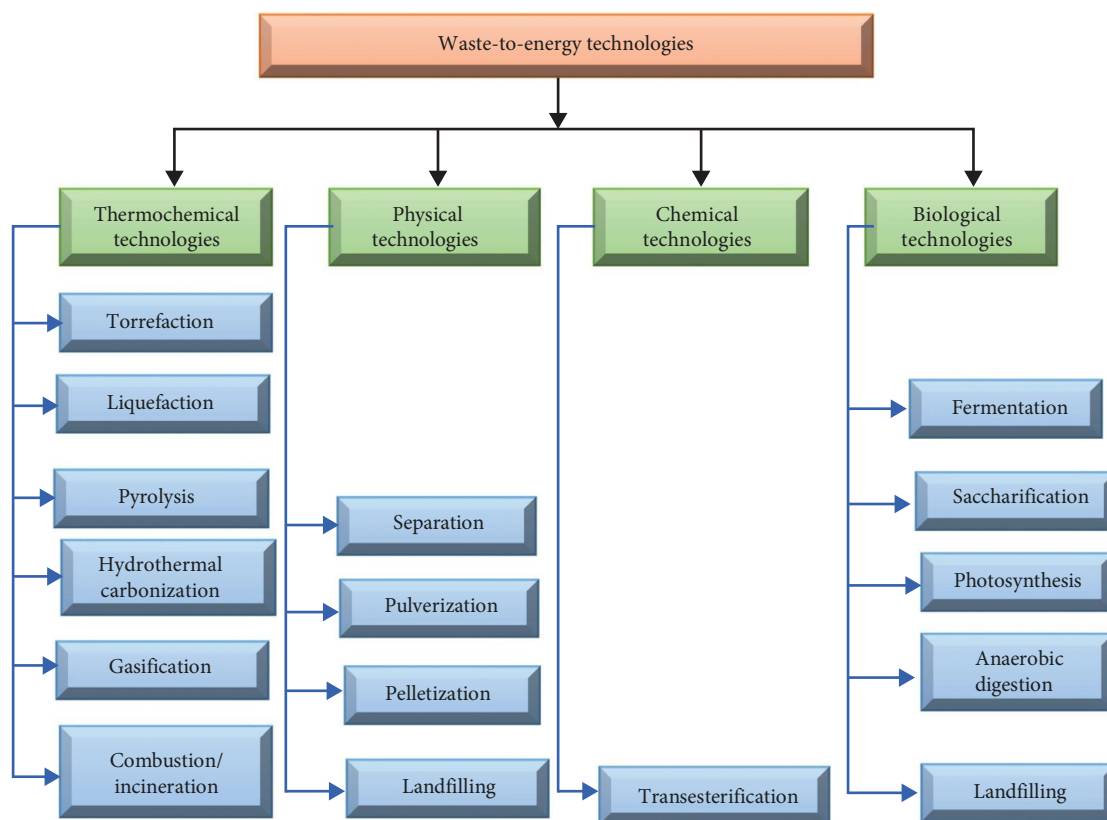


FIGURE 2: Classification of waste-to-energy technologies.

Biochemical conversion offers a gentler approach compared to high-temperature methods [84]. Here, living organisms or their enzymes act as tiny decomposers, breaking down complex organic materials in biomass through fermentation or anaerobic digestion (AD) [81]. This versatile process can yield a variety of products depending on the chosen method and feedstock. Biofuels like ethanol and biogas, valuable biochemicals for industrial applications, and even nutrient-rich compost for soil amendment are all possible outputs [87]. This approach not only creates usable products but also diverts waste from landfills, making it a sustainable and environmentally friendly solution. Research by Güleç et al. [88] emphasizes the importance of understanding how different conversion technologies interact with various biomass feedstocks. Their work highlights the need to optimize these interactions to unlock the full potential of biomass resources for bioenergy applications, paving the way for a more sustainable future.

3.1.1. Anaerobic Digestion. AD or bio-methanation, a process that breaks down organic waste materials anaerobically (without oxygen), offers a promising approach for generating renewable energy [89, 90]. This process yields biogas, a valuable fuel source primarily composed of methane and carbon dioxide. Biogas can be used for cooking, lighting, or even power generation in biogas plants. However, challenges such as poor maintenance and limited technical support can hinder the effectiveness of this technology [83, 87].

AD, the underlying mechanism behind bio-methanation, is a natural process that utilizes microorganisms to convert biomass into biogas and digestate under oxygen-free conditions. It presents an efficient and environmentally friendly way to convert organic waste into valuable resources [86]. Organic materials fed into a digester are broken down by microorganisms, producing biogas (a mixture of methane and carbon dioxide) and digestate (a nutrient-rich byproduct). Biogas can be utilized for electricity and heat generation or even as a transportation fuel, while the digestate finds application as a fertilizer or soil amendment [86].

While naturally occurring in various environments, commercially producing biogas in a digester involves controlled design and technical procedures. Even though AD has been a mainstay for decades, its appeal as a sustainable and environmentally friendly alternative to fossil fuel-based energy generation persists [90].

One promising avenue for expansion is generating biogas from lignocellulosic substrates (plant materials rich in cellulose, lignin, and hemicellulose). This approach offers the potential to transform significant biomass resources into sustainable energy sources. However, efficiently utilizing lignocellulosic biomass for biogas production through AD remains a challenge due to the complex and resistant nature of this feedstock [91]. In conclusion, bio-methanation, or AD, presents a versatile and environmentally friendly technology for converting organic waste into valuable biofuels and soil amendments. Despite some technical hurdles associated with lignocellulosic substrates, continued

TABLE 5: Comparison of torrefaction to other WTE technologies [84, 85, 86].

Feature	Torrefaction	Incineration/ combustion	Gasification	Pyrolysis	Anaerobic digestion	Hydrothermal liquefaction	Hydrothermal carbonization	Fermentation
Process	Thermochemical (low oxygen)	Thermochemical (high oxygen)	Thermochemical (limited oxygen)	Thermochemical (limited oxygen)	Biochemical	Thermochemical (water + pressure)	Thermochemical (water + pressure)	Biochemical (microorganism)
Operating temperature (°C)	200–300	800–1,200	700–1,500	300–700	30–60	250–400	180–250	30–40
Main purpose	Preprocessing for other WTE	Direct energy generation	Syngas production	Bio-oil, charcoal, or fuel production	Biogas production	Bio-oil production	Hydrochar production	Biofuel (ethanol, etc.)
Energy output	Indirect (improves the efficiency of other WTE)	Direct (heat, electricity)	Direct (syngas for various applications)	Indirect (bio-oil or upgraded fuel)	Direct (biogas for cooking, heating)	Direct (liquid fuels)	Indirect (potential for future energy use)	Direct (liquid fuels)
Feedstock	Wide variety	Wide variety	Wide variety	Wide variety	Organic matter (wet)	Wet biomass	Wet biomass	Sugars, starches, cellulose
Emissions	Relatively low	High (requires emission control)	Moderate (syngas composition dependent)	Moderate (depends on pyrolysis type)	Low	Moderate (requires treatment of wastewater)	Low	Low
Advantages	Improve fuel properties and reduces emissions in the next processes	Simple technology, high energy recovery	Versatile product (syngas)	Bio-oil and charcoal production, some fuel flexibility	Renewable energy sources	Production of liquid fuels	Production of hydrochar for soil amendment	Renewable fuel source
Disadvantages	Requires additional processing step, no direct energy output	High cost, potential air pollution	Requires complex technologies; syngas gas cleaning is needed	Requires specific product offtake market	Limited feedstock suitability	Requires complex technology, wastewater treatment	Limited product type (hydrochar)	Limited feedstock type, slow process
Compatibility with torrefaction	Not applicable	Torrefied biomass can improve efficiency	Torrefied biomass improves syngas yield and quality	Torrefied biomass can be used as feedstock	Byproducts from wet torrefaction can be suitable	Torrefied biomass may be suitable feedstock (research needed)	Torrefied biomass may be suitable feedstock (research needed)	Not compatible

research and development hold promise for unlocking the full potential of this renewable energy source.

3.1.2. Fermentation. Fermentation emerges as a biological process that harnesses the power of microorganisms, particularly enzymes, to convert sugars or starch-rich biomass into valuable biofuels like ethanol [17, 92]. Unlike combustion, which directly burns biomass for energy, fermentation thrives in an oxygen-limited (anaerobic) environment. Here, yeast breaks down sugars through a process called glycolysis, producing ethanol and cellular energy. This biofuel production method offers a promising renewable alternative to fossil fuels. Recent research suggests that fermentation has the potential to be even more efficient. Organic matter, including various waste materials and effluents, could be converted into diverse bioenergy forms using microbial cultures under mild conditions [93, 94].

The bioconversion of biomass to biofuel through fermentation typically involves a sequence of stages: pretreatment, hydrolysis (using acid or enzymes), and finally, fermentation itself [81]. However, fermentation itself can be categorized into different modes, each with its own properties. One such mode is photofermentation, which utilizes photosynthetic bacteria to convert organic substrates into biohydrogen through a series of biochemical reactions. The key difference between photofermentation and dark fermentation is the presence of light [95]. Photofermentation occurs in the presence of light, while dark fermentation occurs in its absence [81].

Another widely used process is alcoholic fermentation, where yeast takes center stage. Here, sugars are converted into cellular energy, along with the production of ethanol and carbon dioxide. Since it occurs without oxygen, alcoholic fermentation is considered an anaerobic process [81]. Finally, lipid fermentation offers another approach. Heterotrophic algae or yeast can be used in this process to convert sugars into lipids within their cells. These lipids can then be extracted using suitable solvents [81]. By harnessing the power of microbes in various forms, fermentation offers a versatile and sustainable approach to biofuel production. The ability to utilize various feedstocks, including waste materials, makes it an attractive technology for a circular bioeconomy.

3.2. Thermochemical Conversion Technologies. Thermochemical conversion technologies utilize heat, and sometimes pressure, to break down biomass and convert it into usable fuels and products. This breakdown occurs through chemical reactions driven by the high temperatures [47]. In contrast to biochemical conversion (which relies on living organisms), thermochemical processes offer a wider range of conversion pathways depending on the specific technology and the desired end product [96]. Some common thermochemical technologies include incineration (generating heat and electricity directly from combustion), gasification (converting biomass into a combustible gas called syngas), pyrolysis (producing bio-oil, charcoal, or a combination through thermal decomposition), and torrefaction (pretreating biomass to improve its properties for further processing or direct use as a fuel) [97]. The choice of thermochemical technology depends on various factors like the desired product, the characteristics of the biomass feedstock, and

economic considerations. While these technologies offer efficient conversion of biomass into valuable resources, careful attention needs to be paid to potential environmental impacts like gas emissions [98]. Strict emission control measures are crucial to ensure the sustainable implementation of thermochemical conversion processes. Depending on the applied technology and the production process, the char product can be categorized into three classes: biochar, hydrochar, and char-coal [99].

3.2.1. Torrefaction. Torrefaction is a thermochemical process that transforms biomass into a more usable fuel source [100]. Unlike combustion, which directly generates energy by burning biomass, torrefaction modifies the biomass properties at relatively low temperatures (typically below 300°C) in an oxygen-limited environment [101]. The torrefaction (also known as biomass “roasting”) is considered a pretreatment method for other conversion techniques [102]. This pretreatment process enhances the suitability of biomass for further processing or even direct use as a fuel. The benefits of torrefaction are multifold. First, it increases the energy density of the biomass. By removing moisture and some volatile compounds, torrefaction results in a product with a higher energy content compared to raw biomass [5]. This translates to easier transportation, storage, and potentially more efficient energy conversion in subsequent processes. Second, torrefaction improves the grindability of biomass. The process makes the material more brittle and easier to grind into a uniform powder, facilitating its use in applications like co-firing in coal power plants. Finally, torrefaction reduces smoke and emissions. The removal of volatile components during torrefaction minimizes smoke and harmful emissions during combustion. This makes torrefied biomass a potentially cleaner alternative to directly incinerating raw biomass.

The torrefaction process yields several products. The primary product is torrefied biomass, a dried solid material that constitutes roughly 70% of the original biomass weight [31, 103]. Torrefied biomass boasts improved fuel characteristics, including better ignition and higher hydrophobicity (resistance to water). Additionally, its enhanced resistance to fungal attacks improves storage stability [5, 8]. The remaining 30% of the biomass is converted into various byproducts during torrefaction. These byproducts can be categorized into two main groups: torrefied gas and condensable liquids. Torrefied gas contains about 10% of the initial biomass energy and comprises components like hydrogen (H₂), carbon monoxide (CO), methane (CH₄), and carbon dioxide (CO₂) [24]. Water, acetic acid, alcohols, aldehydes, ketones, furfural, and other mono-aromatic compounds are some of the condensable liquids produced during torrefaction [24].

These byproducts are not simply waste products but rather potential resources waiting to be tapped. The captured gases, with their inherent energy content, could be utilized for various purposes within the energy sector, potentially for electricity generation or heat production. The condensable liquids, containing a complex mix of organic compounds, offer exciting possibilities for further processing into valuable chemicals or biofuels [96]. This ability to not only transform

biomass into a superior fuel source but also generate usable byproducts is a major advantage of torrefaction. Furthermore, research has shown that the thermochemical torrefaction process can generate chars with combustion properties similar to various ranks of coal [104]. This opens doors to using waste materials like MSW as fuel. By converting MSW into a coal-like char through torrefaction, we can potentially address the practical challenges of utilizing waste materials as a sustainable fuel source and reducing our reliance on traditional fossil fuels.

3.2.2. Hydrothermal Liquefaction. Hydrothermal liquefaction (HTL) emerges as a promising technology for transforming biomass into valuable products like biofuels, chemicals, and fertilizers. Unlike other thermochemical conversion processes, HTL thrives on wet biomass, eliminating the need for a costly drying step beforehand. This makes it suitable for processing a wider range of feedstocks, including algae, municipal sludge, lignocellulose, and even the organic fraction of MSW [105, 106]. The HTL process operates under high temperatures (200–374°C) and pressures (15–220 bar) in the presence of a catalyst. This pressurized hot water environment causes the biomass to break down into a liquid bio-oil, the primary product of HTL [86]. Other products include a solid residue, an aqueous phase containing dissolved organic materials, and a gas phase containing gases like hydrogen, carbon dioxide, carbon monoxide, and methane [107].

Compared to other rapid biomass treatment methods like hydrothermal carbonization (HTC), HTL operates at slightly higher temperatures. HTC typically occurs between 180 and 250°C and mainly converts biomass into biochar at the expense of bio-oil production [107]. HTC does, however, generate some bio-oil and biogas as secondary products. Overall, HTL offers a versatile approach for biomass conversion. It utilizes water as the reaction medium and efficiently converts wet biomass into valuable bio-crude oil, a potential replacement for conventional crude oil [105]. Bio-crude derived from HTL requires minimal upgrading due to its favorable properties like low oxygen content, high hydrocarbon yield, good energy density, and improved flowability compared to bio-oil obtained through pyrolysis [97].

3.2.3. Hydrothermal Carbonization. HTC offers a revolutionary approach for converting wet biomass into valuable products. Unlike traditional pyrolysis methods that require dry feedstock, HTC thrives on wet materials, making it ideal for processing sewage sludge, animal waste, and compost. The process unfolds within a closed reactor where biomass mingles with water. This wet pyrolysis typically occurs at moderate temperatures ranging from 180 to 250°C [108]. Here, water plays a starring role, acting as a key reactant. Temperature plays a critical role in HTC. At subcritical temperatures, water facilitates ionic reactions. However, as temperatures rise beyond the critical point, free radical reactions dominate [108]. Residence time, the duration the biomass spends in the reactor, also significantly impacts the process. Extended residence times tend to reduce the yield of solid products [109].

The magic of HTC lies in its ability to transform biomass into a product known as hydrochar. Hydrochar boasts a high carbon content and calorific value, making it a potential fuel source. The process also yields a significant amount of bio-oil in the form of an aqueous solution with minimal gas production [110]. HTC boasts several advantages over traditional methods like torrefaction or pyrolysis for biochar production. The process significantly reduces the oxygen-to-carbon ratio (O/C) in the final product, translating to an increased calorific value. Additionally, HTC-derived biochar exhibits superior grindability and hydrophobicity (water repellency) characteristics [111].

These improved properties make HTC-derived biochar highly sought-after for various applications, including soil amendment. Biochar's ability to retain nutrients like nitrogen and phosphorus makes it a valuable soil conditioner, promoting fertility [112]. The high calorific value of hydrochar also opens doors for its potential use as a renewable fuel source. In general, HTC emerges as a transformative technology for managing wet biomass waste and unlocking valuable products like biochar and bio-oil [14]. By harnessing the power of water and controlled temperature, HTC offers a sustainable solution for waste conversion and resource recovery.

3.2.4. Incineration/Combustion. Incineration, the burning of waste at high temperatures, presents a complex solution for waste management, particularly in developed countries. While it offers attractive benefits like waste reduction and energy generation through processes that capture heat for electricity production [113], widespread adoption faces challenges. The high cost of constructing incinerator facilities and potential competition with recycling initiatives limit its feasibility in many regions [61]. Additionally, strict regulations are necessary to control air emissions and minimize environmental impact on surrounding communities [114].

Biomass combustion, on the other hand, is one of the most traditional methods for converting biomass into energy. It involves burning biomass in a boiler or furnace to generate heat for steam or electricity production [86]. The specific combustion process depends on the chemical makeup of the raw material, as differences in heating value and composition exist across various biomass sources [86]. The process typically follows four stages: drying, pyrolysis, reduction, and finally, the combustion of volatile gases and solid char [86]. Fluidized-bed combustion chambers and grate heating systems, both offering high fuel flexibility, are the two most common boiler designs employed. Fundamentally, a furnace serves as the core component where biomass undergoes combustion [86].

While incineration and biomass combustion share similarities in utilizing combustion processes, key differences exist. Incineration is an exothermic process involving complete oxidation of MSW that generates flue gas, ash, and heat [85]. Air pollution control systems are crucial to ensure emissions like NO_x, dioxins, and sulfur dioxide stay below-regulated limits to minimize environmental impact [85].

Incineration offers several advantages: it recovers energy through burning waste, significantly reduces solid waste



FIGURE 3: Torrefaction phases for municipal solid wastes (MSWs).

volume (up to 90%), and diverts waste from landfills, reducing the need for landfill space. However, drawbacks also exist: the high cost of air pollution control systems, stringent permit requirements in some regions, and the potential need for feedstock predrying if MC is high can all hinder wider adoption. Additionally, leftover ash from incineration often contains leachable pollutants requiring proper disposal, frequently through landfilling, which can create its own set of environmental concerns [85].

The current trend leans toward upgrading MSW feedstock through energy densification pretreatment steps before incineration [85]. This approach aims to improve overall efficiency and environmental impact by altering the fuel source entering the incineration process. In summary, both incineration and biomass combustion offer methods for waste management and energy generation. However, careful consideration of economic feasibility, environmental impact, and technological advancements is crucial when selecting the most suitable approach for a specific region. Factors such as existing infrastructure, waste composition, and regulatory environment will all play a role in determining the optimal waste management strategy.

