waste

Review

Waste-Derived Chars: A Comprehensive Review

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Abstract: The production of heterogeneous solid waste, such as municipal solid waste (MSW), construction and demolition waste (CDW), and industrial solid waste (ISW), has increased dramatically in recent decades, and its management is one of today's biggest concerns. Using waste as a resource to produce value-added materials such as char is one of the most promising strategies for successful and sustainable waste management. Virtually any type of waste, through various thermochemical technologies, including torrefaction, pyrolysis, hydrothermal carbonization, and gasification, can produce char with potential material and energy applications. Pyrolysis is the most widespread technology, and there are more studies on producing and applying waste-derived char using this technology. The properties of waste-derived char seem to be influenced by the conversion technology and conditions, as well as by the composition of the source waste. A literature search indicated that the properties of waste-derived char are highly variable with the composition of the raw material, with carbon content in the range 8–77%, a higher heating value of 2.5–28.4 MJ/kg and a specific surface area of 0.7–12 m^2/g. Depending on the properties of char derived from waste, there are greater or minor difficulties in applying it, with ash content, heavy metals, and polycyclic aromatic hydrocarbon (PAH) concentrations being some of its limiting properties. Therefore, this review attempts to compile relevant knowledge on the production of waste-derived char, focusing on heterogeneous solid waste, applied technologies, and practical application routes in the real world to create a supply chain, marketing, and use of waste-derived char. Some challenges and prospects for waste-derived char are also highlighted in this study.

Keywords: waste-derived char; MSW; pyrolysis; gasification; hydrothermal carbonization

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1. Introduction

Waste production is gradually increasing with the growth of the global population and the related increased consumption of resources, making waste management a very significant concern in recent years [1]. Waste produced from different sources exists in solid, liquid, and gaseous forms. Solid waste includes heterogeneous waste such as municipal solid waste (MSW), construction and demolition waste (CDW), and industrial/commercial solid waste (ISW). It is estimated that 11.2 billion tons of solid waste are collected worldwide every year [2].

Several strategies can be adapted for the subject of waste, from reducing production at the source to strategies for managing waste generated when production cannot be avoided. This second option can include recycling waste into usable products, remanufacturing, as well as recovering materials and energy from waste [2]. Using waste as a resource to produce value-added materials such as waste-derived char is an upcoming strategy for effective waste management, representing a cost-effective and technologically sound way of dealing with solid waste. This approach has the advantage of diverting heterogeneous solid waste and effluents from the environment or landfills, reducing the use of virgin materials, and promoting a circular economy [3]. According to Ganesapillai et al. (2023), there is a growth trend in char production and its applications, which demonstrates the growing importance of char in the scientific and chemical engineering communities [1]. Based on the International Biochar Initiative (IBI), biochar is defined as "a solid material obtained from the thermochemical conversion of biomass in an oxygen-limited environment" [4]. Since char is a carbon-rich material that can be produced not only from woody biomass but also from different waste materials, waste-derived char is produced from heterogeneous solid waste replacing biomass as the starting material. Much like biochar, waste-derived char has distinctive properties, such as high carbon content, large surface area, stable structure, and high cation exchange capacity [5]. Beyond energy conversion, it has the potential to be used in various applications, such as soil improvement, improving resource use efficiency, producing functional materials, remediating and protecting against environmental pollution, and as a means to reduce greenhouse gas (GHG) emissions [4,6,7].

As of late, waste-derived char is being considered an emerging material of interest [7]. As such, there are several wastes that have been investigated as potential precursors, namely MSW [8–10], ISW [11], CDW [12], or textile waste [6]. Furthermore, different thermochemical technologies for waste-derived char production have gained greater prominence as they allow the production of a higher proportion of value-added products, i.e., gasification, hydrothermal carbonization, torrefaction, and pyrolysis [1,5]. Depending on the type of waste, the difficulties in converting it and defining the end-use of the produced waste-derived char can be greater or lower. There are some studies [6,8,10,13] investigating the production and application of char from heterogeneous solid waste, but there is not much information compiled in a single article that explores this topic. Therefore, this review aims to compile relevant knowledge on the production of waste-derived char (from MSW, ISW and CDW), focusing on the most widely used production technologies, physicochemical properties of the waste-derived char, end-uses, and finally, the main challenges and prospects for waste-derived char.