3.2.5. Pyrolysis. Pyrolysis offers a revolutionary approach to unlocking the potential of biomass. This thermochemical process utilizes limited oxygen and temperatures ranging from 300 to 700°C to convert biomass into a diverse range of valuable products [115, 116]. The specific outcome, including bio-oil (fast pyrolysis) or charcoal (slow pyrolysis), depends on the chosen process parameters, such as temperature, pressure, and duration [117]. The process itself yields a fascinating array of products. Gaseous substances, often referred to as syngas, hold promise as a fuel source. A liquid byproduct known as tar can be further refined or utilized for various applications. Char, a solid residue, represents a concentrated form of the original biomass. Finally, ash, an unwanted residue with minimal value, requires proper disposal [118].

However, pyrolysis is not a monolithic process. Several key factors influence its categorization. Heating rate and residence time distinguish fast pyrolysis, which emphasizes rapid heating and conversion, from slow pyrolysis, also known as carbonization, which prioritizes a slower process for maximizing char yield [119, 120]. Depending on the chosen reactor setup, pyrolysis can be categorized as catalytic pyrolysis, which utilizes catalysts to enhance specific product yields, or microwave pyrolysis, which leverages microwave radiation for a more efficient heating process [3, 14]. The specific temperature range employed during pyrolysis plays a crucial role in determining the ultimate product distribution.

Further exploration reveals interesting variations within slow pyrolysis itself. While slow pyrolysis, often referred to as carbonization, primarily uses dry biomass feedstock to

produce biochar, a specific variation exists for processing wet materials [119, 120]. HTC utilizes similar principles but operates in a water-based environment, converting extremely wet biomass into a product known as hydrochar [121, 122, 123, 124]. It is crucial to differentiate between biochar and torrefied biomass, although both products are derived from thermochemical processes. Torrefaction acts as a pretreatment step for pyrolysis. Torrefied biomass retains some of the volatile organic compounds present in the original biomass, resulting in physiochemical properties that fall between those of raw biomass and biochar [125]. Biochar, on the other hand, is a solid product arising from the complete carbonization of biomass in a limited oxygen environment. Interestingly, biochar can also be produced through traditional pyrolysis (fast or slow) or even torrefaction [126].

By understanding the nuances of pyrolysis and its various products, we unlock its potential for sustainable waste management, energy generation, and soil improvement. Various processes can achieve this transformation, including pyrolysis (both fast and slow variants), torrefaction, and HTC [127]. From bio-oil and syngas as fuel sources to biochar for soil enhancement, pyrolysis offers a spectrum of possibilities for a more sustainable future.

3.2.6. Gasification. Gasification partially oxidizes carbonaceous materials like coal or biomass at high temperatures, producing a gaseous energy carrier called syngas [128]. Syngas, composed mainly of CO and H₂ (with a small proportion of CO₂ and CH₄), can be used for various energy applications [129, 130]. The gasification process occurs in two stages: initial devolatilization (or flash pyrolysis) and subsequent gasification reactions. In the initial devolatilization stage, the solid fuel is decomposed into solid carbon (char), H₂, CO, CO₂, CH₄, tars, and other complicated hydrocarbons [131]. In the subsequent gasification process, reactions occur between solid char and gases, and among gases, including the gasification agent [132]. The feedstocks for gasification include a wide range of carbonaceous materials, including raw biomass [133, 134], MSW [135, 136], torrefied biomass [137, 138], biochar [139], and more.

4. Torrefaction Process

The torrefaction process can be divided into distinct phases, according to Ribeiro et al. [5]. These phases include heating, drying, torrefaction, and cooling. However, the drying process is further divided into predrying and postdrying, making the torrefaction process comprise five phases in total [5], depicted in Figure 3.

The first phase is initial heating. During this stage, the biomass is dried due to moisture evaporation caused by the increase in feedstock temperature. The second phase is predrying. This is the most energy-intensive stage, where both

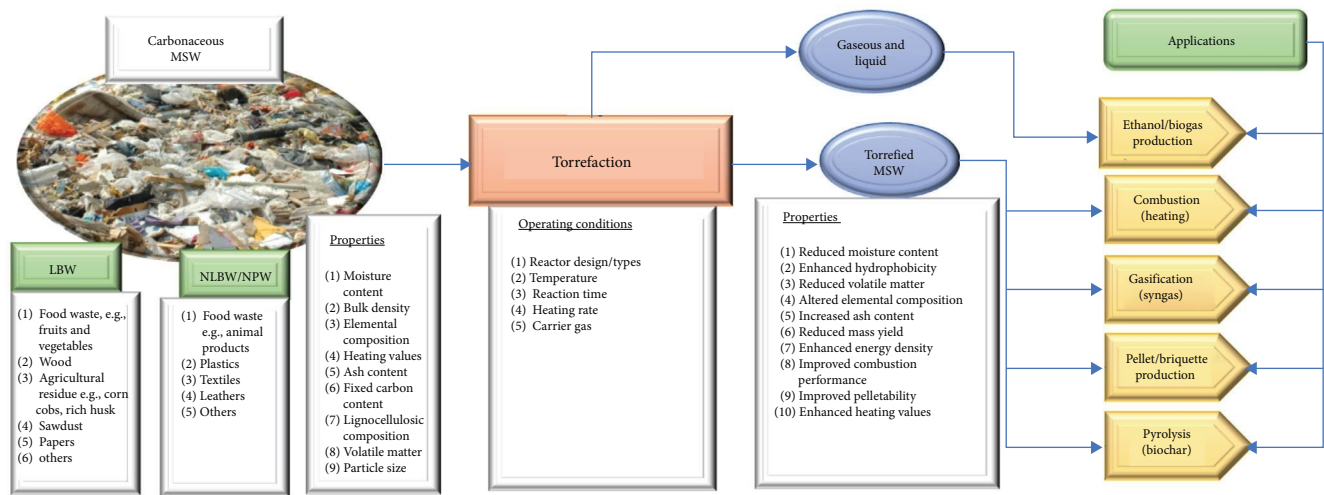


FIGURE 4: Torrefaction process of municipal solid waste. LBW, lignocellulosic biomass waste; NLBW, nonlignocellulosic biomass waste; NPW, nonplant waste; MSW, municipal solid waste.

free and bound water are removed from the biomass [11]. Free water evaporates at a constant rate in the predrying stage at a temperature of 100°C [5]. The third phase is post-drying and intermediate heating. Light fractions of biomass start evaporating at 200°C due to bound water release and mass loss [101]. The fourth phase is torrefaction. Beyond the temperatures used in the previous stages, torrefaction occurs. This leads to a major loss in biomass mass and ends after cooling to 200°C from a predetermined maximum temperature [27]. The fifth and final phase is cooling. The solid product, after torrefaction, is cooled to less than 200°C, typically down to ambient temperature. Figure 4 illustrates the torrefaction process of MSW and the potential applications of torrefied MSW and the byproducts. It shows the different categories of MSW and their properties and the torrefaction operating conditions.

4.1. Classification of Torrefaction. Biomass torrefaction methods vary based on the biomass type, nature, and intended use of the torrefied product [27, 118]. Traditionally, torrefaction is categorized as dry torrefaction and wet torrefaction (WT) [33], which are widely used for both lignocellulosic and nonlignocellulosic biomass feedstocks [27]. Recent research has further refined this classification to include additional processes such as super-heated steam torrefaction [21, 118], ionic-liquid-assisted torrefaction [27], and microwave-assisted torrefaction [24]. Further classification can be based on reactor types [21, 140], atmosphere [86, 141, 142], and feedstock moisture content [98, 143], as depicted in Figure 5. Table 6 summarizes the advantages and limitations of selected torrefaction types.

4.1.1. Dry Torrefaction. Dry torrefaction, typically applied to low-moisture biomass, involves thermal pretreatment at temperatures ranging between 200 and 300°C in a low-oxygen environment, resulting in a refined, uniform, and denser solid biomass product with increased heating value and energy density [27]. While traditional torrefaction occurred in an inert environment, oxidative torrefaction now employs gas

or liquid-phase environments to facilitate oxidative conditions [21, 27]. Carrier gases such as air, flue gas, or gases with varying oxygen concentrations are utilized, influencing the torrefaction rate [118].

Torrefaction can be further categorized into light, mild, and severe based on process temperatures [24, 27]. Light torrefaction ranges from 200 to 235°C, mild from 235 to 275°C, and severe from 275 to 300°C [1, 21, 27]. Dry torrefaction enhances solid product properties, improving combustion stability, efficiency, and gasification quality while reducing byproducts [33]. However, high-moisture feedstocks often require predrying, increasing energy consumption and operational costs. Torrefaction alters biomass composition, necessitating posttreatment for pellet production, which can be challenging and expensive [31, 33]. Additionally, torrefaction increases ash content, exacerbating ash-related issues during combustion [9, 27, 31, 33].

4.1.2. Wet Torrefaction. WT, or HTC, is suitable for high-moisture biomass like animal manure or municipal waste [21, 33]. Operating under compressed hot water between 180 and 260°C, WT produces a solid product called hydrochar along with gas and liquid byproducts [24, 31, 33]. Although WT shares similarities with HTC, differences exist in temperature and pressure ranges [144]. Hydrochar, rich in carbon and lignite-like properties, finds applications in various fields [145]. WT reduces ash content, enhances fuel properties, and saves energy by eliminating predrying requirements [21, 31, 33, 146]. However, WT presents challenges such as equipment corrosion, clogging, and wastewater treatment, impacting operational costs and environmental concerns [7, 118]. Despite these drawbacks, WT offers comparable fuel improvements to dry torrefaction at lower temperatures [21, 33]. In addition, hydrothermal pretreatment that employs high temperatures and pressures is gaining momentum for organics recovery from lignocellulosic biomass, which can attain value-addition. Diverse bioprocesses, such as dark fermentation, AD, etc., can

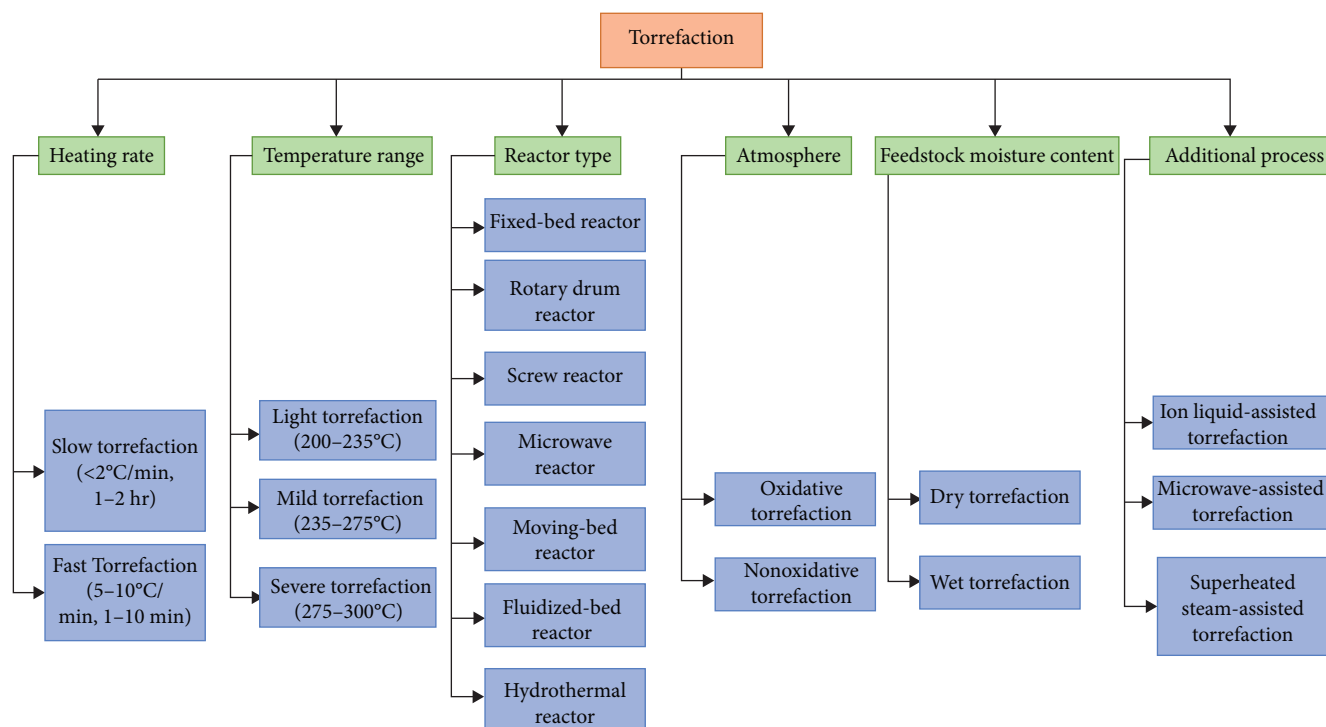


FIGURE 5: Classification of torrefaction methods.

TABLE 6: Advantages and limitations for different torrefaction types.

Torrefaction type	Advantages	Limitation
Dry torrefaction	<ul style="list-style-type: none"> (i) Increases heating value and energy density of biomass (ii) Enhances combustion stability and gasification quality (iii) Reduces byproducts 	<ul style="list-style-type: none"> (i) Requires predrying for high-moisture feedstocks (ii) Increases ash content, leading to ash-related issues during combustion
Wet torrefaction	<ul style="list-style-type: none"> (i) Eliminates predrying requirements, saving energy (ii) Reduces ash content and improves fuel properties (iii) Offers comparable fuel improvements to dry torrefaction 	<ul style="list-style-type: none"> (i) Equipment corrosion and clogging (ii) Requires wastewater treatment and management (iii) Produces less torrefied product
Ionic-liquid-assisted torrefaction	<ul style="list-style-type: none"> (i) Enhances biomass torrefaction rate and product quality (ii) Utilizes environmentally friendly and recyclable ionic liquids (iii) Improves subsequent processing efficiency 	<ul style="list-style-type: none"> (i) Lower energy yield compared to dry torrefaction (ii) High operational costs (iii) Limited commercial application
Super-heated steam torrefaction	<ul style="list-style-type: none"> (i) Minimizes carrier gas usage and associated costs and enhances product uniformity and pelletizing qualities (ii) Reduces risk of explosion 	<ul style="list-style-type: none"> (i) Requires specialized equipment for steam generation and control (ii) Limited commercial scalability due to high capital costs
Microwave-assisted torrefaction	<ul style="list-style-type: none"> (i) Improves energy yield, grindability, and energy density of torrefied biomass (ii) Offers faster processing times and more uniform product distribution 	<ul style="list-style-type: none"> (i) Requires optimization of microwave power and processing parameters (ii) Limited scalability due to equipment costs and complexity

be utilized following the pretreatment of lignocellulosic biomass, which can result in biohydrogen and biomethane production [147].

In addition to its benefits as a pretreatment method for biomass waste, WT holds promise for the production of valuable liquid products. A recent study introduces a chemocatalytic approach, employing various zeolite catalysts in a batch reactor under a nitrogen atmosphere [148]. This method enables the simultaneous one-pot production of levulinic acid and/or bio-ethanol during the WT process of wood cellulose pulp residue, ultimately yielding high-quality solid fuel. The study identifies optimal conditions for bio-ethanol production, achieving high selectivity and yield with specific zeolite catalysts at varying temperatures and torrefaction times. Moreover, WT has been employed in combination with microwave-assisted acid hydrolysis pretreatment on indigenous microalgae, demonstrating its versatility across different biomass types [149]. This highlights the potential of WT as a versatile and efficient pretreatment method with applications in various biomass conversion processes.

4.1.3. Ionic-Liquid-Assisted Torrefaction. Ionic-liquid-assisted torrefaction is an innovative method that combines torrefaction with biomass pretreatment. This approach aims to improve both the rate of biomass torrefaction and the quality of the resulting torrefied solid biomass. In this process, ionic liquids are utilized to pretreat the biomass, breaking down complex lignocellulosic biomass polysaccharides into smaller units, thereby enhancing subsequent processing efficiency [144]. The use of water is essential during ionic-liquid-assisted pretreatment because the solubility of lignocellulosic biomass decreases with increasing water content. While this method shows promise in enhancing torrefaction processes, it presents challenges such as lower energy yield compared to dry torrefaction and higher operational costs. However, ionic liquids offer several advantages, including their ability to dissolve biomass at low temperatures, low viscosity, chemical stability, ease of regeneration and recycling, cost-effectiveness, and nontoxicity to enzymatic and microbial fermentation [150]. Despite its potential, ionic-liquid-assisted torrefaction is currently not widely adopted for commercial applications due to its associated costs and complexities. However, ongoing research aims to address these challenges and optimize this torrefaction method for broader industrial use.

4.1.4. Super-Heated Steam Torrefaction. Super-heated steam torrefaction is a pretreatment technique that utilizes super-heated steam to facilitate the opening of biomass fibers, making the polymer more accessible for subsequent operations such as fermentation, hydrolysis, or densification [118]. Unlike dry torrefaction, super-heated steam torrefaction eliminates the need for nitrogen or flue gas as a carrier gas, minimizing costs associated with gas usage. The torrefied biomass produced through this method typically exhibits high heating value, minimal moisture absorption, and superior pelletizing qualities. Additionally, by preventing oxidation of the product, super-heated steam torrefaction significantly reduces the risk of explosion, making it a safer option for biomass processing [151]. Super-heated steam enhances torrefaction reaction rates and promotes product

uniformity through direct contact with biomass, ensuring even biomass heating. Furthermore, steam's stability, nontoxicity, and ability to recover latent heat from reactor effluent contribute to its energy-saving characteristics [152].

4.1.5. Microwave-Assisted Torrefaction. Microwave-assisted torrefaction is a torrefaction method that utilizes microwave heating to improve process efficiency and product characteristics. Compared to conventional heating methods, microwave heating offers higher heating efficiency, power density, better heat transfer, and process control, resulting in faster internal heating and more uniform distribution [1]. Microwave torrefaction enhances the grindability, energy density, moisture adsorption, and energy yield of torrefied biomass, often at shorter residence times. However, adjustments to microwave power and processing time are necessary to optimize the calorific value and fuel ratio of the torrefied biomass, as mass and energy yield may decline with increasing power and time [144]. Furthermore, microwave heating yields torrefied biomass with a significantly different structure compared to that from conventional heating methods, offering unique properties and potential applications [144].

4.2. Factors Affecting the Torrefaction Process. The quality of torrefaction products is influenced by several process parameters, such as temperature, heating rate, reaction/residence time, type of feedstock, feedstock particle size, reactor type, and carrier gas [23, 24]. Among these parameters, temperature plays a primary role, followed by reaction time and heating [24, 34]. Additionally, the choice of process parameters largely depends on the specific biomass feedstock and the torrefaction method being used [23].

4.2.1. Temperature. Temperature is a crucial factor in torrefaction as it governs the kinetics of the reaction [23]. Higher torrefaction temperatures lead to increased production of liquid and gaseous torrefaction products, along with higher energy density [23]. However, high temperatures also decrease the mass and energy yield of most biomass types while increasing energy density and calorific value, except for sewage sludge [11]. This is due to the reduction in hydrogen and oxygen content at higher temperatures, resulting in increased FC content [38]. Different temperature ranges influence the decomposition of biomass components differently. For instance, hemicellulose decomposes predominantly at lower temperatures, while cellulose and lignin decomposition occur at higher temperatures [21]. The decomposition of these components affects the proximate and ultimate analyses of biomass, particularly VM and FC [27].

In a study focused on the torrefaction of pulp industry sludge, torrefaction at 300°C resulted in an increased heating value and FC content. The ash content was comparable to that of agricultural waste, while the cellulose content decreased significantly [153]. Additionally, another study recommended torrefaction at 300°C under a CO₂ flow rate of 50 mL/min as the promising condition for producing biochar to replace lignite coal [154].

Further research delved into the influence of torrefaction temperature on the hydrophobic properties of various waste

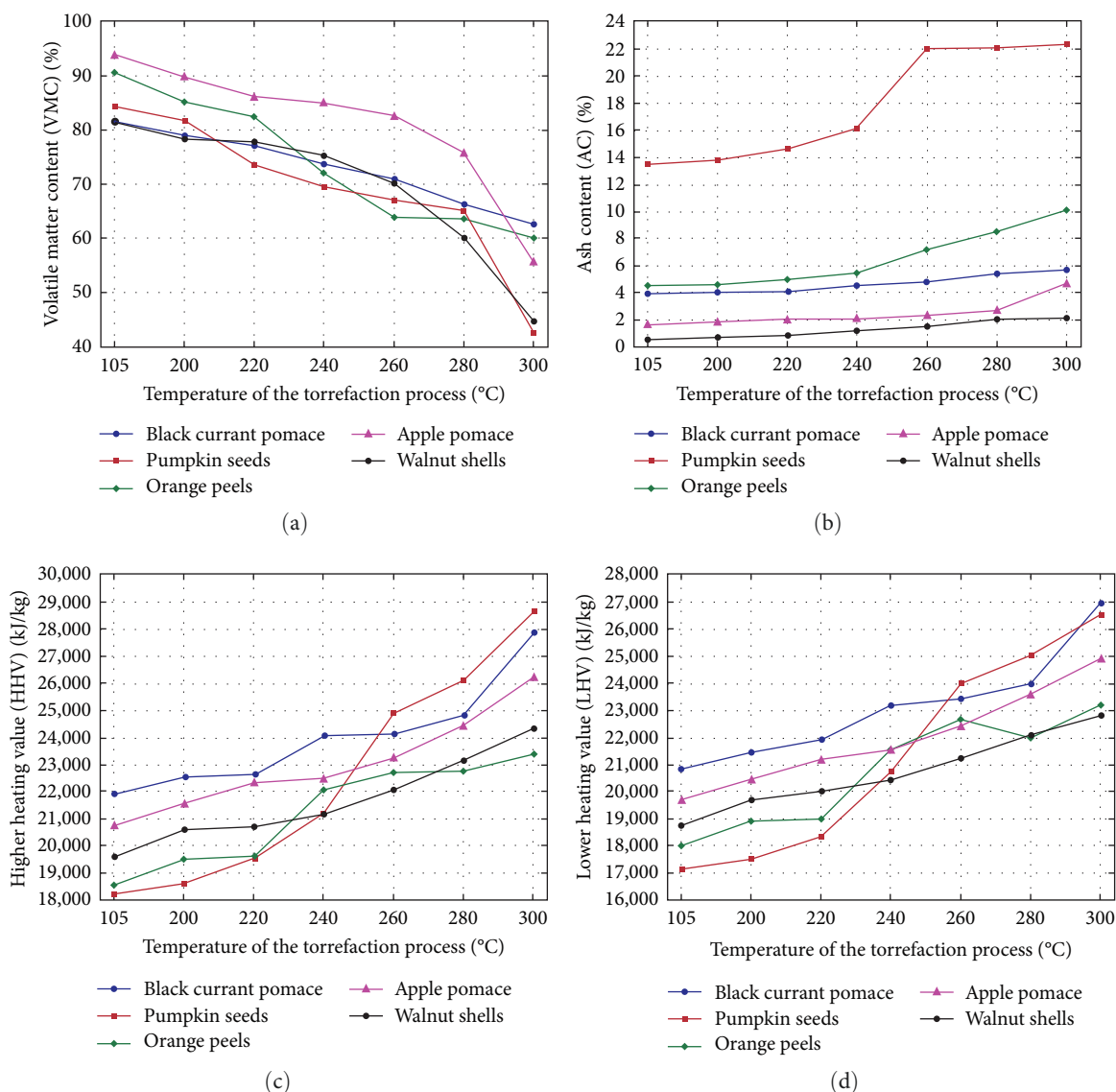


FIGURE 6: Influence of temperature of the torrefaction process on (a) volatile matter content, (b) ash content, (c) higher heating value, and (d) lower heating value. Source. Adapted from [155]. Copyright © MDPI (Basel, Switzerland).

biomass types. Findings revealed that subjecting the biomass to the torrefaction process improved its hydrophobic properties, with some samples exhibiting extreme hydrophobicity at higher temperatures [155, 156]. However, increasing the temperature of the torrefaction process also led to an increase in ash content due to the release of VM [155]. Analyzing the physical–chemical properties of torrefied food waste biomass revealed improvements in hydrophobic properties, heating values, and FC content compared to unprocessed raw materials [157]. Similarly, torrefaction improved the fuel properties of forestry fruit residues, making them comparable to hard coal [158].

Recent studies have also investigated the impact of torrefaction temperature on the hydrophobicity and performance of beverage and agricultural waste. Temperature was found to have a significant impact on energy yield, specific energy consumption, and hygroscopic reduction

equilibrium [159]. Additionally, a study by Jagodzińska et al. [160] revealed that the concentration of polyaromatic hydrocarbons and the formation of more ringed species increased with temperature, emphasizing the importance of temperature control in torrefaction processes. Similarly, Tamelová et al. [161] reported that torrefaction has a positive effect on the properties of fuels, with increased carbon content and calorific value observed at higher temperatures.

Furthermore, analyzing the obtained data of the physical properties of torrefied food waste biomass, some similarities to other wastes were observed (Figure 6). As the temperature of the torrefaction process increased, the ash content in the materials also increased. The VM content in these materials decreased with the increase in torrefaction temperature, while the heating values (both LHV and HHV) were higher as the temperature of the process increased [155]. Additionally, Khairy et al. [162] found that 275°C and 30 min were

the optimal conditions for balanced torrefaction of bean husk and sesame stalks, achieving high heating values and energy yields. In conclusion, temperature is a crucial parameter in torrefaction, affecting various properties of torrefied biomass and offering opportunities for optimization and product development across different biomass feedstocks.

4.2.2. Heating Rate. The heating rate during torrefaction affects polymer cracking in lignocellulose [11]. Higher heating rates result in faster dehydration and depolymerization of biomass, leading to reduced mass yield [23]. Conversely, slower heating rates allow for more secondary degradation, affecting the distribution of solid, liquid, and gas products [11]. Increasing the heating rate decreases VM, oxygen content, and hydrogen content, while increasing the calorific value, FC, ash, and carbon contents of biomass [11]. Although the heating rate primarily affects the heating stage, it also influences the physicochemical characteristics of torrefied biomass [163].

4.2.3. Reaction/Residence Time. Residence time, influenced by torrefaction temperature and biomass type, affects the torrefaction process to a lesser extent compared to temperature [27]. WT generally requires shorter residence times compared to dry torrefaction [1]. The residence time influences the decomposition of biomass components, with longer times resulting in more severe dehydration and carbonization and subsequent changes in biomass composition [5]. Increased residence time leads to reduced hydrogen and oxygen content, increased carbon content, and higher energy density of torrefied biomass [11, 21, 77]. However, it also decreases mass and energy yield, as noted in studies on microalgal biomass [1].

The influence of torrefaction temperature and reaction time on the properties of torrefied sun-dried millet and sorghum straws from the arid and semi-arid zones of western Africa was investigated in a study by Ajikashile et al. [164]. The optimum conditions for pretreatment of sun-dried millet straw and sorghum straw were found to be 240°C and 60 min, respectively. Under these conditions, increased energy density significantly compensated for severe mass loss and significant degradation of hemicellulose and cellulose.

Similarly, Manatura et al. [165] studied the co-torrefaction of rice straw and waste medium-density fiberboard, focusing on process optimization using response surface methodology. The findings revealed that temperature was the main effect, with no interaction effect between the inputs. Thus, lower temperature optimized co-torrefaction. The optimum conditions for maximizing the heating value (22.13 MJ/kg) and energy yield (99.60%) were found to be a rice straw ratio of 25%, a temperature of 208.10°C, and a residence time of 50 min.

4.2.4. Feedstock. Different biomass types exhibit varying mass and energy yields under identical torrefaction conditions [23]. The decomposition of biomass components, namely hemicellulose, cellulose, and lignin, varies with feedstock type and composition [26, 38]. For instance, biomass with higher hemicellulose and cellulose compositions tends to lose more weight during torrefaction. The choice of feedstock also influences torrefaction outcomes. For example, the torrefaction of

food waste and wood waste yields different mass and energy values due to variations in their compositions [166]. Additionally, interactions between biomass and other materials, such as plastic, during co-torrefaction can further influence torrefaction outcomes [68].

4.2.5. Feedstock Particle Size. Particle size plays a crucial role in torrefaction as it directly impacts the heat and mass transfer processes within the biomass material [3]. While smaller particle sizes offer advantages such as increased surface area for more efficient heat transfer and uniform heating, larger particles may experience challenges related to nonuniform heat distribution and slower reaction rates [23]. Moreover, large biomass particle size limits reactor performance and decreases the solid yield and energy yield of torrefied biomass [21]. Additionally, the choice of particle size can influence the overall process economics, as reducing particle size typically involves additional costs for size reduction equipment and operations [38]. Furthermore, optimizing particle size distribution can be essential for achieving desired product quality and properties, such as uniformity in torrefied biomass characteristics.

4.2.6. Reactor Type. The selection of the appropriate reactor type for torrefaction is critical for optimizing process efficiency and product quality [8, 118]. Each reactor design offers unique advantages and limitations in terms of heat transfer mechanisms, residence time control, scalability, and operational flexibility [118]. For instance, fluidized bed reactors provide excellent heat and mass transfer rates due to intimate contact between biomass particles and the fluidizing medium, but they may require higher energy inputs and maintenance costs compared to other reactor types [118]. On the other hand, rotary drum reactors offer simplicity and ease of operation but may have limitations in achieving precise temperature control and uniform heating [5]. Understanding the specific requirements of the torrefaction process, such as temperature profiles, residence time, and product specifications, is essential for selecting the most suitable reactor type.

4.2.7. Moisture Content. MC significantly influences the torrefaction process by affecting reaction kinetics, heat transfer characteristics, and product properties [4, 24, 167]. High MC in biomass can impede heat transfer and prolong torrefaction times, leading to reduced process efficiency and energy yields [38]. Moreover, excessive moisture levels may result in steam generation, which can dilute torrefaction gases and affect product quality. Conversely, low MC biomass tends to exhibit more rapid torrefaction kinetics and higher energy yields but may require additional drying operations, adding to process complexity and costs [1]. Balancing MC to optimize process efficiency while maintaining product quality is essential for achieving desired torrefaction outcomes.

4.2.8. Carrier Gas. The choice of carrier gas during torrefaction can influence reaction kinetics, product composition, and energy efficiency [21]. While nitrogen is commonly used as an inert carrier gas to create an oxygen-free atmosphere and prevent unwanted combustion reactions, alternative gases such as CO₂ and air have also been investigated for

their potential effects on process performance. CO₂, for example, exhibits reactive behavior during torrefaction, promoting thermal degradation reactions and altering product compositions [21]. Similarly, air, which contains oxygen, may lead to combustion rather than torrefaction, but controlled oxygen concentrations can enhance certain reaction pathways and product properties. Understanding the interactions between different carrier gases and biomass feedstocks is essential for optimizing torrefaction conditions and achieving desired product specifications.

4.3. Effects of Lignocellulosic Composition on the Torrefaction Process. The composition of lignocellulosic biomass, encompassing hemicellulose, cellulose, and lignin, profoundly influences the torrefaction process. Each component reacts differently to thermal treatment, impacting the yield and quality of torrefied biomass [22]. The insights gained from studying the effects of lignocellulosic composition on the torrefaction process have significant implications for bioenergy applications. By understanding how different biomass components behave during thermal treatment, researchers can develop strategies to optimize torrefaction processes, enhance the yield and quality of torrefied biomass, and improve the overall efficiency and sustainability of bioenergy production. Moreover, advancements in biomass characterization techniques and process optimization methodologies will further facilitate the development of tailored torrefaction solutions for diverse feedstocks and applications, ultimately contributing to the transition toward a more sustainable bio-based economy [22, 63].

4.3.1. Hemicellulose Degradation. Hemicellulose, a heteropolymer comprising various sugar units, is particularly susceptible to thermal degradation during torrefaction. Research has shown that hemicellulose degradation initiates at relatively low temperatures, typically around 200°C, and progresses rapidly until approximately 320°C, at which point it is nearly completely decomposed. As hemicellulose breaks down, it releases volatile compounds, contributing to the formation of liquid products. This degradation process not only alters the chemical composition of the biomass but also affects its physical properties, such as moisture affinity and grindability [22, 38, 43].

4.3.2. Cellulose Decomposition. Cellulose, a linear polysaccharide consisting of glucose units linked by β (1→4) glycosidic bonds, exhibits distinct thermal behavior during torrefaction. While cellulose degradation occurs over a broader temperature range compared to hemicellulose, typically between 240 and 350°C, it contributes significantly to the production of VM and solid char residues. Factors such as the degree of crystallinity, polymerization degree, and chain orientation influence the thermal stability and degradation kinetics of cellulose [42, 63]. Understanding these factors is essential for predicting the behavior of cellulose-rich biomass feedstocks during torrefaction.

4.3.3. Lignin Degradation. Lignin, a complex phenolic polymer that provides structural support to plant cell walls, displays remarkable resistance to thermal degradation. Although lignin decomposition can occur over a wide temperature

range (200–800°C), significant degradation typically occurs at temperatures above 275°C during torrefaction. Biomass feedstocks rich in lignin content tend to produce higher char yields due to the recalcitrant nature of lignin. However, the presence of lignin also introduces challenges, such as increased ash content and potential fouling of processing equipment, which must be addressed during biomass conversion processes.

4.3.4. Variability in Biochar Yields. The variability in biochar yields observed among different biomass feedstocks underscores the importance of understanding their lignocellulosic composition. Feedstocks with higher lignin content typically yield more biochar at elevated temperatures due to lignin's resistance to thermal degradation. In contrast, feedstocks rich in hemicellulose may exhibit lower biochar yields, as hemicellulose readily decomposes at lower temperatures, leading to greater VM loss. By selecting appropriate feedstocks and adjusting torrefaction conditions, it is possible to tailor the process to achieve desired outcomes in terms of product yield, quality, and energy efficiency [41, 168].

In a recent study exploring the catalytic and char-promoting effects of potassium on the torrefaction and pyrolysis of lignocellulosic biomass [169], it was observed that the altered weight loss effect may be linked to the relative increase in lignin content compared to cellulose and hemicelluloses. At higher temperatures (380°C), potassium exhibited a rapid catalytic effect, resulting in a more pronounced increase in char content. Notably, potassium primarily targeted cellulose and hemicelluloses. These findings offer novel insights into the role of potassium in biomass thermal treatment, enhancing our understanding of thermal degradation mechanisms. This knowledge could facilitate the reduction of operating time and/or temperature, thus promoting torrefaction as an environmentally friendly approach for waste wood valorization [169].

4.4. Effects of Torrefaction on Biochar Properties. Torrefaction significantly improves the physical and chemical properties of biomass, leading to enhanced energy efficiency, product quality, and process economics. Through MC reduction, mass yield reduction, and improvements in grindability, particle properties, pelletability, and calorific value, torrefied biomass becomes a more viable and sustainable energy source for diverse applications in the renewable energy sector. Table 7 summarizes the effects of the torrefaction process on the biomass and biochar characteristics.

4.4.1. MC and VM Reduction. When biomass is subjected to torrefaction, a thermal treatment process conducted in the absence of oxygen, its MC undergoes a notable reduction [23]. Biomass inherently contains moisture due to the presence of hydroxyl (OH) groups in its cell walls, which attract water molecules [24]. Torrefaction effectively removes a significant portion of this moisture, typically reducing the MC by 1%–3% [5, 27]. This reduction is attributed to the dehydration of biomass during the torrefaction process. As a result, torrefied biomass exhibits enhanced hydrophobicity, or water resistance, due to partial removal of hydroxyl groups and prevention of hydrogen bond formation [3, 23, 24, 27].

TABLE 7: Effects of torrefaction on proximate and ultimate analyses of various biomass.