2. Feedstock for Waste-Derived Char Production

Waste-derived char is attracting increasing attention, owing to its low cost and desirable properties. Many solid wastes can be used as feedstocks to produce this value-added product. Differently from the feedstocks used for biochar production (e.g., forestry or agricultural wastes), heterogeneous solid wastes (e.g., MSW, CDW, or ISW), which are the considered feedstocks for waste-derived char, are used less [14,15].

2.1. Municipal Solid Waste

MSW is defined as the solid portion of non-hazardous waste generated by residential, commercial, and institutional buildings [16]. Every year, around 2.01 billion tons of MSW are produced worldwide and at least 33% of that is not managed in an environmentally safe manner. By 2050, waste production is expected to increase by 70% to 3.40 billion tons [17]. The United States and Denmark are two of the largest per capita generators of MSW in the world, at over 800 kg/year. The richest countries, despite representing only around 16% of the population, tend to produce around 34% of the global MSW [18]. Denmark produces 845 kg/year of MSW per capita, almost double the average per capita generation of MSW in the European Union (EU). This country's high waste generation is associated with a mostly urban population combined with high purchasing power [19].

Waste composition differs according to income levels, reflecting varying consumption patterns. MSW is mainly made up of food and green waste, paper, cardboard, plastic, glass, and metal [17]. Figure 1 demonstrates the general composition of MSW.

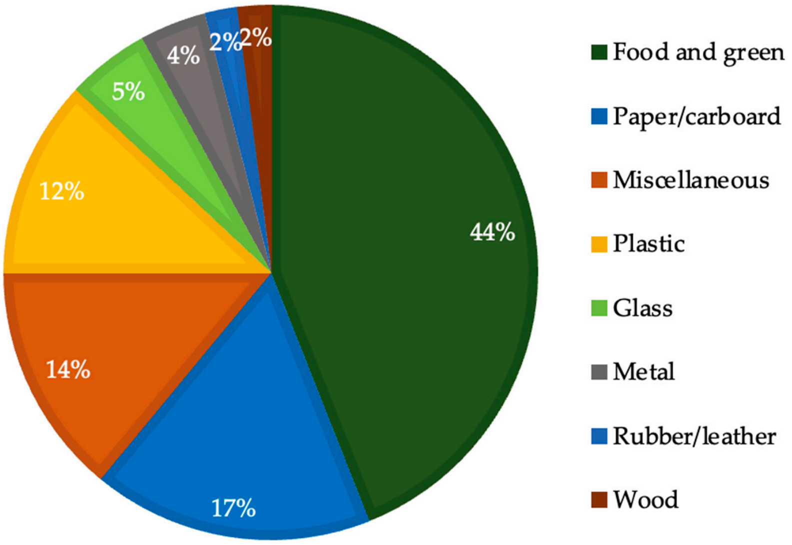


Figure 1. General composition of MSW [20].

Due to the heterogeneous nature of MSW, its physical and chemical characteristics vary significantly [21]. Table 1 shows different characterization data for MSW. Some characteristics, such as the sulfur and ash contents, which are relatively high, in the ranges 0.2–4.5% and 6.8–26.4%, respectively, may limit the energy application of the char resulting from this waste.

Table 1. Representative chemical characterization of MSW samples.

Characteristics	Units	MSW				RDF/SRF	RDF
Moisture	wt.%, wb	8.3	6.3	5.5	8.5	22.9	8.5
Volatile matter	wt.%, db	64.6	78.6	64.8	57.4	76.0	70.4
Fixed carbon		20.2	9.0	6.4	16.2	n.d	3.6
Ash		6.8	12.4	23.3	26.4	14.3	26.0
C		70.6	51.6	61.1	36.9	57.0	46.8
H		11.9	6.3	6.8	4.2	7.2	5.4
N		0.2	0.8	0.9	0.8	n.d	1.1
O		10.8	28.7	30.3	31.7	n.d	20.4
S		4.5	0.2	0.9	n.d	0.3	0.3
HHV	MJ/kg, db	35.2	21.2	n.d	14.4	26.9	11.4
Ref.		[22]	[23]	[24]	[25]	[26]	[27]

db—dry basis; n.d—no data.