Waste	Proximate analysis (%)				Ultimate analysis (%)					Mass yield (%)	Energy yield (MJ/kg)	HHV (MJ/kg)	Ref
	MC	VM	FC	Ash	C	H	N	S	O				
Mango branches													
Raw	5.21	74.55	20.16	5.26	44.95	6.15	0.52	0.19	42.92	—	—	17.73	
300°C	—	66.80	28.98	4.22	53.85	5.71	0.51	—	35.64	—	—	20.81	
Newspaper													
Raw	4.43	87.67	12.10	0.23	46.08	7.21	0.01	0.03	46.45	—	—	18.24	
300°C	—	81.61	17.96	0.43	51.33	5.71	0.08	—	41.94	—	—	19.56	
Mango branches + newspaper													
Raw	—	—	—	—	—	—	—	—	—	—	—	—	
300°C	—	70.67	27.19	2.15	53.66	5.88	0.42	—	37.52	—	—	21.44	[68]
Mango branches + LDPE													
Raw	—	—	—	—	—	—	—	—	—	—	—	—	
300°C	—	86.68	11.33	2.00	71.94	10.71	0.20	—	15.10	—	—	35.84	
Newspaper + LDPE													
Raw	—	—	—	—	—	—	—	—	—	—	—	—	
300°C	—	91.83	8.06	0.21	71.38	10.76	0.23	—	17.05	—	—	29.38	
Mango branches + newspaper + LDPE													
Raw	—	—	—	—	—	—	—	—	—	—	—	—	
300°C	—	79.47	18.90	1.64	69.06	9.04	0.24	—	20.00	—	—	31.05	
Rice husks													
Raw	3.81	66	22.01	8.18	43.83	6.76	0.93	—	46.07	—	—	15.81	
200°C	—	—	—	7.33	51.89	6.01	0.92	—	41.33	—	—	19.34	
250°C	—	—	—	6.12	52.44	5.90	0.92	—	40.53	—	—	20.33	
300°C	—	—	—	5.55	53.56	5.81	0.77	—	39.45	—	—	20.87	
Corn cobs													
Raw	5.44	64	21.08	9.48	45.02	6.51	0.31	—	45.41	—	—	17.12	
200°C	—	—	—	7.92	52.11	5.90	0.29	—	40.24	—	—	20.66	[170]
250°C	—	—	—	7.02	52.73	5.77	0.29	—	40.01	—	—	21.44	
300°C	—	—	—	6.41	53.91	5.63	0.29	—	39.01	—	—	21.92	
Groundnut shells													
Raw	8.44	63.81	19.33	8.42	45.32	6.03	0.51	—	43.54	—	—	18.42	
200°C	—	—	—	3.12	52.30	5.73	0.51	—	39.41	—	—	21.34	
250°C	—	—	—	2.44	53.45	5.41	0.51	—	38.11	—	—	22.11	
300°C	—	—	—	2.02	55.00	5.29	0.51	—	37.7	—	—	22.66	
Black alder waste cone-like flowers													
Raw	6.4	84.2	29.6	2.6	50.8	5.4	1.6	0.08	42.1	—	—	15.9	
250°C	2.4	57.8	38.8	2.4	59.3	5.0	2.1	0.16	33.5	—	96	21.3	
300°C	2.5	48.2	52.0	2.5	66.1	4.0	2.1	0.04	27.8	—	81	22.7	
400°C	2.9	27.3	67.3	2.9	74.8	4.0	2.1	0.01	19.1	—	68	25.2	
500°C	3.6	16.8	76.6	3.6	83.6	2.9	2.2	0.01	11.3	—	63	27.2	
600°C	3.2	14.0	82.9	3.2	89.0	2.9	2.2	0.01	5.9	—	58	27.9	
800°C	4.3	8.7	89.0	4.3	89.3	1.7	2.2	0.01	6.8	—	54	27.0	
Black alder waste wood chips													
Raw	7.5	81.8	18.1	0.5	53.0	5.5	1.0	0.03	40.5	—	—	20.3	[171]
250°C	3.1	65.8	33.7	1.3	57.1	5.3	0.8	0.02	36.8	—	78	21.4	
300°C	3.4	37.4	60.9	2.8	69.7	4.5	0.7	0.01	25.0	—	54	26.3	
400°C	3.9	23.7	73.9	3.0	76.4	3.4	1.0	0.00	19.2	—	46	29.1	
500°C	3.7	14.4	82.9	3.2	84.2	2.7	0.9	0.00	12.2	—	40	29.1	
600°C	3.1	12.2	83.7	4.6	86.7	2.1	1.0	0.00	10.3	—	39	29.1	
800°C	2.8	7.9	87.1	5.4	90.5	1.8	0.6	0.00	7.1	—	35	29.7	

TABLE 7: Continued.

Waste	Proximate analysis (%)				Ultimate analysis (%)					Mass yield (%)	Energy yield (MJ/kg)	HHV (MJ/kg)	Ref
	MC	VM	FC	Ash	C	H	N	S	O				
Bagasse													
Raw	—	83.46	14.26	2.17	46.37	6.29	0.55	0.11	46.76	1.00	1.00	—	[69]
200°C	—	71.18	26.94	1.77	41.92	4.21	0.23	0.10	53.64	0.88	0.92	—	
225°C	—	71.86	25.52	2.49	47.16	4.73	0.25	0.13	47.85	0.79	0.78	—	
250°C	—	62.19	34.46	3.22	52.70	3.80	0.28	0.14	43.22	0.71	0.70	—	
275°C	—	51.85	44.04	3.95	58.25	2.81	0.31	0.15	38.68	0.65	0.62	—	
Food waste													
Raw	—	75.92	7.19	16.89	47.39	6.90	3.32	0.27	38.67	100.00	100.03	—	[166]
240°C	—	64.86	16.18	18.96	49.07	6.63	3.55	0.28	36.32	81.99	93.12	—	
270°C	—	53.96	25.01	21.03	50.52	6.39	3.95	0.29	34.10	69.89	87.01	—	
300°C	—	42.55	34.36	23.09	52.43	6.11	4.32	0.31	31.69	58.91	83.06	—	
330°C	—	31.68	43.16	25.16	54.30	5.69	4.67	0.33	29.19	48.93	78.04	—	
Wood waste													
Raw	—	73.54	19.09	7.37	52.62	6.85	1.88	0.16	38.24	100.00	100.15	—	[166]
240°C	—	62.17	26.19	11.64	54.56	6.45	2.22	0.18	35.67	77.86	95.05	—	
270°C	—	51.94	33.42	14.64	56.88	6.02	2.56	0.21	33.29	66.92	90.03	—	
300°C	—	42.72	40.57	16.71	59.21	5.69	2.89	0.23	30.62	59.87	86.01	—	
330°C	—	33.45	47.65	18.90	61.51	5.32	3.23	0.26	28.43	46.88	74.06	—	
Food waste													
Raw	62.15	15.30	17.14	5.41	45.32	6.22	2.00	0	46.47	—	—	—	[172]
225°C	—	—	—	—	51.01	5.77	3.56	0	40.06	—	—	—	
275°C	—	—	—	—	61.22	5.77	3.37	0	29.65	—	—	—	
300°C	—	—	—	—	62.2	5.34	3.64	0	28.28	—	—	—	
Food waste													
Raw	4.94	64.83	30.23	—	44.72	7.13	3.49	0.40	44.26	—	—	19.26	[173]
220°C	4.31	59.21	36.49	—	47.23	7.19	2.94	0.16	42.48	93.37	99.12	20.98	
240°C	3.71	57.34	38.95	—	48.18	7.17	3.81	0.22	40.62	91.36	98.93	21.40	
260°C	3.67	54.50	41.83	—	50.61	7.23	3.94	0.17	38.05	81.78	93.58	22.61	
MSW (food waste, sawdust)													
Raw	—	68.54	11.04	20.42	40.56	5.62	3.66	0.27	28.01	—	—	17.5	[74]
250°C	—	60.43	14.63	24.94	43.54	5.17	4.14	—	20.49	—	87	19	
300°C	—	48.53	20.02	31.45	43.57	4.35	4.03	—	14.4	—	69	19.334	
350°C	—	39.6	23.92	36.48	42.39	3.86	3.71	—	10.9	—	56	17.6	
400°C	—	32.19	25.82	41.99	39.35	3.16	3.47	—	9.48	—	43	16.4	
450°C	—	25.25	28.51	46.24	34.72	2.17	3.27	—	10.69	—	35.52	13.9	
Food waste													
Raw	11.95	81.00	3.77	3.28	44.61	7.34	3.48	0.40	44.16	—	—	19.63	[77]
280°C	—	—	—	—	50.67	7.17	4.26	0.30	37.60	58.62	—	21.82	
300°C	—	—	—	—	58.57	6.58	4.84	0.17	29.84	53	—	24.35	
320°C	—	—	—	—	59.06	6.26	5.53	0.15	5.53	44	—	24.45	

TABLE 7: Continued.

Waste	Proximate analysis (%)				Ultimate analysis (%)					Mass yield (%)	Energy yield (MJ/kg)	HHV (MJ/kg)	Ref
	MC	VM	FC	Ash	C	H	N	S	O				
Reed canary grass													
Raw	4.7	82.5	12.1	5.5	48.6	6.8	0.3	—	37.3	—	—	19.5	
230°C	2.5	—	—	—	49.3	6.5	0.1	—	—	92.6	93.5	—	
250°C	1.9	80.3	13.3	6.4	50.3	6.3	0.0	—	37.0	84.0	86.6	20.0	
270°C	1.3	76.6	16.1	7.3	52.2	6.0	0.1	—	37.3	72.0	77.1	20.8	
290°C	1.2	70.5	21.3	8.3	54.3	6.1	0.1	—	36.3	61.5	69.0	21.8	
Wheat straw													
Raw	4.1	76.4	17.3	6.3	47.3	6.8	0.8	—	37.7	—	—	18.9	
230°C	1.5	—	—	—	48.7	6.3	0.7	—	—	91.0	93.5	19.4	
250°C	0.9	77.0	15.6	7.4	49.6	6.1	0.9	—	35.6	82.6	86.2	19.8	[65]
270°C	0.3	65.2	26.5	8.4	51.9	5.9	0.8	—	33.2	71.5	78.2	20.7	
290°C	0.8	51.8	38.0	10.2	56.4	5.6	1.0	—	27.6	55.1	65.8	22.6	
Willow													
Raw	2.8	87.6	10.7	1.7	49.9	6.5	0.2	—	39.9	—	—	20.0	
230°C	0.5	82.7	16.1	1.8	50.7	6.2	0.2	—	39.5	95.1	96.5	20.2	
250°C	0.1	79.8	18.4	1.9	51.7	6.1	0.2	—	38.7	89.6	92.7	20.6	
270°C	0.1	79.3	18.6	2.1	53.4	6.1	0.2	—	37.2	79.8	85.8	21.4	
290°C	0.0	77.2	20.5	2.3	54.7	6.0	0.1	—	36.4	72.0	79.2	21.9	
Rice husks													
Raw	—	62.83	27.60	9.57	45.87	5.87	0.56	0.14	38.00	—	—	18.78	
200°C	—	60.33	29.98	9.69	47.86	5.36	0.61	0.12	36.35	—	—	19.06	
250°C	—	42.43	43.28	14.30	57.16	4.52	0.93	0.14	22.95	—	—	22.59	
300°C	—	26.64	54.78	18.58	60.74	3.55	0.99	0.13	16.01	—	—	23.33	
Coconut husks													
Raw	—	61.78	31.52	6.70	49.03	5.37	0.41	0.13	38.36	—	—	19.33	
200°C	—	52.18	40.13	7.70	53.01	4.78	0.55	0.10	33.86	—	—	20.47	
250°C	—	40.40	49.96	9.64	58.61	4.19	0.59	0.10	26.88	—	—	22.40	
300°C	—	32.32	56.16	11.52	62.53	3.70	0.57	0.10	21.58	—	—	23.70	
Cassava rhizomes													
Raw	—	71.92	23.13	4.95	45.14	5.82	0.84	0.13	43.12	—	—	18.04	[41]
200°C	—	67.00	26.29	6.71	52.27	5.40	1.27	0.23	34.12	—	—	20.92	
250°C	—	40.45	50.53	9.03	58.72	4.98	1.38	0.11	25.78	—	—	23.49	
300°C	—	30.80	58.37	10.83	64.24	4.27	1.43	0.11	19.13	—	—	25.22	
Corncoobs													
Raw	—	76.04	21.95	2.01	46.74	6.04	0.84	0.15	44.23	—	—	18.80	
200°C	—	61.65	29.25	9.10	55.52	5.46	1.26	0.13	28.53	—	—	22.65	
250°C	—	38.99	57.04	3.97	62.20	5.14	1.47	0.15	27.08	—	—	24.86	
300°C	—	30.39	66.26	3.35	72.94	4.05	1.63	0.14	17.88	—	—	28.29	

LDPE, low-density polyethylene.

Consequently, torrefied biomass is less prone to absorbing moisture from the environment, making it more suitable for storage, transportation, and combustion. The reduction in MC also contributes to increased energy efficiency during combustion, as less energy is required to vaporize water content. Studies have shown that the degree of MC reduction in torrefied biomass correlates with process parameters such as temperature and residence time, with higher temperatures and longer residence times leading to greater moisture reduction [173, 174].

Similarly, torrefaction induces a reduction in VM content in biomass, primarily due to the release of volatiles like CO₂

and CO, with this reduction becoming more pronounced at higher temperatures [166, 175, 176]. This decrease is crucial to improving the energy yield during combustion and reducing energy generation costs. However, excessive volatilization during torrefaction can lead to high tar and smoke production, undesirable outcomes that need to be mitigated [38].

4.4.2. Increase in FC and Energy Yield. FC content in biomass increases with torrefaction temperature, contributing to higher char yields, which are desirable outcomes of the torrefaction process. However, the composition of the waste, particularly the presence of hemicellulose and ash, can

significantly influence FC production. Nakason et al. [41] observed that waste with high hemicellulose content tends to produce maximum FC due to enhanced devolatilization reactions, while wastes with high ash content may hinder degradation and reduce FC content. As torrefaction temperature rises, the carbon content of waste samples typically increases, leading to enhanced energy yield. However, beyond certain temperatures, the carbon content may decrease. For instance, Rago et al. [68] found that torrefied blended waste showed higher carbon percentages compared to torrefied independent wastes, particularly in blends containing LDPE.

Conversely, in a study by Yuan et al. [74], MSW comprising food waste and sawdust exhibited lower carbon content compared to independent food waste and wood waste torrefied at 300°C. Moreover, Yuan et al. [74] observed that increasing torrefaction temperature led to an increase in the carbon content of MSW samples, resulting in higher energy yields. However, beyond certain temperatures, the carbon content started to decrease, indicating the need for precise temperature control during torrefaction to optimize energy yield. This underscores the importance of understanding the relationship between torrefaction temperature and biomass composition to achieve desirable outcomes in terms of energy yield and product quality.

4.4.3. Impact on Ash Content. While torrefaction offers a transformative approach to unlocking the potential of biomass, its impact on ash content presents a critical consideration. Studies have consistently revealed a direct correlation between higher torrefaction temperatures and a subsequent increase in ash content following combustion [38]. This underscores the importance of optimizing torrefaction conditions to minimize ash content. The presence of excessive ash following combustion often serves as a telltale sign of suboptimal torrefaction quality, highlighting the need for precise control over the process parameters [38].

Further reinforcing this concept is research conducted by Nakason et al. [41]. Their investigation focused on the impact of torrefaction on various biomass sources, including rice husks, coconut husks, cassava rhizome, and corncob. The findings were clear (Table 7): across all these feedstocks, ash content consistently increased following the torrefaction process [41]. This emphasizes the crucial role of carefully considering torrefaction parameters to mitigate potential problems arising from ash accumulation. Uncontrolled ash accumulation can lead to a cascade of negative consequences, impacting boiler efficiency, increasing maintenance costs, and potentially posing environmental concerns.

Understanding the mechanisms behind this phenomenon is crucial. During torrefaction, the biomass undergoes a thermochemical process that drives off moisture and some volatile components [177]. While this generally improves the fuel properties of the biomass, it also concentrates the inorganic mineral matter originally present within the biomass. This concentrated mineral matter ultimately manifests as ash during the combustion process. Therefore, finding the optimal balance between maximizing the desired benefits of torrefaction, such as increased energy density and improved

grindability, while minimizing the negative effects of ash content, is essential. This delicate balancing act requires careful consideration of factors such as torrefaction temperature, residence time, and even the specific type of biomass being processed [178].

Fortunately, several strategies can help mitigate ash-related concerns. Selecting a lower torrefaction temperature can be a powerful tool, but it is crucial to find the sweet spot that achieves desired fuel property improvements without sacrificing necessary biomass conversion [8]. Additionally, utilizing biomass sources naturally low in ash content can inherently minimize the final ash burden [179]. Screening and selecting feedstock with lower initial ash levels can be a valuable strategy. Pretreatment techniques like washing or leaching the biomass prior to torrefaction can also be explored, although their feasibility and cost-effectiveness require careful evaluation [21, 180].

Beyond temperature control, research suggests that the chosen torrefaction method itself can influence ash content. For instance, studies by Isemin et al. [181] compared the effects of superheated steam torrefaction and gaseous torrefaction products on sunflower husks. Their findings revealed that superheated steam torrefaction not only increased the calorific value of the husks but also significantly reduced the chlorine content within the ash. This reduction in chlorine content translates to a lower risk of corrosion on boiler heat exchange surfaces when burning biochar derived from superheated steam torrefaction. While this specific study focused on chlorine content, it highlights the potential for exploring different torrefaction methods to potentially influence not just the overall ash content but also the composition of the ash itself.

4.4.4. Impact on Elemental Composition. The torrefaction process significantly alters the elemental composition of biomass. Research by Mamvura and Danha [8], Bach and Skreiberg [31], Rudolfsson et al. [182], and Araújo et al. [183] indicates that increasing torrefaction temperature boosts carbon, nitrogen, sulfur, and chlorine content, while diminishing hydrogen and oxygen levels due to profound dehydration and carbonization [65, 74, 77, 166]. The elevated carbon content posttorrefaction is attributed to the formation of C=C, C-C, and C-H bonds, which possess higher energy compared to O-H bonds [173].

4.4.5. Mass Yield Reduction and Enhancement of Energy Density. During torrefaction, biomass undergoes significant weight loss, primarily due to the removal of moisture and VM [24]. This reduction in mass yield is a natural consequence of the thermal cracking and devolatilization processes that occur at elevated temperatures. However, despite the decrease in mass yield, torrefaction leads to an enhancement in energy density, which refers to the amount of energy stored in a given volume of biomass [11, 69, 184]. This increase in energy density is attributed to the concentration of carbon-rich components in the torrefied biomass, resulting in higher calorific values. Higher torrefaction temperatures and longer residence times generally lead to greater increases in energy density, as more VM is removed, leaving behind a denser,

carbon-rich material. While the reduction in mass yield may raise concerns about biomass utilization efficiency, the improved energy density of torrefied biomass often outweighs the decrease in mass yield in terms of overall energy production and efficiency.

4.4.6. Improvement in Grindability. Grinding biomass into smaller particles is a crucial step in various biomass conversion processes, including combustion, gasification, and pelletization [21, 24]. However, the fibrous and tenacious nature of raw biomass makes it inherently difficult to grind efficiently [3, 5]. Torrefaction plays a vital role in improving the grindability of biomass by modifying its microstructure [11]. The thermal treatment weakens the complex cellulose–hemicellulose–lignin matrix present in raw biomass, making it more susceptible to mechanical grinding. As a result, torrefied biomass exhibits enhanced grindability, requiring significantly less power for grinding compared to raw biomass. Studies have shown that the power required for grinding torrefied biomass can be reduced by 40%–90% compared to nontorrefied biomass [5, 21, 23, 24]. This reduction in grinding energy consumption not only improves process efficiency but also reduces operational costs associated with biomass processing [11, 27]. Additionally, torrefaction leads to the production of biomass particles with finer sizes, further enhancing their suitability for various applications such as combustion and pelletization [24].

4.4.7. Enhancement of Particle Properties for Combustion. Biomass holds immense promise as a renewable energy source, but unlocking its full potential requires overcoming challenges related to combustion efficiency. Particle size distribution, sphericity, and specific surface area all significantly influence how a fuel burns [23, 27]. These factors often lead to inconsistent burning behavior and can hinder the efficient utilization of biomass in power plants. Fortunately, a pretreatment process called torrefaction offers a solution. Torrefaction significantly improves the combustion behavior of biomass by modifying its physical makeup at the particle level. Studies have shown that torrefaction leads to the formation of particles with several key advantages [23, 27].