According to CEWEP (2021), around 23% of MSW in EU countries was landfilled. While Denmark sends around 1% of MSW to landfills, Portugal sends 53%, and Malta around 85% [28]. According to Directive 2018/850/EC, landfilling should be minimized and other waste management and treatment strategies should be considered [29]. The transformation of MSW into refuse-derived fuel (RDF) and solid recovered fuel (SRF) is one of the simplest and most straightforward recovery strategies to implement and can be applied at the MSW management and treatment site itself, thus avoiding waste disposal. SRF and RDF are manufactured by applying a combination of processes, including sorting, shredding, sanitizing, drying, and densification. The metals and glass components are non-combustible, so they are physically separated, and as such are not present in the MSW or RDF/SRF char precursor. SRF is a fuel produced from non-hazardous waste (such as MSW, ISW, or CDW) that meets standards for fuel quality such as CEN/TS 343 [30], whereas RDF does not meet the any particular quality standard. SRF and RDF have better consistency and overall quality when compared to MSW, allowing these waste-derived fuels to be marketed as commodities to solid fuel consumers. However, SRF and RDF are still quite heterogeneous, so most of the time, both MSW and SRF/RDF end up being landfilled [31]. Overall, landfilling is still the most popular method for disposing of MSW [28]. However, since landfills require large extensions of land, the scarcity of space for new landfills in highly metropolitan cities and developing countries is leading to implementation of options for recovering waste by transforming it into energy or valuable products such as waste-derived char [21].

2.2. Industrial Solid Waste

One of the biggest liabilities regarding solid waste worldwide is undoubtedly industrial waste [32]. ISW is an inevitable by-product of manufacturing processes and includes all types of waste generated in industrial, manufacturing, and mining activities. To meet the demands of technological development as well as consumer requirements, huge quantities of ISW are generated in parallel with the development of a new product [33,34]. This waste has a greater potential to contaminate the environment due to its composition and its physical and chemical heterogeneity, representing a social and environmental challenge due to its disposal and poor management [32,34]. ISW can include different forms of hazardous and non-hazardous components [33]. The composition of ISW depends on several aspects, such as the type of industry in which it is generated, and the production process involved. Therefore, proper treatment of this highly variable waste is expected to be expensive and energy-intensive [32].

ISW management is particularly important, especially in industry-based economies [35]. China is the fastest-growing industrial country in the world and the largest producer of ISW [36]. In the EU, around 10.6% (229 million tons) of the total waste produced was ISW in 2020 [37].

ISW includes organic and inorganic compounds such as wood products, waste paper and cardboard, plastics, textiles, rubber, ceramics, slag, and metal waste [36]. Moreover, ISW also contains a considerable mass fraction of impurities such as polyvinyl chloride (PVC), highly chlorinated rubber material, and inert material [38]. The fractions that constitute impurities are usually separated. Only paper and cardboard, plastic and textiles (the combustible mass fraction), or ISW-based RDF/SRF are considered for char production [38]. In the study by Edirisinghe et al. (2023), it was found that paper and cardboard made up the largest fraction of ISW components, representing approximately 43.2% of the total waste generated, followed by plastic (30.78%) in an Export Processing Zone in Sri Lanka (Figure 2) [39].

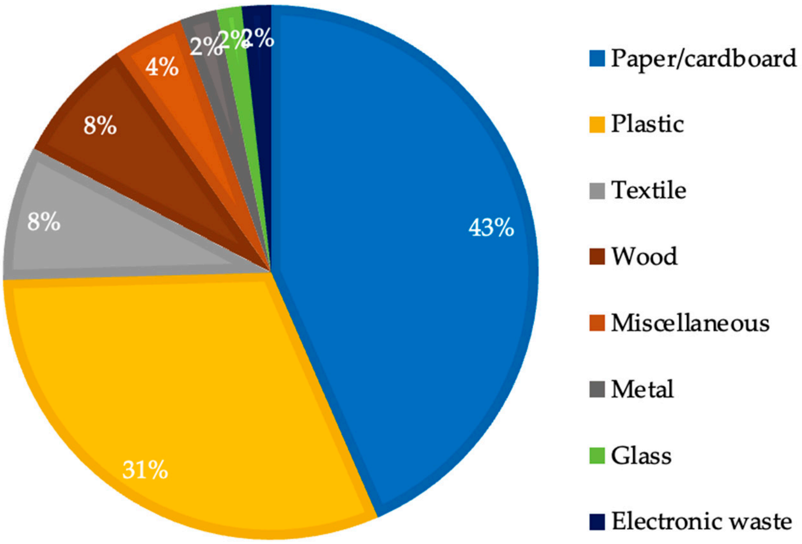


Figure 2. Composition of ISW [39].