One key benefit is a more uniform fuel with a consistent burn. In addition, torrefaction promotes better packing and improved airflow. It nudges particles toward a more spherical shape, improving their packing density and promoting better airflow within the fuel bed. This allows for a more even distribution of oxygen throughout the fuel, leading to more complete combustion. Finally, torrefaction leads to faster ignition and higher efficiency. A higher specific surface area, achieved through torrefaction, refers to the amount of surface area a particle has per unit of its volume. This increased surface area allows for better contact between the fuel and oxidizer (typically oxygen), resulting in faster ignition, more efficient combustion, and ultimately, a more efficient energy conversion process [5].

The benefits of torrefaction extend beyond the microscopic level. Torrefied biomass boasts improved flowability, making it easier to handle and transport within a power plant. This translates to more efficient use of space during

storage and transportation [185]. More importantly, the enhanced particle properties lead to better combustion efficiency in co-firing applications, where torrefied biomass is blended with traditional fuels like coal. The environmental impact is another positive aspect [107]. The reduced particle size achieved through torrefaction promotes a more homogeneous fuel mixture, potentially leading to lower emissions during the burning process. Studies like the one by Pambudi et al. [186] support this notion. Their research investigating biochar derived from spent coffee grounds showed that torrefaction resulted in lower CO₂ emissions and significantly less dust compared to traditional coals.

4.4.8. Improving Pelletability and Densification. Pelletization is a common process used to convert biomass into densified pellets, which are easier to handle, transport, and store compared to loose biomass [187]. The pelletability of biomass depends on its ability to bind together during the pelletization process, which is primarily influenced by the lignin content. Torrefaction enhances pelletability by opening up more lignin-active sites and breaking down the hemicellulose matrix, thus facilitating better binding of biomass particles [23]. However, it is important to note that higher degrees of torrefaction can lead to the production of brittle, noncompressible material with limited intraparticle bond strength, which may hinder pelletization. To overcome this challenge, plasticizers like water or steam, as well as binders like lignin, starch, and additives, are often used to improve cohesion between biomass particles and enhance pellet durability [34]. Despite potential challenges, torrefied biomass generally exhibits improved pelletability compared to untreated biomass, making it a preferred feedstock for pellet production.

4.4.9. Increasing Calorific Value for Enhanced Energy Content. The calorific value, or heating value, of biomass fuels is a critical parameter that determines their energy content and suitability for various applications [21]. During torrefaction, biomass undergoes thermal decomposition, leading to the release of VM and an increase in the concentration of carbon-rich components. This results in a significant enhancement of the calorific value of torrefied biomass [5]. Studies have shown that torrefaction can lead to linear increases in the HHV of biomass fuels, with reductions in MC and increases in residence time contributing to higher HHV values [188, 189]. Additionally, optimization studies have demonstrated substantial increments in the HHV of torrefied biomass, with some cases recording up to 54.37% enhancements compared to untreated biomass [184]. The rise in calorific value is attributed to the removal of VM and the decomposition of the lignocellulosic structure during torrefaction, resulting in a more energy-dense fuel suitable for various thermal conversion processes.

5. Potential Applications of Torrefied MSW

Torrefied MSW has emerged as a promising alternative fuel source [190]. However, its applications extend far beyond simply replacing coal or other traditional fuels. Torrefaction, the process of pretreating biomass at moderate temperatures in a limited oxygen environment, unlocks a range of valuable

properties that make torrefied MSW a versatile tool across various industries.

5.1. Environmental Remediation through Wastewater Treatment. While torrefied MSW is gaining recognition as a fuel source [191], its potential extends to environmental cleanup efforts. Studies have demonstrated that biochar derived from torrefaction outperforms biochar from pyrolysis in removing pollutants like methylene blue dye from wastewater [185]. This is because torrefaction alters the internal structure of MSW, increasing its surface area and porosity. These characteristics make torrefied biochar a highly effective adsorbent, capable of trapping and removing pollutants through physical and chemical interactions.

Utilizing torrefied MSW for wastewater treatment offers a sustainable and cost-effective solution. Torrefaction can be performed on a variety of waste materials, including agricultural residues and forestry leftovers, diverting them from landfills and creating a valuable product for environmental remediation. Furthermore, the process can potentially be integrated with existing wastewater treatment facilities, reducing the need for expensive infrastructure upgrades. By incorporating torrefied MSW into wastewater treatment processes, we can contribute to cleaner water sources, a crucial aspect of environmental health and a sustainable future.

5.2. Enhancing Fuel Properties through Densification. Torrefaction offers a powerful tool for improving the fuel properties of biomass itself. When biomass is pelletized after undergoing torrefaction, the resulting product boasts several advantages. Torrefaction removes some of the moisture and volatile components from biomass, leading to HHVs and energy densities in the final pellets [187]. This translates to more efficient combustion, requiring less fuel to generate the same amount of heat compared to raw biomass. Additionally, torrefaction enhances the pellets' resistance to water absorption [192]. Biomass is hygroscopic, meaning it readily absorbs moisture from the surrounding environment. This can lead to degradation during storage and transportation, reducing the fuel's overall heating value. Torrefied biomass pellets exhibit superior hydrophobicity, making them more resistant to moisture uptake and ensuring consistent fuel quality.

Furthermore, torrefaction improves the durability of biomass pellets. Raw biomass pellets are prone to breakage and generate dust during handling and use [30]. The torrefaction process strengthens the cell walls of the biomass, resulting in more robust pellets that are less susceptible to breakage and generate less dust. This not only improves the efficiency of handling and transportation but also reduces respiratory issues associated with dust inhalation during biomass combustion [177]. It is important to note, however, that there might be a slight decrease in the overall mass and energy efficiency of the pelletized fuel due to the removal of some volatile components during torrefaction [185]. Finding the right balance between these factors requires careful consideration of the feedstock type and the desired outcome of the final product.

5.3. Unlocking Higher Quality Products through Pyrolysis Pretreatment. The benefits of torrefaction extend even further when used as a pretreatment step for pyrolysis. Pyrolysis, the thermochemical decomposition of biomass in an oxygen-limited environment, can be significantly enhanced by using torrefied biomass as the feedstock [28]. Using torrefied biomass as a feedstock for pyrolysis unlocks a range of improvements in the final products. First, torrefaction leads to increased-quality biochar: Torrefied biomass subjected to pyrolysis produces higher-quality biochar with improved properties [192, 193]. Biochar is a carbon-rich material with a variety of applications, including soil amendment, carbon sequestration, and pollutant removal. Torrefaction enhances the physical and chemical characteristics of biochar derived from pyrolysis, making it more effective for these applications. Second, torrefaction enhances bio-oil quality from pyrolysis. The bio-oil derived from the pyrolysis of torrefied biomass is less acidic and has a higher calorific value compared to bio-oil obtained from untorrefied biomass [194]. Bio-oil is a complex liquid mixture that can be further refined into biofuels. The reduced acidity and higher energy content of bio-oil derived from torrefied biomass make it a more valuable product for biofuel production. Further, torrefaction can be used in the production of advanced bio-oils. Researchers are even exploring the use of torrefaction in combination with specific catalysts and pyrolysis to produce bio-oil rich in aromatic hydrocarbons [195]. Aromatic hydrocarbons are a group of organic compounds found in fossil fuels and are valuable components of gasoline and other transportation fuels. Developing a sustainable and efficient method for producing bio-oil rich in aromatic hydrocarbons could be a game-changer in the transition away from fossil fuels. These examples showcase the versatility of torrefaction in unlocking the hidden potential within biomass. However, the applications do not stop there.

5.4. Optimizing Feedstock for Gasification Processes. While the impact of torrefaction on gasification, another thermochemical conversion process, can vary depending on the feedstock, it still offers advantages in terms of handling and logistics [175]. Gasification involves converting biomass into syngas, a mixture of gases like hydrogen, carbon monoxide, and methane, which can be used for various purposes, such as generating electricity or producing synthetic fuels [130]. Torrefaction can improve the grindability of some biomass feedstocks, making them easier to process for gasification. Additionally, torrefaction can increase the energy density of biomass, reducing the transportation costs associated with delivering feedstock to gasification plants [196, 197].

However, the impact of torrefaction on the actual gasification process itself can vary depending on the specific feedstock and gasification technology employed [196]. For example, torrefaction might decrease the tar content in the syngas produced from some feedstocks, making it easier to clean and upgrade for further use [9]. On the other hand, torrefaction might reduce the overall gas yield from other feedstocks [197]. Further research is needed to optimize torrefaction and gasification

processes for different feedstocks and conditions to maximize efficiency and product quality. Despite the potential variations, torrefaction presents a promising approach for improving the handling characteristics and overall efficiency of biomass utilization in gasification processes.

5.5. Revolutionizing AD Systems. The potential of torrefaction does not stop at fuel production or environmental remediation. Integrating torrefaction with AD, a process that breaks down organic matter in the absence of oxygen to produce biogas (primarily methane), shows promise for improved economic viability and environmental benefits [98]. AD is a widely used technology for converting organic waste into a renewable source of energy. However, the process can be limited by the nature of the feedstock. Some organic materials have low biodegradability, hindering the efficiency of biogas production.

Torrefaction can pretreat these challenging feedstocks, making them more susceptible to degradation in AD systems. Additionally, the heat generated during the torrefaction process can potentially be reused to heat the AD digesters, improving the overall efficiency of the system and reducing operational costs [84]. Furthermore, the torrefied biochar itself might be used within the AD process as a bulking agent or to enhance biogas production through specific microbial interactions [198].

By integrating torrefaction with AD, we can potentially unlock the full potential of various organic waste streams for biogas production. This combined approach could lead to more efficient and cleaner waste or wastewater treatment facilities, contributing to a more sustainable future with reduced reliance on fossil fuels and improved waste management strategies.

6. Challenges, Research Directions, and Future Perspectives

While MSW shows promise as a feedstock for torrefaction, several challenges and opportunities exist for future research. MSW's inherent variability in composition, limitations in its lignocellulosic content, high MC, and presence of ash all present hurdles that need to be addressed for widespread adoption of this technology. However, these challenges are balanced by exciting possibilities for optimizing the process through co-torrefaction, exploring alternative drying methods, and refining WT techniques. Additionally, developing strategies for ash management and conducting life cycle assessments can play a crucial role in ensuring the environmental and economic sustainability of MSW torrefaction.

6.1. Challenges for MSW Torrefaction. The significant geographical variation in MSW composition presents a significant obstacle for optimizing torrefaction processes [199]. The makeup of MSW can vary dramatically depending on factors like population density, economic activity, and living standards. For instance, studies conducted in major cities often show a higher proportion of organic waste compared to rural areas. This variability necessitates a detailed characterization of

MSW from different regions. This information can be used to determine appropriate torrefaction parameters for each specific waste stream, maximizing efficiency and product quality. Without proper characterization, the torrefaction process may not be optimized for the specific composition of the MSW, leading to lower yields of biochar or biochar with undesirable properties.

MSW typically has a lower lignin content compared to other biomass sources like woody biomass or agricultural residues. Lignin plays a crucial role in torrefaction, influencing the amount of solid yield (biochar) produced. The lower lignin content in MSW can limit the achievable solid yield during torrefaction [200]. Research on co-torrefaction, the process of torrefying MSW with other biomass types with higher lignin content, is needed to explore potential improvements in solid yield. By combining MSW with biomass feedstocks rich in lignin, researchers can potentially increase the amount of biochar produced from the torrefaction process.

The high MC of MSW can significantly increase the cost of dry torrefaction [166]. Dry torrefaction requires the removal of moisture from the MSW before the actual torrefaction process can begin. This drying step consumes additional energy, driving up the overall cost of torrefaction. While WT might be more suitable considering the MC of MSW, it is a more complex and expensive process compared to dry torrefaction. WT necessitates specialized reactors that can withstand high pressure and temperature while handling a slurry feedstock. Additionally, the wastewater produced during WT requires proper treatment before disposal, adding another layer of complexity and cost to the process.

High ash content in MSW can lead to increased solid yield during torrefaction. However, ash is undesirable during combustion as it can cause problems like slagging, fouling, and corrosion in boilers and furnaces. Slagging occurs when molten ash deposits adhere to the walls of the combustion chamber, reducing heat transfer efficiency. Fouling refers to the accumulation of ash deposits on heat transfer surfaces, similarly hindering efficiency. Corrosion is the deterioration of boiler components due to the chemical reactions between the ash and the metal surfaces. Utilizing MSW with lower ash content or developing methods to remove ash during pre-processing could be beneficial for improving the quality of the torrefied product and minimizing potential problems during combustion. Separating the ash from the MSW before torrefaction can lead to cleaner burning biochar and minimize environmental concerns associated with ash disposal.

6.2. Research Directions for MSW Torrefaction. Investigating the optimal combinations of MSW with other biomass feedstocks to improve the overall lignocellulosic composition and maximize solid yield during co-torrefaction is crucial [201]. This research can lead to the development of more efficient and productive torrefaction processes for MSW utilization. By identifying the ideal ratios of MSW to biomass feedstocks with higher lignin content, researchers can optimize the torrefaction process to produce a higher yield of biochar. This co-torrefaction approach can potentially unlock the full potential of MSW as a feedstock for biochar production.

Exploring alternative drying methods for MSW before torrefaction, potentially using waste heat from other processes, could improve the economic viability of dry torrefaction. Currently, dry torrefaction often relies on dedicated heating systems to remove moisture from the MSW, which can be energy-intensive and costly. Identifying alternative drying methods that utilize waste heat from other industrial processes could significantly reduce the energy consumption and overall cost of dry torrefaction. For instance, utilizing of gaseous products emitted during torrefaction for heat applications. This would make dry torrefaction a more attractive option for MSW conversion, promoting its wider adoption as a waste management strategy.

Research on optimizing WT processes for MSW, focusing on reducing complexity and cost, could lead to a more sustainable approach for utilizing MSW with high MC. WT offers several potential advantages for MSW due to its inherent MC. However, the current WT processes are often complex and expensive. Research efforts directed at simplifying the reactor design and streamlining the overall process can make WT a more viable option for MSW conversion. Additionally, exploring methods to reduce the cost of wastewater treatment associated with WT would further enhance its attractiveness as a sustainable waste management technology.

Developing strategies to manage or remove ash from MSW before torrefaction can improve the quality of the biochar product and minimize potential combustion issues. Ash content in the biochar can negatively impact its burning characteristics and contribute to environmental concerns during combustion. Research on preprocessing techniques for ash removal or separation from MSW can lead to the production of cleaner-burning biochar with fewer environmental consequences. Separating the inorganic ash fraction from the organic matter in MSW before torrefaction can result in biochar with a higher energy density and improved grindability. This higher energy density translates to more efficient combustion, requiring less biochar to generate the same amount of heat. Additionally, improved grindability allows for easier processing and transportation of the biochar. Furthermore, by removing the ash component, the risk of slagging, fouling, and corrosion in combustion systems is significantly reduced. This not only improves the efficiency and lifespan of boilers and furnaces but also minimizes the need for frequent maintenance and associated costs.

Conducting life cycle assessments to compare the environmental impact of torrefaction with other MSW management strategies can help determine its overall sustainability. A life cycle assessment considers all the environmental burdens associated with a product or process, from resource extraction and production to use and disposal. By comparing the life cycle impact of torrefaction with other MSW management options like landfilling or incineration, researchers can gain valuable insights into its environmental footprint. If the life cycle assessment reveals that torrefaction has a lower environmental impact than other options, it can be promoted as a more sustainable waste management solution.

6.3. Future Perspectives for MSW Torrefaction. Establishing standardized methods for characterizing MSW composition across different regions would facilitate the development of more universally applicable torrefaction processes. Currently, the methods used to characterize MSW composition can vary significantly between different research groups and geographical locations. This lack of standardization makes it difficult to develop universally applicable torrefaction processes. By establishing standardized characterization protocols, researchers can ensure consistency in the data collected on MSW composition. This would allow for the development of torrefaction processes that are effective for a wider range of MSW feedstocks, regardless of their geographical origin. Such universally applicable processes can then be adapted and optimized for specific regions based on the characterization data.

Conducting comprehensive cost–benefit analyses of MSW torrefaction compared to other treatment options can provide valuable insights for large-scale implementation. The economic feasibility of MSW torrefaction as a large-scale waste management solution hinges on a thorough understanding of its costs and benefits. A comprehensive cost–benefit analysis would not only consider the capital and operational costs associated with torrefaction but also factor in the potential revenue generated from the sale of biochar or energy derived from its combustion. By comparing these costs and benefits with those of alternative MSW treatment options, policymakers and waste management companies can make informed decisions about the most suitable approach for their specific needs.

Investigating the potential environmental and health impacts of torrefaction emissions and the final biochar product is crucial for ensuring responsible and sustainable waste management practices. The torrefaction process itself, as well as the combustion of the resulting biochar, can potentially generate emissions that could impact air quality. Additionally, the biochar itself may contain trace elements or contaminants that could pose environmental or health risks if not properly managed. Research in this area is essential for mitigating any potential negative effects and promoting the safe and environmentally friendly use of MSW-derived biochar. By developing strategies to capture and treat emissions from the torrefaction process and ensuring the proper disposal or utilization of biochar, researchers can help ensure that MSW torrefaction contributes to a circular economy while minimizing environmental and health risks.

7. Limitations and Practical Implications

The review provides valuable insights into the potential of MSW for torrefaction, but there are areas that could benefit from further exploration.

7.1. Limitations of the Current Review. One limitation is the limited scope on MSW composition. While the review acknowledges the variation in MSW, it does not fully explore how specific components beyond lignocellulose content might influence the torrefaction process. For instance, the presence of plastics can

significantly impact the process efficiency and product characteristics. Plastics typically have LHVs compared to lignocellulosic materials. During torrefaction, a high plastic content in the MSW feedstock could lead to a decrease in the overall energy yield of the resulting product. Additionally, the melting of plastics at elevated torrefaction temperatures can cause issues like slagging and fouling within the reactor, requiring additional measures for mitigation and potentially increasing operational costs. A more in-depth analysis that considers the influence of various material fractions on factors like heating value, yield, and reactor behavior would be beneficial for optimizing the torrefaction process for diverse MSW compositions.

Another limitation is the lack of information on MSW blending strategies. The review identifies the potential advantages of blending different MSW fractions to achieve an optimal lignocellulose content. Ideally, the MSW feedstock should have a specific range of lignocellulose content for efficient torrefaction. However, the review does not delve into existing strategies for creating suitable blends. For example, it would be helpful to explore how different MSW streams, such as yard waste and woody debris, can be incorporated into the main MSW stream to achieve the desired lignocellulose content. Additionally, recommendations for separation techniques or preprocessing methods to improve the homogeneity of the blended feedstock would be valuable for practical applications. Exploring these aspects could significantly improve the efficiency and effectiveness of MSW torrefaction by ensuring a consistent feedstock quality and optimizing the torrefaction process parameters for the blended material.

The review also lacks specific recommendations on optimal torrefaction parameters. Although it emphasizes the importance of optimizing these parameters for different MSW compositions, it does not provide concrete guidance or discuss the challenges associated with this tailoring process. Torrefaction parameters like temperature, residence time, and heating rate significantly influence the properties of the torrefied product. However, finding the optimal combination of these parameters for a specific MSW feedstock can be challenging. The review could be strengthened by including examples of how different MSW compositions might necessitate adjustments to these parameters. Additionally, acknowledging the complexities involved in this optimization process, such as the tradeoffs between maximizing energy yield and product quality, would provide a more realistic perspective for practical applications.

Finally, the review primarily focuses on the impact of lignocellulose content. While this is an important factor influencing the torrefaction process, other components of MSW, such as MC and the presence of nonlignocellulosic materials, can also influence the outcome. Moisture in the feedstock can significantly reduce the energy efficiency of the torrefaction process as it requires additional energy for evaporation. Additionally, the presence of nonlignocellulosic materials like metals and glass may require additional post-processing steps to separate them from the desired torrefied product. A more comprehensive analysis that considers these additional factors would provide a more holistic understanding

of MSW torrefaction and the potential challenges that need to be addressed for successful implementation.

7.2. Practical Implications of the Review. Despite the limitations, the review highlights several practical implications for utilizing MSW in torrefaction processes. First, the review emphasizes MSW as a viable source for torrefaction. This readily available and renewable resource offers a promising avenue for both waste management and energy production. MSW generation is a continuous process in urban centers, and torrefaction presents a sustainable solution for diverting this waste from landfills. The torrefied product can be used as a solid fuel source in various applications, including power generation, industrial processes, and even domestic heating. This not only reduces reliance on traditional fossil fuels but also creates a valuable energy source from waste materials.

Second, the review underscores the importance of characterization. By emphasizing the need to characterize the lignocellulose content of MSW before utilizing it in torrefaction processes, the review underscores the importance of a thorough understanding of the feedstock to optimize the process. Characterization involves analyzing the composition of the MSW feedstock, including the proportions of different materials and their properties. This information is crucial for selecting appropriate torrefaction parameters and predicting the potential yield and quality of the final product.

Third, the review suggests that MSW torrefaction can contribute to a more sustainable waste management system. This technology offers the possibility of diverting waste from landfills and converting it into a valuable energy source. Landfills are not only reaching capacity but also pose environmental concerns like methane emissions. MSW torrefaction presents an opportunity to reduce landfill waste while generating renewable energy. This can contribute to a more circular economy where waste materials are transformed into valuable resources. Finally, the limitations identified in the review provide valuable insights for future research. By investigating the impact of specific MSW components, developing optimal blending strategies, and exploring methods for tailoring torrefaction parameters for diverse feedstocks, researchers and practitioners can refine MSW torrefaction as a sustainable technology for both waste management and renewable energy generation.

8. Conclusions and Recommendations

This review delves into the complex relationship between MSW composition and its physical, chemical, and lignocellulosic properties, while also examining how these properties impact the outcomes of the torrefaction process. An important observation is the inconsistency in defining “MSW” across studies, where it is sometimes used to denote mixed waste streams and, at other times, to refer to individual waste components. Despite this variability, organic waste consistently emerges as the primary component across studies, followed by smaller fractions such as plastics, paper, glass, textiles, and metals. This diversity significantly influences the cellulose, hemicellulose, and lignin content of MSW. Both

the inherent lignocellulosic characteristics of the waste and the specific torrefaction process parameters employed significantly affect the quality and quantity of the resulting torrefied products. Moreover, the physical and chemical attributes of MSW contribute to variations in the biochar's calorific value and ash content. A noteworthy finding from our review is the positive correlation observed between the lignin content of MSW and biochar yield during torrefaction. However, further investigation is warranted to enhance biochar yields from MSW with lower lignin content. One potential strategy involves blending different MSW fractions to achieve a more balanced composition, although determining the optimal combinations and ratios requires further research. Additionally, exploring pretreatment methods to increase the effective lignin content of low-lignin MSW streams could be beneficial. Effectively utilizing MSW through torrefaction offers several advantages, including waste diversion from landfills, recovery of valuable energy resources, and contributing to a more sustainable waste management system. This review provides valuable insights for researchers, practitioners, and policymakers involved in developing and implementing sustainable waste management solutions using biomass conversion technologies like torrefaction. Standardizing the definition of MSW across studies would facilitate data comparison and improve our understanding of how specific waste fractions influence torrefaction outcomes. Looking ahead, future research should not only focus on optimizing biochar yield but also delve deeper into the impact of MSW composition on the quality and applications of the biochar produced. Understanding how variations in cellulose, hemicellulose, and lignin content influence the physical and chemical properties of biochar is essential for identifying its most suitable applications. This knowledge will be instrumental in advancing waste management practices and promoting a circular economy for energy production.

Data Availability

Data are available within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

Authors' Contributions

Ibrahim Luqman Mpungu was responsible for conceptualization, methodology, investigation, formal analysis, data curation, writing—original draft, and writing—review and editing. Patrick Nziu was responsible for conceptualization, investigation, data curation, and writing—original draft. Obadiah Maube was responsible for conceptualization, methodology, investigation, writing—original draft, and writing—review and editing. Josphat Igadwa Mwasiagi was responsible for resources, writing—review and editing, writing—review and editing, supervision, and funding acquisition. Benson Dulo was responsible for resources, validation, writing—review and editing, supervision, and funding acquisition. Ocident

Bongomin was responsible for writing and editing the revised manuscript, methodology, visualization, writing—review and editing, validation, and formal analysis.

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References

- [1] Y. Y. Gan, H. C. Ong, P. L. Show et al., "Torrefaction of microalgal biochar as potential coal fuel and application as bio-adsorbent," *Energy Conversion and Management*, vol. 165, pp. 152–162, 2018.
- [2] S. E. Ibitoye, T.-C. Jen, R. M. Mahamood, and E. T. Akinlabi, "Densification of agro-residues for sustainable energy generation: an overview," *Bioresources and Bioprocessing*, vol. 8, no. 1, pp. 1–19, 2021.
- [3] H. C. Ong, K. L. Yu, W.-H. H. Chen et al., "Variation of lignocellulosic biomass structure from torrefaction: a critical review," *Renewable and Sustainable Energy Reviews*, vol. 152, Article ID 111698, 2021.
- [4] P. N. Y. Yek, Y. W. Cheng, R. K. Liew et al., "Progress in the torrefaction technology for upgrading oil palm wastes to energy-dense biochar: a review," *Renewable and Sustainable Energy Reviews*, vol. 151, Article ID 111645, 2021.
- [5] J. Ribeiro, R. Godina, J. Matias, and L. Nunes, "Future perspectives of biomass torrefaction: review of the current state-of-the-art and research development," *Sustainability*, vol. 10, no. 7, Article ID 2323, 2018.
- [6] O. Bongomin and P. Nziu, "A critical review on the development and utilization of energy systems in Uganda," *The Scientific World Journal*, vol. 2022, Article ID 2599467, 25 pages, 2022.
- [7] C. M. S. da Silva, A. de C. O. Carneiro, B. R. Vital et al., "Biomass torrefaction for energy purposes—definitions and an overview of challenges and opportunities in Brazil," *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 2426–2432, 2018.
- [8] T. A. Mamvura and G. Danha, "Biomass torrefaction as an emerging technology to aid in energy production," *Heliyon*, vol. 6, no. 3, Article ID e03531, 2020.
- [9] H. Lu, Y. Gong, C. Areeprasert et al., "Integration of biomass torrefaction and gasification based on biomass classification: a review," *Energy Technology*, vol. 9, no. 5, pp. 1–20, 2021.
- [10] A. Knapczyk, S. Francik, M. Jewiarz, A. Zawi, and R. Francik, "Thermal treatment of biomass: a bibliometric analysis—the torrefaction case," *Energies*, vol. 14, no. 162, 2021.
- [11] K. A. Abdulyekeen, A. A. Umar, M. F. A. Patah, and W. M. A. W. Daud, "Torrefaction of biomass: production of enhanced solid biofuel from municipal solid waste and other types of biomass," *Renewable and Sustainable Energy Reviews*, vol. 150, Article ID 111436, 2021.
- [12] D. Mboowa, N. Banadda, N. Kiggundu, I. Kabenge, and A. J. Komakech, "Estimation of methane generation based on anaerobic digestion and mass balance at Kiteezi Landfill, Kampala, Uganda," *African Journal of Environmental Science and Technology*, vol. 9, no. 9, pp. 741–746, 2015.
- [13] EPA, "Advancing sustainable materials management: 2018 fact sheet," in *Assessing Trends in Materials Generation and Management in the United States*, EPA, 2020.

- [14] J. W. Gabhane, V. P. Bhangé, P. D. Patil, S. T. Bankar, and S. Kumar, "Recent trends in biochar production methods and its application as a soil health conditioner: a review," *SN Applied Sciences*, vol. 2, no. 7, pp. 1–21, 2020.
- [15] J. J. Abdullah, D. Greetham, N. Pensupa, G. A. Tucker, and C. Du, "Optimizing cellulase production from municipal solid waste (MSW) using solid state fermentation (SSF)," *Journal of Fundamentals of Renewable Energy and Applications*, vol. 6, no. 3, 2016.
- [16] S. Farmanbordar, H. Amiri, and K. Karimi, "Synergy of municipal solid waste co-processing with lignocellulosic waste for improved biobutanol production," *Waste Management*, vol. 118, pp. 45–54, 2020.
- [17] E. Schmitt, R. Bura, R. Gustafson, J. Cooper, and A. Vajzovic, "Converting lignocellulosic solid waste into ethanol for the State of Washington: an investigation of treatment technologies and environmental impacts," *Bioresource Technology*, vol. 104, pp. 400–409, 2012.
- [18] A. K. Das, M. N. Islam, M. M. Billah, and A. Sarker, "COVID-19 and municipal solid waste (MSW) management: a review," *Environmental Science and Pollution Research*, vol. 28, no. 23, pp. 28993–29008, 2021.
- [19] Y. D. Tong, T. D. X. Huynh, and T. D. Khong, "Understanding the role of informal sector for sustainable development of municipal solid waste management system: a case study in Vietnam," *Waste Management*, vol. 124, pp. 118–127, 2021.
- [20] M. Azam, S. S. Jahromy, W. Raza, C. Jordan, M. Harasek, and F. Winter, "Comparison of the combustion characteristics and kinetic study of coal, municipal solid waste, and refuse-derived fuel: model-fitting methods," *Energy Science & Engineering*, vol. 7, no. 6, pp. 2646–2657, 2019.
- [21] W.-H. Chen, B.-J. Lin, Y.-Y. Lin et al., "Progress in biomass torrefaction: principles, applications and challenges," *Progress in Energy and Combustion Science*, vol. 82, Article ID 100887, 2021.
- [22] L. Dai, Y. Wang, Y. Liu et al., "Integrated process of lignocellulosic biomass torrefaction and pyrolysis for upgrading bio-oil production: a state-of-the-art review," *Renewable and Sustainable Energy Reviews*, vol. 107, pp. 20–36, 2019.
- [23] S. Negi, G. Jaswal, K. Dass, K. Mazumder, S. Elumalai, and J. K. Roy, "Torrefaction: a sustainable method for transforming of agri- wastes to high energy density solids (biocoal)," *Reviews in Environmental Science and Bio/Technology*, vol. 19, no. 2, pp. 463–488, 2020.
- [24] T. R. Sarker, S. Nanda, A. K. Dalai, and V. Meda, "A review of torrefaction technology for upgrading lignocellulosic biomass to solid biofuels," *BioEnergy Research*, vol. 14, no. 2, pp. 645–669, 2021.
- [25] M. A. Fuad, H. Mohd, M. Faizal, F. Nasir, M. A. H. M. Fuad, and M. F. Hasan, "Microwave torrefaction for viable fuel production: a review on theory, affecting factors, potential and challenges," *Fuel*, vol. 253, pp. 512–526, 2019.
- [26] Y. Niu, Y. Lv, Y. Lei et al., "Biomass torrefaction: properties, applications, challenges, and economy," *Renewable and Sustainable Energy Reviews*, vol. 115, Article ID 109395, 2019.
- [27] T. O. Olugbade and O. T. Ojo, "Biomass torrefaction for the production of high-grade solid biofuels: a review," *BioEnergy Research*, vol. 13, no. 4, pp. 999–1015, 2020.
- [28] J. S. Tumuluru, S. Sokhansanj, J. R. Hess, C. T. Wright, and R. D. Boardman, "A review on biomass torrefaction process and product properties for energy applications," *Industrial Biotechnology*, vol. 7, no. 5, pp. 384–401, 2011.
- [29] D. Nhuchhen, P. Basu, and B. Acharya, "A comprehensive review on biomass torrefaction," *International Journal of Renewable Energy & Biofuels*, vol. 2014, pp. 1–56, 2014.
- [30] W. Chen, J. Peng, and X. T. Bi, "A state-of-the-art review of biomass torrefaction, densification and applications," *Renewable and Sustainable Energy Reviews*, vol. 44, pp. 847–866, 2015.
- [31] Q.-V. Bach and Ø. Skreiberg, "Upgrading biomass fuels via wet torrefaction: a review and comparison with dry torrefaction," *Renewable and Sustainable Energy Reviews*, vol. 54, pp. 665–677, 2016.
- [32] S. Barskov, M. Zappi, P. Buchireddy et al., "Torrefaction of biomass: a review of production methods for biocoal from cultured and waste lignocellulosic feedstocks," *Renewable Energy*, vol. 142, pp. 624–642, 2019.
- [33] C. He, C. Tang, C. Li et al., "Wet torrefaction of biomass for high quality solid fuel production: a review," *Renewable and Sustainable Energy Reviews*, vol. 91, pp. 259–271, 2018.
- [34] A. A. Adeleke, J. K. Odusote, P. P. Ikubanni, O. A. Lasode, M. Malathi, and D. Paswan, "Essential basics on biomass torrefaction, densification and utilization," *International Journal of Energy Research*, vol. 45, no. 2, pp. 1375–1395, 2021.
- [35] U. M. A. Devaraja, C. L. W. Dissanayake, D. S. Gunarathne, and W.-H. Chen, "Oxidative torrefaction and torrefaction-based biorefining of biomass: a critical review," *Biofuel Research Journal*, vol. 9, no. 3, pp. 1672–1696, 2022.
- [36] M. A. Waheed, O. A. Akogun, and C. C. Enweremadu, "An overview of torrefied bioresource briquettes: quality-influencing parameters, enhancement through torrefaction and applications," *Bioresources and Bioprocessing*, vol. 9, no. 1, Article ID 122, 2022.
- [37] M. Ivanovski, A. Petrovič, D. Goričanec, D. Urbanč, and M. Simonič, "Exploring the properties of the torrefaction process and its prospective in treating lignocellulosic material," *Energies*, vol. 16, no. 18, pp. 1–21, 2023.
- [38] M. A. Sukiran, F. Abnisa, W. M. A. W. Daud, N. A. Bakar, and S. K. Loh, "A review of torrefaction of oil palm solid wastes for biofuel production," *Energy Conversion and Management*, vol. 149, pp. 101–120, 2017.
- [39] N. Khan, S. Mohan, and P. Dinesha, "Regimes of hydrochar yield from hydrothermal degradation of various lignocellulosic biomass: a review," *Journal of Cleaner Production*, vol. 288, Article ID 125629, 2021.
- [40] M. Ivanovski, D. Urbanč, A. Petrovic, J. Stergar, D. Goricaneč, and M. Simonic, "Improving lignocellulosic and non-lignocellulosic biomass characteristics through torrefaction process," *Applied Sciences*, vol. 12, no. 23, Article ID 12210, 2022.
- [41] K. Nakason, J. Pathomrotsakun, and W. Kraithong, "Torrefaction of agricultural wastes: influence of lignocellulosic types and treatment temperature on fuel properties of biochar," *International Energy Journal*, vol. 19, pp. 253–266, 2019.
- [42] S. Gerassimidou, C. A. Velis, P. T. Williams, and D. Komilis, "Characterisation and composition identification of waste-derived fuels obtained from municipal solid waste using thermogravimetry: a review," *Waste Management & Research: The Journal for a Sustainable Circular Economy*, vol. 38, no. 9, pp. 942–965, 2020.
- [43] A. T. Hoang, S. Nizetic, H. C. Ong et al., "Insight into the recent advances of microwave pretreatment technologies for the conversion of lignocellulosic biomass into sustainable biofuel," *Chemosphere*, vol. 281, Article ID 130878, 2021.
- [44] J. Amulen, H. Kasedde, J. Serugunda, and J. D. Lwanyaga, "The potential of energy recovery from municipal solid waste in