The higher fraction of paper, cardboard, and plastic is justified based on the fact that industries receive feedstocks in packaging that use these three materials and use a significant amount of packaging and packaging materials for finished products [39]. Plastic waste has serious environmental impacts, and dealing with plastic pollution both on land and in the ocean entails significant financial costs [36]. Global plastics production doubled to 460 million tons, between 2000 and 2019, with plastic waste production doubling in the same period to 353 million tons. Of the plastic waste, only 9% was recycled and 49% ended up in landfills [40].

Textile waste, another significant fraction of ISW, has been largely produced because of the rise of fast fashion. In 20 years, the global production of textile fibers has almost doubled [41,42]. In 2015, the global textile and clothing industry was responsible for the production of 92 million tons of waste and it is estimated that by 2030, in a business-as-usual scenario, this figure will increase by at least 50% [42]. Clothing manufacturing waste comprises between 10% and 20% of the materials used. Considering the overall flow of materials for clothing manufacturing in 2015, only 13% of the materials used were recycled. Of these, 12% were transferred to other industries and used in lower-value applications (e.g., insulation material, cleaning clothes, and mattress stuffing), and less than 1% of textiles were recycled into new clothes. Around 14% of the feedstock was lost during the manufacturing process. Most used textiles ended up in landfills, at approximately 73%. This practice, as well as meaning a loss of value, is associated with high costs. For instance, New York City alone expends upwards of 20 million dollars annually on landfilling and incinerating textiles, while the United Kingdom (UK) faces an estimated cost of around 108 million dollars per year. By 2050, under a business-as-usual scenario, over 150 million tons of clothing are projected to end up in landfills or incinerated [43]. Although discarded used clothing is generally included in the MSW category, if the Extended Producer Responsibility (EPR) law was applied in the EU (currently only adopted by France), the manufacturing industries would have to deal with the management of this by-product and/or waste [42]. Based on concepts such as circular economy, industries looking for an innovative concept such as waste recovery will be able to reduce and manage their waste, creating more economic value. By taking such measures, they not only decrease their reliance on feedstocks or fossil fuels but also minimize waste disposal expenses and circumvent the need to outsource waste treatment to other organizations [33]. Table 2 shows the characterization of different ISW samples.

Table 2. Representative chemical characterization of ISW samples.

Characteristics	**Units**	**ISW**		
Moisture	wt.%, wb	10.5	26.5	4.8
Volatile matter	wt.%, db	74.9	n.d	68.3
Fixed carbon		8.2	n.d	7.6
Ash		16.9	16.6	24.1
C	wt.%, db	41.1 [a]	48.8	42.6
H		5.6 [a]	7.0	5.6
N		2.5 [a]	0.6	0.6
O		50.4 [a]	18.0	27.1
S		0.4 [a]	0.2	0.0
HHV	MJ/kg, db	16.4	19.8	17.2
Ref.		[11]	[38]	[8]

[a] daf—dry ash-free basis; n.d—no data.

2.3. Construction and Demolition Waste

Due to the persistent rise in urbanization and the substantial level of construction activity, effectively managing construction and demolition waste (CDW) has become a crucial global concern [44]. According to the EU's waste strategy, this waste is considered a "priority" waste stream and is covered by a mandatory recovery target under the Waste Framework Directive 2008/98/EC [38,45]. Annually, approximately 10 billion tons of CDW are produced globally. China leads as the largest contributor, generating about 2.3 billion tons, followed by the EU with over 800 million tons, and the United States with around 700 million tons [46]. CDW in the EU represents more than one-third of all the produced waste, representing approximately 37.5% in 2020 [37]. CDW includes waste generated by economic activities involving the construction, maintenance, demolition, and deconstruction of buildings and civil engineering works, as well as road planning and maintenance. It contains a wide variety of materials, such as concrete, clinker, bricks, metals, and glass, and combustible materials such as wood, plastic, textiles, paper, cardboard, and rubber, referred to as solid combustible waste, which comes from doors, windows, pipes, decorations, and furniture during the construction of buildings and demolition of old buildings [44,47,48]. Only the combustible materials from CDW are considered for RDF/SRF production and thermochemical conversion (e.g., char production), enabling comprehensive and effective use to be achieved [44].

As an example, Figure 3 shows the composition of CDW produced in New Zealand.

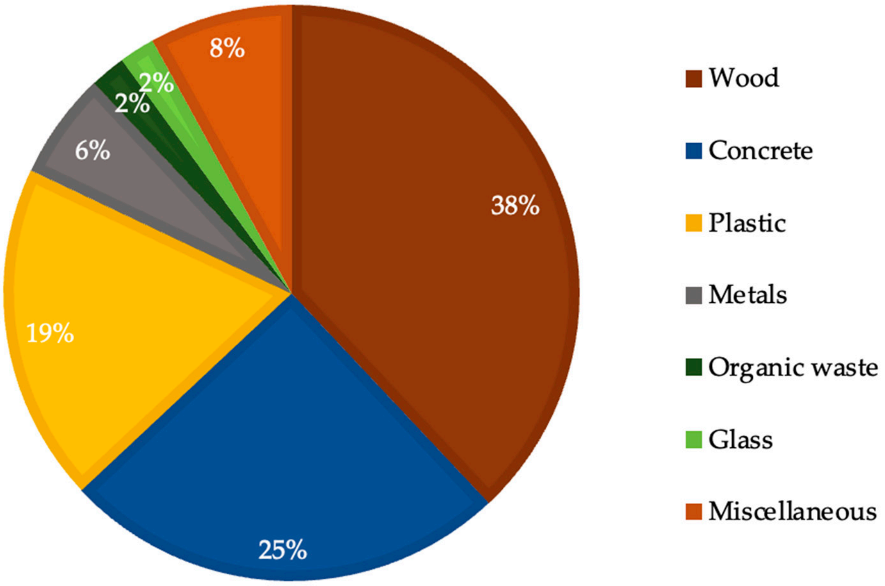


Figure 3. Composition of CDW [20].

However, the composition of this waste differs greatly due to the heterogeneity of construction activities. For instance, pre-molded and pre-fabricated structures tend to produce less construction waste. Additionally, the choice between wooden or concrete/reinforced concrete structures significantly influences the expected amount and composition of CDW [47]. Inert waste such as concrete is usually reused and recycled in new constructions. Wood waste is incinerated with energy recovery in some countries (Sweden, Norway, and Denmark) and in Finland, for example, it is incinerated without energy recovery [32,46]. In most situations, CDW is landfilled [20]. According to a 2015 report, following collection, approximately 11% of CDW was allocated for backfilling, 18% for landfill disposal, and the remaining 71% underwent separation into distinct materials. Metals, plastics, and wood were either recycled or utilized for energy recovery. The surplus aggregates were recycled onsite to create secondary aggregates, or when uncontaminated, were reused after cleaning or transformation. A small part of the secondary aggregates went to the industries and the rest went to landfill (the percentage is unknown) [49,50]. Landfilling CDW, or even not treating it at all, not only consumes a lot of land resources and has a negative economic impact due to the disposal of waste without recycling and reusing material, but also has serious environmental impacts involving the deterioration of landscapes and contamination of soil and water resources [38,44]. While the specific environmental impact of CDW by weight may be lower compared to other waste streams, the substantial presence of inert materials in CDW still raises significant environmental concerns. Consequently, there is an urgent call to develop innovative, sustainable, and feasible solutions to address CDW generation. This urgency underscores why CDW management stands as a priority in numerous environmental programs globally, particularly in Europe [47]. The chemical characterization of CDW is given in Table 3.

Table 3. Representative chemical characterization of CDW samples.

Characteristics	**Units**	**CDW**			
Moisture	wt.%, wb	n.d	11.9	9.4	6.0
Volatile matter	wt.%, db	78.1	92.4	93.9	85.5
Fixed carbon		11.6	1.6	0.0	9.5
Ash		10.4	6.0	6.1	5.0
C	wt.%, daf	52.3	51.7	52.5	52.7
H		6.8	6.3	6.3	6.6
N		2.8	1.5	1.4	1.3
O		27.5	40.4	39.8	39.3
S		0.2	0.1	0.1	0.1
HHV	MJ/kg, db	26.9	18.5	21.0	24.7
Ref.		[51]	[52]		

daf—dry ash-free basis; n.d—no data.