- Kampala City, Uganda by incineration,” *Energy Conversion and Management*: X, vol. 14, Article ID 100204, 2022.
- [45] K. P. Contreras, J. M. S. Yáñez, Q. Aguilar-virgen, P. Taboada-Gonzalez, and L. Marquez-Benavides, “Potential for methane generation by lignocellulosic household waste,” *Sustainability*, vol. 10, no. 10, pp. 1–15, 2018.
- [46] A. J. Komakech, N. E. Banadda, J. R. Kinobe et al., “Characterization of municipal waste in Kampala, Uganda,” *Journal of the Air & Waste Management Association*, vol. 64, no. 3, pp. 340–348, 2014.
- [47] R. Nandhini, D. Berslin, B. Sivaprakash, N. Rajamohan, and D.-V. N. Vo, “Thermochemical conversion of municipal solid waste into energy and hydrogen: a review,” *Environmental Chemistry Letters*, vol. 20, no. 3, pp. 1645–1669, 2022.
- [48] L. Sekhohola-Dlamini and M. Tekere, “Microbiology of municipal solid waste landfills: a review of microbial dynamics and ecological influences in waste bioprocessing,” *Biodegradation*, vol. 31, no. 1–2, pp. 1–21, 2020.
- [49] A. Almasi, M. Mohammadi, A. Azizi et al., “Assessing the knowledge, attitude and practice of the kermanshahi women towards reducing, recycling and reusing of municipal solid waste,” *Resources, Conservation and Recycling*, vol. 141, pp. 329–338, 2019.
- [50] J. R. Kinobe, C. B. Niwagaba, G. Gebresenbet, A. J. Komakech, and B. Vinnerås, “Mapping out the solid waste generation and collection models: the case of Kampala City,” *Journal of the Air & Waste Management Association*, vol. 65, no. 2, pp. 197–205, 2015.
- [51] E. N. Richard, A. Hilonga, R. L. Machunda, and K. N. Njau, “Life cycle analysis of potential municipal solid wastes management scenarios in Tanzania: the case of Arusha City,” *Sustainable Environment Research*, vol. 31, no. 1, pp. 1–13, 2021.
- [52] J. Okot-Okumu and R. Nyenje, “Municipal solid waste management under decentralisation in Uganda,” *Habitat International*, vol. 35, no. 4, pp. 537–543, 2011.
- [53] D. Cudjoe and P. M. Acquah, “Environmental impact analysis of municipal solid waste incineration in African countries,” *Chemosphere*, vol. 265, Article ID 129186, 2021.
- [54] C. Joshi, J. Seay, and N. Banadda, “A perspective on a locally managed decentralized circular economy for waste plastic in developing countries,” *Environmental Progress & Sustainable Energy*, vol. 38, no. 1, pp. 3–11, 2019.
- [55] D. Mboowa, I. Kabenge, N. Banadda, and N. Kiggundu, “Energy potential of municipal solid waste in kampala, a case study of Kiteezi landfill site,” *International Scholars Journal*, vol. 4, no. 1, pp. 190–194, 2017.
- [56] D. R. Pathak, B. Mainali, H. Abuel-Naga, M. Angove, and I. Kong, “Quantification and characterization of the municipal solid waste for sustainable waste management in newly formed municipalities of Nepal,” *Waste Management & Research*, vol. 38, no. 9, pp. 1007–1018, 2020.
- [57] T. Kabera, D. C. Wilson, and H. Nishimwe, “Benchmarking performance of solid waste management and recycling systems in East Africa: comparing Kigali Rwanda with other major cities,” *Waste Management & Research: The Journal for a Sustainable Circular Economy*, vol. 37, no. 1_suppl, pp. 58–72, 2019.
- [58] D. Christensen, D. Drysdale, K. Hansen, J. Vanhille, and A. Wolf, “Partnerships for development: municipal solid waste management in Kasese, Uganda,” *Waste Management & Research: The Journal for a Sustainable Circular Economy*, vol. 32, no. 11, pp. 1063–1072, 2014.
- [59] G. Ntagisanimana, Z. Yu, and H. Ma, “Current situation of solid waste management in East African countries and the proposal for sustainable management,” *African Journal of Environmental Science and Technology*, vol. 15, no. 1, pp. 1–15, 2021.
- [60] L. Hirpe and C. Yeom, “Municipal solid waste management policies, practices, and challenges in Ethiopia: a systematic review,” *Sustainability*, vol. 13, no. 20, Article ID 11241, 2021.
- [61] S. van Niekerk and V. Wegmann, “Municipal solid waste management services in Africa,” 2019.
- [62] Q. N. Hoang, M. Vanierschot, J. Blondeau, T. Croymans, R. Pittoors, and J. Van Caneghem, “Review of numerical studies on thermal treatment of municipal solid waste in packed bed combustion,” *Fuel Communications*, vol. 7, Article ID 100013, 2021.
- [63] B. Acharya, A. Dutta, and J. Minaret, “Review on comparative study of dry and wet torrefaction,” *Sustainable Energy Technologies and Assessments*, vol. 12, pp. 26–37, 2015.
- [64] X. Yuan, B. Wen, X. Ma et al., “Enhancing the anaerobic digestion of lignocellulose of municipal solid waste using a microbial pretreatment method,” *Bioresource Technology*, vol. 154, pp. 1–9, 2014.
- [65] T. G. Bridgeman, J. M. Jones, I. Shield, and P. T. Williams, “Torrefaction of reed canary grass, wheat straw and willow to enhance solid fuel qualities and combustion properties,” *Fuel*, vol. 87, no. 6, pp. 844–856, 2008.
- [66] T. Hardianto, F. F. Pambudi, and A. R. Irhamna, “A study on lignin characteristic as internal binder in hot briquetting process of organic municipal solid waste,” in *AIP Conference Proceedings*, vol. 1984, p. 30013, AIP, 2018.
- [67] A. R. Irhamna, A. I. Utama, and T. Hardianto, “Preliminary investigation on the starch potential as natural binder in the hot binderless briquetting process of torrefied municipal solid waste,” in *AIP Conference Proceedings*, vol. 1984, AIP, 2018.
- [68] Y. P. Rago, F.-X. Collard, J. F. Görgens, D. Surroop, and R. Mohee, “Torrefaction of biomass and plastic from municipal solid waste streams and their blends: evaluation of interactive effects,” *Fuel*, vol. 277, Article ID 118089, 2020.
- [69] K. Manatura, “Inert torrefaction of sugarcane bagasse to improve its fuel properties,” *Case Studies in Thermal Engineering*, vol. 19, Article ID 100623, 2020.
- [70] J. Poudel, T.-I. Ohm, and S. C. Oh, “A study on torrefaction of food waste,” *Fuel*, vol. 140, pp. 275–281, 2015.
- [71] F. Amalina, A. S. A. Razak, S. Krishnan, H. Sulaiman, A. W. Zularisam, and M. Nasrullah, “Biochar production techniques utilizing biomass waste-derived materials and environmental applications—a review,” *Journal of Hazardous Materials Advances*, vol. 7, Article ID 100134, 2022.
- [72] K. Wang and J. W. Tester, “Sustainable management of unavoidable biomass wastes,” *Green Energy and Resources*, vol. 1, no. 1, Article ID 100005, 2023.
- [73] L. Puri, Y. Hu, and G. Naterer, “Critical review of the role of ash content and composition in biomass pyrolysis,” *Frontiers in Fuels*, vol. 2, pp. 1–19, 2024.
- [74] H. Yuan, Q. Yang, Y. Wang, J. Gu, M. He, and F. Sun, “Impact of torrefaction on the fuel properties and combustion characteristics of compost of food waste and sawdust,” *Energy & Fuels*, vol. 32, no. 3, pp. 3469–3476, 2018.
- [75] P. Siritheerasas, P. Waiyanate, H. Sekiguchi, and S. Kodama, “Torrefaction of municipal solid waste (MSW) pellets using microwave irradiation with the assistance of the char of

- agricultural residues,” *International Conference on Alternative Energy in Developing Countries and Emerging Economies*, vol. 138, pp. 668–673, 2017.
- [76] M. Azam, S. S. Jahromy, W. Raza et al., “Status, characterization, and potential utilization of municipal solid waste as renewable energy source: Lahore case study in Pakistan,” *Environment International*, vol. 134, Article ID 105291, 2020.
- [77] R. A. Rasid, T. M. Chin, M. Ismail, and R. N. U. A. Rahman, “Effect of torrefaction temperature, residence time and particle size on the properties of torrefied food waste,” *Indonesian Journal of Chemistry*, vol. 19, no. 3, pp. 753–760, 2019.
- [78] M. S. Santanna, E. A. Silveira, and A. Caldeira-pires, “Thermochemical pathways for municipal lignocellulosic waste as biofuel,” *29th European Biomass Conference and Exhibition*, pp. 1–5, 2021.
- [79] S. Y. Park, S. J. Kim, K. C. Oh, L. H. Cho, Y. K. Jeon, and D. H. Kim, “Evaluation of the optimal conditions for oxygen-rich and oxygen-lean torrefaction of forestry byproduct as a fuel,” *Energies*, vol. 16, no. 12, Article ID 4763, 2023.
- [80] M. Shehzad, A. Asghar, N. Ramzan, U. Aslam, and M. M. Bello, “Impacts of non-oxidative torrefaction conditions on the fuel properties of indigenous biomass (bagasse),” *Waste Management and Research*, vol. 38, no. 11, pp. 1284–1294, 2020.
- [81] A. I. Osman, N. Mehta, A. M. Elgarahy et al., “Conversion of biomass to biofuels and life cycle assessment: a review,” *Environmental Chemistry Letters*, vol. 19, no. 6, 2021.
- [82] A. Farooq, P. Haputta, T. Silalertruksa, and S. H. Gheewala, “A framework for the selection of suitable waste to energy technologies for a sustainable municipal solid waste management system,” *Frontiers in Sustainability*, vol. 2, pp. 1–17, 2021.
- [83] W. H. L. Stafford, “WtE Best Practices and Perspectives in Africa,” in *Municipal Solid Waste Energy Conversion in Developing Countries*, pp. 185–217, Elsevier Inc, 2020.
- [84] A. S. Giwa, N. Ali, M. Vakili, X. Guo, D. Liu, and K. Wang, “Opportunities for holistic waste stream valorization from food waste treatment facilities: a review,” *Reviews in Chemical Engineering*, vol. 38, no. 1, pp. 35–53, 2022.
- [85] C. Mukherjee, J. Denney, E. G. Mbonimpa, J. Slagley, and R. Bhowmik, “A review on municipal solid waste-to-energy trends in the USA,” *Renewable and Sustainable Energy Reviews*, vol. 119, Article ID 109512, 2020.
- [86] A. I. Osman, Z. Y. Lai, M. Farghali et al., “Optimizing biomass pathways to bioenergy and biochar application in electricity generation, biodiesel production, and biohydrogen production,” *Environmental Chemistry Letters*, vol. 21, no. 5, pp. 2639–2705, 2023.
- [87] Y. V. Fan, J.D. J.D. Klemeš, C. T. Lee, and S. Perry, “Anaerobic digestion of municipal solid waste: energy and carbon emission footprint,” *Journal of Environmental Management*, vol. 223, pp. 888–897, 2018.
- [88] F. Güleç, O. Williams, E. T. Kostas, A. Samson, and E. Lester, “A comprehensive comparative study on the energy application of chars produced from different biomass feedstocks via hydrothermal conversion, pyrolysis, and torrefaction,” *Energy Conversion and Management*, vol. 270, Article ID 116260, 2022.
- [89] L. Matsakas, Q. Gao, S. Jansson, U. Rova, and P. Christakopoulos, “Green conversion of municipal solid wastes into fuels and chemicals,” *Electronic Journal of Biotechnology*, vol. 26, pp. 69–83, 2017.
- [90] Z. Mousania, R. Rafiee, M. Moeinaddini, and J. D. Atkinson, “Anaerobic digestion of the organic fraction of municipal solid waste in a simulated bioreactor to improve predictive modeling of landfill systems,” *Journal of Hazardous Materials Advances*, vol. 13, Article ID 100396, 2024.
- [91] P. Seruga, “The municipal solid waste management system with anaerobic digestion,” *Energies*, vol. 14, no. 8, Article ID 2067, 2021.
- [92] G. Mtui and Y. Nakamura, “Bioconversion of lignocellulosic waste from selected dumping sites in Dar es Salaam, Tanzania,” *Biodegradation*, vol. 16, no. 6, pp. 493–499, 2005.
- [93] K. Kumar, L. Ding, H. Zhao, and M. H. Cheng, “Waste-to-energy pipeline through consolidated fermentation-microbial fuel cell (MFC) system,” *Processes*, vol. 11, no. 8, pp. 1–22, 2023.
- [94] Y. Zhang, X. Wang, W. Zhu et al., “Anaerobic fermentation of organic solid waste: recent updates in substrates, products, and the process with multiple products co-production,” *Environmental Research*, vol. 233, Article ID 116444, 2023.
- [95] A.-P. Becerra-Quiroz, S.-A. Rodríguez-Morón, P.-A. Acevedo-Pabón, J. Rodrigo-Illarri, and M.-E. Rodrigo-Clavero, “Evaluation of the dark fermentation process as an alternative for the energy valorization of the organic fraction of municipal solid waste (OFMSW) for Bogotá, Colombia,” *Applied Sciences*, vol. 14, no. 8, Article ID 3437, 2024.
- [96] A. Škorjanc, D. Goričanec, and D. Urbančič, “Assessing energy potential and chemical composition of food waste thermodynamic conversion products: a literature review,” *Energies*, vol. 17, no. 8, Article ID 1897, 2024.
- [97] S. Jha, S. Nanda, B. Acharya, and A. K. Dalai, “A review of thermochemical conversion of waste biomass to biofuels,” *Energies*, vol. 15, no. 17, Article ID 6352, 2022.
- [98] P. F. Chiang, M. J. Claire, S. Han, N. J. Maurice, and A. S. Giwa, “Effectiveness of torrefaction by-products as additive in vacuum blackwater under anaerobic digestion and economic significance,” *Processes*, vol. 11, no. 12, Article ID 3330, 2023.
- [99] S. Safarian, “Performance analysis of sustainable technologies for biochar production: a comprehensive review,” *Energy Reports*, vol. 9, pp. 4574–4593, 2023.
- [100] M. Preradovic, S. Papuga, and A. Kolundžija, “Torrefaction: process review,” *Periodica Polytechnica Chemical Engineering*, vol. 67, no. 1, pp. 49–61, 2023.
- [101] E. A. Christoforou and P. A. Fokaides, “Recent advancements in torrefaction of solid biomass,” *Current Sustainable/ Renewable Energy Reports*, vol. 5, no. 2, pp. 163–171, 2018.
- [102] A. Białowiec, J. Pulka, M. Styczyńska et al., “Is biochar from the torrefaction of sewage sludge hazardous waste?” *Materials*, vol. 13, no. 16, Article ID 3544, 2020.
- [103] Y. P. Rago, R. Mohee, and D. Surroop, “A review of thermochemical technologies for the conversion of waste biomass to biofuel and energy in developing countries,” *Green Energy and Technology*, pp. 127–143, 2018.
- [104] K. O. Iwuozor, E. Chizitere, J. O. Ighalo, F. O. Omoarukhe, P. E. Omuku, and A. George, “A review on the thermochemical conversion of sugarcane bagasse into biochar,” *Cleaner Materials*, vol. 6, Article ID 100162, 2022.
- [105] D. Mahesh, S. Ahmad, R. Kumar, S. R. Chakravarthy, and R. Vinu, “Hydrothermal liquefaction of municipal solid wastes for high quality bio-crude production using glycerol as co-solvent,” *Bioresource Technology*, vol. 339, Article ID 125537, 2021.
- [106] D. Yu, J. Guo, J. Meng, and T. Sun, “Biofuel production by hydro-thermal liquefaction of municipal solid waste: process characterization and optimization,” *Chemosphere*, vol. 328, Article ID 138606, 2023.

- [107] X. Tan, F. Zhang, H. Wang, and S.-H. Ho, "The magic of algae-based biochar: advantages, preparation, and applications," *Bioengineered*, vol. 14, no. 1, 2023.
- [108] M. Ganesapillai, R. Mehta, A. Tiwari et al., "Waste to energy: a review of biochar production with emphasis on mathematical modelling and its applications," *Heliyon*, vol. 9, no. 4, Article ID e14873, 2023.
- [109] M. M. Hasan, M. G. Rasul, M. I. Jahirul, and M. Mofijur, "Fuelling the future: unleashing energy and exergy efficiency from municipal green waste pyrolysis," *Fuel*, vol. 357, Article ID 129815, 2024.
- [110] T. Wang, Y. Zhai, Y. Zhu, C. Li, and G. Zeng, "A review of the hydrothermal carbonization of biomass waste for hydrochar formation: process conditions, fundamentals, and physico-chemical properties," *Renewable and Sustainable Energy Reviews*, vol. 90, pp. 223–247, 2018.
- [111] A. Khosravi, H. Zheng, Q. Liu, M. Hashemi, Y. Tang, and B. Xing, "Production and characterization of hydrochars and their application in soil improvement and environmental remediation," *Chemical Engineering Journal*, vol. 430, Article ID 133142, 2022.
- [112] J. Petrović, M. Ercegović, M. Simić et al., "Hydrothermal carbonization of waste biomass: a review of hydrochar preparation and environmental application," *Processes*, vol. 12, no. 1, Article ID 207, 2024.
- [113] Y. Shi, Y. Wang, Y. Yue, J. Zhao, T. Maraseni, and G. Qian, "Unbalanced status and multidimensional influences of municipal solid waste management in Africa," *Chemosphere*, vol. 281, no. 99, Article ID 130884, 2021.
- [114] T. Omara, N. Othieno, J. Obonge, S. Ssebulime, and M. Kansime, "Characterization and prognostication of wastes generated by industries in Kampala industrial and business park—Namanve," *OALib*, vol. 6, no. 3, pp. 1–15, 2019.
- [115] L. Chen, C. Wen, W. Wang et al., "Combustion behaviour of biochars thermally pretreated via torrefaction, slow pyrolysis, or hydrothermal carbonisation and co-fired with pulverised coal," *Renewable Energy*, vol. 161, pp. 867–877, 2020.
- [116] D. K. Omol, O. Acaye, D. F. Okot, and O. Bongomin, "Production of fuel oil from municipal plastic wastes using thermal and catalytic pyrolysis," *Journal of Energy Research and Reviews*, vol. 4, no. 2, pp. 1–8, 2020.
- [117] R. Volpe, A. Messineo, M. Millan, M. Volpe, and R. Kandiyoti, "Assessment of olive wastes as energy source: pyrolysis, torrefaction and the key role of H loss in thermal breakdown," *Energy*, vol. 82, pp. 119–127, 2015.
- [118] P. Piersa, H. Unyay, S. Szufa et al., "An extensive review and comparison of modern biomass torrefaction reactors vs. biomass pyrolysis—part 1," *Energies*, vol. 15, no. 6, Article ID 2227, 2022.
- [119] M. Maniscalco, G. Infurna, G. Caputo, L. Botta, and N. T. Dintcheva, "Slow pyrolysis as a method for biochar production from carob waste: process investigation and products' characterization," *Energies*, vol. 14, no. 24, Article ID 8457, 2021.
- [120] A. Tomczyk, Z. Sokolowska, and P. Boguta, "Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects," *Reviews in Environmental Science and Bio/Technology*, vol. 19, no. 1, pp. 191–215, 2020.
- [121] G. Sztancs, A. Kovacs, A. J. Toth, P. Mizsey, P. Billen, and D. Fozzer, "Catalytic hydrothermal carbonization of microalgae biomass for low-carbon emission power generation: the environmental impacts of hydrochar co-firing," *Fuel*, vol. 300, Article ID 120927, 2021.
- [122] C. Wang, S. Zhang, S. Wu, M. Sun, and J. Lyu, "Multi-purpose production with valorization of wood vinegar and briquette fuels from wood sawdust by hydrothermal process," *Fuel*, vol. 282, Article ID 118775, 2020.
- [123] T. Wang, Y. Zhai, Y. Zhu et al., "Feedwater pH affects phosphorus transformation during hydrothermal carbonization of sewage sludge," *Bioresource Technology*, vol. 245, pp. 182–187, 2017.
- [124] G. Zhang, Y. Sun, and Y. Xu, "Review of briquette binders and briquetting mechanism," *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 477–487, 2018.
- [125] H. S. Kambo and A. Dutta, "A comparative review of biochar and hydrochar in terms of production, physico-chemical properties and applications," *Renewable and Sustainable Energy Reviews*, vol. 45, pp. 359–378, 2015.
- [126] S. Bipin, S. Pandit, P. Kumar et al., "Recent advances in the application of biochar in microbial electrochemical cells," *Fuel*, vol. 311, Article ID 122501, 2022.
- [127] T. Sharma, I. Gbolahan, A. Bhushan et al., "Parametric influence of process conditions on thermochemical techniques for biochar production: a state-of-the-art review," *Journal of the Energy Institute*, vol. 113, no. January, Article ID 101559, 2024.
- [128] G. J. Miito and N. Banadda, "Waste to energy technologies for solid waste management a case study of Uganda," *Agricultural Engineering International: CIGR Journal*, vol. 18, no. 3, pp. 136–146, 2016.
- [129] B. B. Nyakuma, A. Ahmada, A. Joharia, T. A. T. Abdullaha, O. Oladokuna, and H. Alkali, "Gasification of oil palm empty fruit bunches (OPEFB) briquettes for bio-syngas production," *Journal of Technology*, vol. 3, no. 78, pp. 83–88, 2016.
- [130] B. X. Zhao, K. Li, M. E. Lamm, S. Celik, L. Wei, and S. Ozcan, "Solid waste gasification: comparison of single- and multi-staged reactors," in *Gasification*, Intechopen, 2021.
- [131] O. Bongomin, C. Nzila, J. I. Mwasiagi, and O. Maube, "Exploring insights in biomass and waste gasification via ensemble machine learning models and interpretability techniques," *International Journal of Energy Research*, vol. 2024, no. 1, Article ID 6087208, 10 pages, 2024.
- [132] S. Pang, "Fuel flexible gas production: biomass, coal and bio-solid wastes," in *Fuel Flexible Energy Generation*, pp. 241–269, Elsevier Ltd., 2020.
- [133] A. Anniwaer, N. Chaihad, M. Zhang et al., "Hydrogen-rich gas production from steam co-gasification of banana peel with agricultural residues and woody biomass," *Waste Management*, vol. 125, pp. 204–214, 2021.
- [134] J. George, P. Arun, and C. Muraleedharan, "Experimental investigation on co-gasification of coffee husk and sawdust in a bubbling fluidised bed gasifier," *Journal of the Energy Institute*, vol. 92, no. 6, pp. 1977–1986, 2019.
- [135] N. Indrawan, S. Thapa, P. R. Bhoi, R. L. Huhnke, and A. Kumar, "Electricity power generation from co-gasification of municipal solid wastes and biomass: generation and emission performance," *Energy*, vol. 162, pp. 764–775, 2018.
- [136] C. Smith Lewin, A. R. Fonseca de Aguiar Martins, and F. Pradelle, "Modelling, simulation and optimization of a solid residues downdraft gasifier: application to the co-gasification of municipal solid waste and sugarcane bagasse," *Energy*, vol. 210, Article ID 118498, 2020.
- [137] B. Cabuk, G. Duman, J. Yanik, and H. Olgun, "Effect of fuel blend composition on hydrogen yield in co-gasification of coal and non-woody biomass," *International Journal of Hydrogen Energy*, vol. 45, no. 5, pp. 3435–3443, 2020.