3. Waste-Derived Char Production Technologies

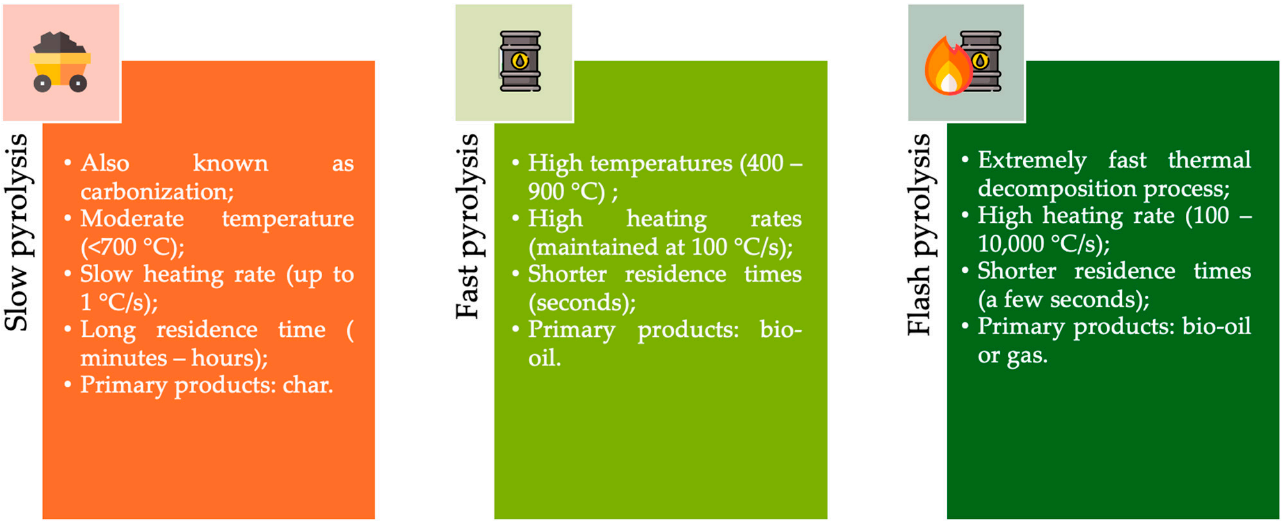
3.1. Torrefaction

Torrefaction, also known as mild pyrolysis, takes place at a low temperature range, between 200 and 300 °C, in an atmosphere with little or no oxygen, at atmospheric pressure, removing mainly water and some volatiles from the feedstock to produce a stabilized and friable char [5,11]. In the article by Bialowik et al. (2017), it is highlighted that temperature and residence time represent two crucial parameters affecting the efficiency of the torrefaction process. Specifically, temperatures ranging from 200 to 300 °C are sustained for durations spanning 15 to 60 min. The selection of precise values for these parameters is deemed vital for ensuring a cost-effective torrefaction process [26]. Torrefaction offers some benefits as the obtained char has hydrophobic properties, homogeneity, greater durability, excellent grindability, higher bulk density, and high calorific value, which could increase the efficiency of waste utilization. Therefore, this process could reduce grinding and transportation costs and increase the storage properties of the waste [53]. Torrefaction is commonly applied to the treatment of lignocellulosic biomass, but the feedstocks currently used on a commercial scale include not only lignocellulosic biomass, but also sewage sludge, food waste, MSW, RDF, and SRF [26]. The high ash content, characteristic of heterogeneous waste such as MSW, ISW, and CDW during the application of thermochemical processes such as torrefaction, becomes concentrated, so this enrichment in inorganic components must be considered when defining the application of these chars [54].

3.2. Pyrolysis

Pyrolysis stands out as a promising process for recycling and recovering energy, fuels, and value-added products. This method aligns well with the three principles of solid waste treatment: reduction, resource recovery, and pollutant mitigation [55]. This is a heat treatment in a wide range of temperatures (300–900 °C) that takes place in the absence of oxygen/air, where the polymers and monomers of the waste are decomposed into smaller hydrocarbon molecules as three main products (i.e., bio-oil, gas, and char). Pyrolysis of heterogeneous solid waste represents an innovative and promising decentralized technology. However, existing commercial pyrolysis technologies often integrate with gasification and combustion processes, primarily generating electricity or heat. Consequently, they fall short of fully maximizing the potential of pyrolysis products [9].

The composition of the waste, process conditions such as temperature, heating rate, and reaction gas, as well as the presence or absence of catalysts all play significant roles in determining the product and yield composition [56,57]. Pyrolysis can therefore be classified into slow, fast, and flash pyrolysis (Figure 4) according to the heating rate and residence time, and as catalytic or thermal pyrolysis depending on the presence or absence of a catalyst [58]. Since catalytic pyrolysis is a more interesting solution when the emphasis is on producing gas or bio-oil, only thermal pyrolysis will be discussed in this article [59].



Slow pyrolysis

- Also known as carbonization;
- Moderate temperature (<700 °C);
- Slow heating rate (up to 1 °C/s);
- Long residence time (minutes – hours);
- Primary products: char.

Fast pyrolysis

- High temperatures (400 – 900 °C) ;
- High heating rates (maintained at 100 °C/s);
- Shorter residence times (seconds);
- Primary products: bio-oil.

Flash pyrolysis

- Extremely fast thermal decomposition process;
- High heating rate (100 – 10,000 °C/s);
- Shorter residence times (a few seconds);
- Primary products: bio-oil or gas.

Figure 4. Main differences between slow, fast, and flash pyrolysis.

3.2.1. Slow Pyrolysis

Slow pyrolysis, also known as carbonization, involves heating the feedstock in the absence of oxygen to a moderate temperature (<700 °C), employing a slow heating rate (up to 1 °C/s), and allowing for a long residence time. This method primarily yields solid char as the main product, which typically contains a significant proportion, often around 80%, of carbon. It is a process ideally conducted in reactor subtypes such as electric or muffle furnaces and fixed-bed reactors [1,60,61]. Slow pyrolysis is usually the used approach for char production, given its technological maturity technology and guarantee of high char yields [58]. As for the heterogeneous waste, which is available in large quantities and has a considerable moisture content, slow pyrolysis is the most suitable type of pyrolysis for valorization through char production [62]. The composition of the waste has been shown to significantly influence the quality of char from the slow pyrolysis of MSW, IW, and CDW [12].

3.2.2. Fast Pyrolysis

Fast pyrolysis means rapidly heating the feedstock at relatively high temperatures (400–900 °C), high heating rates (maintained at 100 °C/s), and shorter residence times (a few seconds), with the emphasis on producing bio-oil. The char obtained in this process is normally used as an adsorbent due to its greater porosity. Fast pyrolysis is the most common method for pyrolyzing plastic waste from heterogeneous solid waste [1,57]. Bio-oil/wax yields of up to 54% and heating values of up to 41.7 MJ kg have been demonstrated for the fast pyrolysis of industrial waste from plastic-contaminated fiber recycling plants [63].

3.2.3. Flash Pyrolysis

It is an extremely fast thermal decomposition process with considerably shorter residence times and a high heating rate (100–10,000 °C/s), promoting the production of gases and bio-oil [57,61]. Bio-oil is mainly produced at more moderate temperatures, and increasing the temperature promotes gas production. The gas resulting from the flash pyrolysis of industrial textile waste proved to be composed mainly of combustible gases, with a high HHV (15.34 MJ/kg) and low CO_2 content, and the bio-oil showed an HHV of up to 34.15 MJ/kg [61].

3.3. Gasification

Gasification is a thermochemical process that transforms any solid carbonaceous material into combustible gases (such as CO, H_2, CO_2, and CH_4) through partial oxidation using various gasifying agents like pure oxygen, air, steam, or carbon dioxide. This occurs at atmospheric pressure and temperatures ranging from 700 to 1500 °C. Alongside combustible gas, by-products like char and tar (a blend of high molecular weight aromatic and oxygenated hydrocarbons) are also generated. The gasification of solid waste involves a series of intricate endothermic and exothermic reactions, including dehydration, pyrolysis (thermal decomposition) in the absence of an oxidizer, partial oxidation or gasification, and a reduction zone [64,65]. The primary challenges hindering the industrial-scale implementation of gasification processes for heterogeneous solid waste stem from the variability and quality of the feedstock. Overcoming these challenges involves enabling the process to effectively handle highly variable and contaminated heterogeneous waste. Additionally, finding the ideal balance between the added value of gasification products is crucial for successful implementation [65]. As a by-product of gasification, which represents at least 10% of the original feedstock, gasification char must be properly disposed of and handled so that it represents added value and has a positive impact on the economic viability of the gasification process. The carbon conversion process is more efficient in gasifiers operating at higher temperatures, thereby reducing the amount of generated char. At lower temperatures, the amount of char increases. Top-light updraft gasification (TLUD) is recognized for its significant potential in char production, boasting relatively high yields of up to 39% and relatively low energy consumption. The utilization of gasification char has been extensively regarded as a model for closing the loop in sustainable energy practices. In 2020, this market experienced a remarkable growth rate of 70%. Gasification char is characterized by its unique chemical composition, including high carbon and mineral content, as well as its physical properties such as high porosity and surface area, rendering it suitable for various potential applications [16,66,67]. The partial oxidation environment inherent in the gasification process can enhance both the textural and chemical properties of waste-derived char, making them suitable for practical applications. However, there remains a shortage of literature focusing on the characterization of gasification char, particularly concerning chars derived from heterogeneous solid waste sources, like MSW, CDW, and ISW.