- [138] Z. He, Y. Sun, S. Cheng et al., "The enhanced rich H₂ from co-gasification of torrefied biomass and low rank coal: the comparison of dry/wet torrefaction, synergetic effect and prediction," *Fuel*, vol. 287, Article ID 119473, 2021.
- [139] G. Wang, J. Zhang, X. Huang, X. Liang, X. Ning, and R. Li, "Co-gasification of petroleum coke-biomass blended char with steam at temperatures of 1173-1373 K," *Applied Thermal Engineering*, vol. 137, pp. 678–688, 2018.
- [140] J. S. Tumuluru, B. Ghiasi, N. R. Soelberg, and S. Sokhansanj, "Biomass torrefaction process, product properties, reactor types, and moving bed reactor design concepts," *Frontiers in Energy Research*, vol. 9, pp. 1–20, 2021.
- [141] A. Leontiev, B. Kichatov, A. Korshunov et al., "Oxidative torrefaction of pine pellets in the quiescent layer of mineral filler," *Fuel Processing Technology*, vol. 182, pp. 113–122, 2018.
- [142] S. Pambudi, J. S. Jongyingcharoen, and W. Saechua, "Thermochemical treatment of spent coffee grounds via torrefaction: a statistical evidence of biochar properties similarity between inert and oxidative conditions," *Results in Engineering*, vol. 21, Article ID 102012, 2024.
- [143] C. Lokmit, K. Nakason, S. Kuboon, A. Jiratanachotikul, and B. Panyapinyopol, "A comparison of char fuel properties derived from dry and wet torrefaction of oil palm leaf and its techno-economic feasibility," *Materials Science for Energy Technologies*, vol. 6, pp. 192–204, 2023.
- [144] Z. Huang, L. Shi, Y. Muhammad, and L. Li, "Effect of ionic liquid assisted hydrothermal carbonization on the properties and gasification reactivity of hydrochar derived from eucalyptus," *Journal of Colloid And Interface Science*, vol. 586, pp. 423–432, 2021.
- [145] P. Brachi, F. Miccio, G. Ruoppolo, and M. Miccio, "Pressurized steam torrefaction of biomass: focus on solid, liquid and gas phases distribution," *Industrial & Engineering Chemistry Research*, vol. 56, no. 42, pp. 12163–12173, 2017.
- [146] K. J. Moscicki, L. Niedzwiecki, P. Owczarek, and M. Wnukowski, "Commoditization of wet and high ash biomass: wet torrefaction—a review," *Journal of Power Technologies*, vol. 97, no. 4, pp. 354–369, 2017.
- [147] G. Mohanakrishna and J. A. Modestra, "Value addition through biohydrogen production and integrated processes from hydrothermal pretreatment of lignocellulosic biomass," *Bioresource Technology*, vol. 369, Article ID 128386, 2023.
- [148] A. Kostyniuk and B. Likozar, "Wet torrefaction of biomass waste into value-added liquid product (5-HMF) and high quality solid fuel (hydrochar) in a nitrogen atmosphere," *Renewable Energy*, vol. 226, Article ID 120450, 2024.
- [149] K. L. Yu, W.-H. Chen, H.-K. Sheen et al., "Production of microalgal biochar and reducing sugar using wet torrefaction with microwave-assisted heating and acid hydrolysis pretreatment," *Renewable Energy*, vol. 156, pp. 349–360, 2020.
- [150] S. Han, C. Park, G. Kwon, N. Kim, J. Kim, and S.-H. Lee, "Ionic liquid pretreatment of lignocellulosic," *Journal of Forest and Environmental Science*, vol. 36, no. 2, pp. 69–77, 2020.
- [151] B. Roy, P. Kleine-möllhoff, and A. Dalibard, "Superheated steam torrefaction of biomass residues with valorisation of platform chemicals—part 1: ecological assessment," *Sustainability*, vol. 14, no. 3, Article ID 1212, 2022.
- [152] D. Zhang, X. Chen, Z. Qi et al., "Superheated steam as carrier gas and the sole heat source to enhance biomass torrefaction," *Bioresource Technology*, vol. 331, Article ID 124955, 2021.
- [153] T. R. K. C. Doddapaneni, L. Pärn, and T. Kikas, "Torrefaction of pulp industry sludge to enhance its fuel characteristics," *Energies*, vol. 15, no. 17, Article ID 6175, 2022.
- [154] K. Nakason, P. Khemthong, W. Kraithong et al., "Upgrading properties of biochar fuel derived from cassava rhizome via torrefaction: effect of sweeping gas atmospheres and its economic feasibility," *Case Studies in Thermal Engineering*, vol. 23, Article ID 100823, 2021.
- [155] A. Dyjakon, T. Noszczyk, and M. Smędzik, "The influence of torrefaction temperature on hydrophobic properties of waste biomass from food processing," *Energies*, vol. 12, no. 24, Article ID 4609, 2019.
- [156] A. Dyjakon, T. Noszczyk, Ł. Sobol, and D. Misiakiewicz, "Influence of torrefaction temperature and climatic chamber operation time on hydrophobic properties of agri-food biomass investigated using the EMC method," *Energies*, vol. 14, no. 17, Article ID 5299, 2021.
- [157] A. Dyjakon, Ł. Sobol, T. Noszczyk, and J. Mitreğa, "The impact of torrefaction temperature on the physical–chemical properties of residual exotic fruit (avocado, mango, lychee) seeds," *Energies*, vol. 15, no. 2, Article ID 612, 2022.
- [158] A. Dyjakon and T. Noszczyk, "Alternative fuels from forestry biomass residue: torrefaction process of horse chestnuts, oak acorns, and spruce cones," *Energies*, vol. 13, no. 10, Article ID 2468, 2020.
- [159] N. Kaewtrakulchai, S. Wongrekdee, B. Chalermisinsuwan, N. Samsalee, C.-W. Huang, and K. Manatura, "Hydrophobicity and performance analysis of beverage and agricultural waste torrefaction for high-grade bio-circular solid fuel," *Carbon Resources Conversion*, Article ID 100243, 2024.
- [160] K. Jagodzińska, M. Czerep, E. Kudlek, M. Wnukowski, M. Pronobis, and W. Yang, "Torrefaction of agricultural residues: Effect of temperature and residence time on the process products properties," *Journal of Energy Resources Technology, Transactions of the ASME*, vol. 142, no. 7, pp. 1–8, 2020.
- [161] B. Tamelová, J. Malařák, J. Velebil, A. Gendek, and M. Aniszewska, "Impact of torrefaction on fuel properties of aspiration cleaning residues," *Materials*, vol. 15, no. 19, Article ID 6949, 2022.
- [162] M. Khairy, M. Amer, M. Ibrahim, S. Ookawara, H. Sekiguchi, and A. Elwardany, "The influence of torrefaction on the biochar characteristics produced from sesame stalks and bean husk," *Biomass Conversion and Biorefinery*, vol. 14, no. 15, pp. 17127–17148, 2024.
- [163] M. Chai, L. Xie, X. Yu et al., "Poplar wood torrefaction: kinetics, thermochemistry and implications," *Renewable and Sustainable Energy Reviews*, vol. 143, Article ID 110962, 2021.
- [164] J. O. Ajikashile, M. Alhndi, M. Bishir, and A. Kruse, "The influence of torrefaction temperature and reaction time on the properties of torrefied sun-dried millet and sorghum straws from the arid and semi-arid zones of western Africa," *Biofuels, Bioproducts and Biorefining*, vol. 17, no. 3, pp. 751–767, 2023.
- [165] K. Manatura, B. Chalermisinsuwan, N. Kaewtrakulchai, Y.-C. Chao, and Y.-H. Li, "Co-torrefaction of rice straw and waste medium density fiberboard: a process optimization study using response surface methodology," *Results in Engineering*, vol. 18, Article ID 101139, 2023.
- [166] N. A. F. Abdul Samad, N. A. Jamin, and S. Saleh, "Torrefaction of municipal solid waste in Malaysia," *Energy Procedia*, vol. 138, pp. 313–318, 2017.
- [167] M. N. Cahyanti, T. R. K. C. Doddapaneni, and T. Kikas, "Biomass torrefaction: an overview on process parameters, economic and environmental aspects and recent advancements," *Bioresource Technology*, vol. 301, Article ID 122737, 2020.

- [168] U. B. Surono, H. Saptoadi, and T. A. Rohmat, "The effects of torrefaction on lignocellulose composition and moisture absorption ability of cocoa pod husk," *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, vol. 71, no. 1, pp. 83–91, 2020.
- [169] L. Richa, B. Colin, A. Pétrissans et al., "Catalytic and char-promoting effects of potassium on lignocellulosic biomass torrefaction and pyrolysis," *Environmental Technology & Innovation*, vol. 31, Article ID 103193, 2023.
- [170] M. U. Garba, S. U. Gambo, U. Musa, K. Tauheed, M. Alhassan, and O. D. Adeniyi, "Impact of torrefaction on fuel property of tropical biomass feedstocks," *Biofuels*, vol. 9, no. 3, pp. 369–377, 2016.
- [171] J. Mokrzycki, M. Gazińska, M. Fedyna, R. Karcz, E. Lorenc-Grabowska, and P. Rutkowski, "Pyrolysis and torrefaction of waste wood chips and cone-like flowers derived from black alder (*Alnus glutinosa* L. Gaertn.) for sustainable solid fuel production," *Biomass and Bioenergy*, vol. 143, Article ID 105842, 2020.
- [172] G. Pahl, F. Ntuli, and E. Muzenda, "Torrefaction of landfill food waste for possible application in biomass co-firing," *Waste Management*, vol. 71, pp. 512–520, 2018.
- [173] R. N. U. A. Rahman, M. Ismail, R. A. Rasid, and N. I. A. A. Nordin, "Torrefaction of food waste as a potential biomass energy," *Indonesian Journal of Chemistry*, vol. 19, no. 4, pp. 993–999, 2019.
- [174] C. Nobre, C. Vilarinho, O. Alves, B. Mendes, and M. Gonçalves, "Upgrading of refuse derived fuel through torrefaction and carbonization: evaluation of RDF char fuel properties," *Energy*, vol. 181, pp. 66–76, *Energy*, 2019.
- [175] D. Singh and S. Yadav, "Steam gasification with torrefaction as pretreatment to enhance syngas production from mixed food waste," *Journal of Environmental Chemical Engineering*, vol. 9, no. 1, Article ID 104722, 2020.
- [176] K.-Q. Tran, T. N. Trinh, and Q.-V. Bach, "Development of a biomass torrefaction process integrated with oxy-fuel combustion," *Bioresource Technology*, vol. 199, pp. 408–413, 2016.
- [177] J. Eling, D. K. Okot, E. Menya, and M. R. Atim, "Densification of raw and torrefied biomass: a review," *Biomass and Bioenergy*, vol. 184, Article ID 107210, 2024.
- [178] X. Yang, Z. Zhao, Y. Zhao et al., "Effects of torrefaction pretreatment on fuel quality and combustion characteristics of biomass: a review," *Fuel*, vol. 358, Article ID 130314, 2024.
- [179] J. L. Míguez, J. Porteiro, F. Behrendt, D. Blanco, D. Patiño, and A. Dieguez-Alonso, "Review of the use of additives to mitigate operational problems associated with the combustion of biomass with high content in ash-forming species," *Renewable and Sustainable Energy Reviews*, vol. 141, Article ID 110502, 2021.
- [180] K. Yan, C. Wen, T. Liu et al., "Effects of torrefaction and water-washing on the mineral transformation behavior during co-combustion of straw and coal: a CCSEM analysis," *Journal of the Energy Institute*, vol. 98, pp. 124–130, 2021.
- [181] R. Isemin, F. Tabet, A. Nebyvaev et al., "Prediction of the behavior of sunflower husk ash after its processing by various torrefaction methods," *Energies*, vol. 15, no. 20, pp. 7483–14, 2022.
- [182] M. Rudolfsson, E. Borén, L. Pommer, A. Nordin, and T. A. Lestander, "Combined effects of torrefaction and pelletization parameters on the quality of pellets produced from torrefied biomass," *Applied Energy*, vol. 191, pp. 414–424, 2017.
- [183] S. O. Araújo, D. M. Neiva, A. C. Carneiro, B. Esteves, and H. Pereira, "Potential of mild torrefaction for upgrading the wood energy value of different eucalyptus species," *Forests*, vol. 9, no. 9, Article ID 535, 2018.
- [184] A. A. Arpia, W.-H. Chen, A. T. Ubando et al., "Catalytic microwave-assisted torrefaction of sugarcane bagasse with calcium oxide optimized via Taguchi approach: product characterization and energy analysis," *Fuel*, vol. 305, Article ID 121543, 2021.
- [185] B. C. Çetinkaya, S. Erkent, K. Ekinçi, M. Civan, M. E. Bilgili, and S. Yurdakul, "Effect of torrefaction on fuel properties of biopellets," *Heliyon*, vol. 10, no. 2, Article ID e23989, 2024.
- [186] S. Pambudi, W. Saechua, and J. S. Jongyingcharoen, "A thermogravimetric assessment of eco-friendly biochar from oxidative torrefaction of spent coffee grounds: combustion behavior, kinetic parameters, and potential emissions," *Environmental Technology & Innovation*, vol. 33, Article ID 103472, 2024.
- [187] A. Białowiec, M. Micuda, and J. A. Koziel, "Waste to carbon: densification of torrefied refuse-derived fuel," *Energies*, vol. 11, no. 11, 2021.
- [188] K. L. Iroba, O. Baik, and L. G. Tabil, "Torrefaction of biomass from municipal solid waste fractions II: Grindability characteristics, higher heating value, pelletability and moisture adsorption," *Biomass and Bioenergy*, vol. 106, pp. 8–20, 2017.
- [189] M. A. Sukiran, F. Abnisa, S. Syafie et al., "Experimental and modelling study of the torrefaction of empty fruit bunches as a potential fuel for palm oil mill boilers," *Biomass and Bioenergy*, vol. 136, Article ID 105530, 2020.
- [190] F. Güleç, O. Williams, E. T. Kostas, A. Samson, L. A. Stevens, and E. Lester, "A comprehensive comparative study on methylene blue removal from aqueous solution using biochars produced from rapeseed, whitewood, and seaweed via different thermal conversion technologies," *Fuel*, vol. 330, Article ID 125428, 2022.
- [191] X. Yang, Y. Zhao, L. Zhang et al., "Effects of torrefaction pretreatment on the structural features and combustion characteristics of biomass-based fuel," *Molecules*, vol. 28, no. 12, Article ID 4732, 2023.
- [192] Z. Yang, M. Sarkar, A. Kumar, J. S. Tumuluru, and R. L. Huhnke, "Effects of torrefaction and densification on switchgrass pyrolysis products," *Bioresource Technology*, vol. 174, pp. 266–273, 2014.
- [193] S. Jiang, M. Tan, Z. Huang et al., "Combining oxidative torrefaction and pyrolysis of *Phragmites australis*: improvement of the adsorption capacity of biochar for tetracycline," *Frontiers in Energy Research*, vol. 9, pp. 1–13, 2021.
- [194] N. Abdullah, A. S. Aliyu, and F. Sulaiman, "Investigation into the effects of torrefaction on the quality of pyrolysis products," *International Journal of Technology*, vol. 8, no. 8, pp. 1376–1384, 2017.
- [195] H. Tian, R. Zhu, L. Chen, J. Wang, and Y. Cheng, "Aromatic hydrocarbons rich bio-oil production from *Miscanthus* pyrolysis by coupling torrefaction and MoO₃/ZSM-5 dual catalysis process," *Industrial Crops and Products*, vol. 204, no. PA, Article ID 117314, 2023.
- [196] G. A. Tsalidis, M. Di Marcello, G. Spinelli, W. de Jong, and J. H. A. Kiel, "The effect of torrefaction on the process performance of oxygen-steam blown CFB gasification of hardwood and softwood," *Biomass and Bioenergy*, vol. 106, pp. 155–165, 2017.
- [197] S. Yadav and D. Singh, "Assessment of biochar developed via torrefaction of food waste as feedstock for steam gasification

- to produce hydrogen rich gas,” *Carbon Research*, vol. 2, no. 1, pp. 1–13, 2023.
- [198] A. Kostyniuk and B. Likozar, “Catalytic wet torrefaction of biomass waste into bio-ethanol, levulinic acid, and high quality solid fuel,” *Chemical Engineering Journal*, vol. 485, Article ID 149779, 2024.
- [199] M. Ivanovski, D. Goričanec, and D. Urbanč, “The thermochemical conversion of municipal solid waste by torrefaction process,” *Thermo*, vol. 3, no. 2, pp. 277–288, 2023.
- [200] D. G. C. Wickramasinghe, M. Narayana, and S. Witharana, “Optimization of process parameters for organic municipal solid waste torrefaction,” *2019 Advances in Science and Engineering Technology International Conferences, ASET*, vol. 2019, pp. 1–5, 2019.
- [201] M. Ivanovski and D. Gorič, “The evaluation of torrefaction efficiency for lignocellulosic,” *Energies*, vol. 16, no. 9, Article ID 3694, 2023.