3.4. Hydrothermal Carbonization

The main disadvantage of thermochemical processes is that they often require drying of the feedstock, making them difficult to scale up for industrial applications. Hydrothermal carbonization (HTC) is a thermochemical process conducted in the presence of water, which serves as the reaction medium. This process occurs at relatively low temperatures ranging from 180 to 350 °C, under autogenous pressure and in an inert atmosphere. Therefore, it has the advantage of being able to be applied to wastes with a high moisture content without having to resort to drying processes. The water in this process acts as a solvent or catalyst, which contributes to the leaching of minerals present in the waste. During HTC, a series of reactions occur, such as hydrolysis, dehydration, decarboxylation, condensation polymerization, and aromatization. During the HTC process, approximately 35–80% of a solid product known as hydrochar is generated, displaying a carbon content ranging from 55–70%. Additionally, a liquid product often referred to as process water is produced, alongside a gaseous product comprising primarily CO_2 with smaller quantities of hydrocarbons. Hydrochar generally has a high carbon content, high calorific value, increased hydrophobicity, and low oxygen and ash contents [53,66,68]. Compared to other thermochemical char production processes, HTC has the advantage of requiring lower amounts of energy because the waste does not require drying. In the case of dry heterogeneous waste, such as MSW, CDW, ISW, RDF, and SRF, HTC can be used to obtain hydrocarbons with a low ash concentration and reduce the conversion temperature, improving the economic viability of the process [69]. Although the HTC process makes it possible to produce a hydrochar with positive characteristics and various potential applications, the process water needs to be properly managed, which is a major challenge for the process. This liquid product represents a significant fraction of the HTC process and contains leached organic and inorganic compounds that must be removed prior to disposal [68]. Recirculating the process water can be a sustainable management solution with environmental and economic benefits [70,71]. Another solution for the HTC process water can be the application of solid waste hydrocarbons that have properties that allow them to be used in wastewater remediation [69].

3.5. Summary of Thermochemical Process Conditions for Producing Waste-Derived Char

The different thermochemical technologies for producing waste-derived char differ mainly in the severity of the treatment and the reaction medium/atmosphere in which they occur. Table 4 presents a summary of the main conditions under which the processes of torrefaction, pyrolysis, gasification, and HTC take place and the potential yields of waste-derived char.

Table 4. Thermochemical production processes for generating waste-derived char and their primary distinctions regarding operating conditions [57,60,66–68,72].

Process Conditions	**Process**					
	Torrefaction	**Pyrolysis**			**Gasification**	**HTC**
		Slow	**Fast**	**Flash**		
T (°C)	200–300	<700	<800	<1200	<1200	<350
Residence time	Minutes–hours	Hours	Seconds	Few seconds	Seconds–minutes	Minutes–hours
Heating rate (°C/s)	0.07–0.18	0.02–1.0	10–200	>1000	Moderate–very fast	1–12
Primary product	Char	Char	Bio-oil	Bio-oil or gas	Syngas	Hydrochar
Waste-derived char yield (%)	60–80	35–89	12	25	10–39	35–80

Considering Table 4, it is noteworthy that the less severe processes have a higher char yield. Lower process temperatures and extended residence times are conducive to char production. Typically, gasification processes yield less char compared to other thermochemical methods, as carbon undergoes conversion into carbon monoxide and carbon dioxide owing to the partial oxidation conditions [73]. The yield of char from HTC is about 35–80%, from torrefaction is 60–80%, and from slow pyrolysis is 35–89% [60,66]. According to Adeniyi et al. (2024), slow pyrolysis and HTC are the two most effective thermochemical techniques for producing waste-derived char, given their wide range of compatibility with heterogeneous solid waste and high char yields [60].

For each thermochemical process employed, parameters such as residence time, heating rate, and temperature affect the quality and quantity of the primary and secondary products. Thus, these parameters must be adapted to heterogeneous solid waste since char composition is strongly affected by the characteristics of the feedstock.

4. Properties of Waste-Derived Chars

Regardless of the type of thermochemical treatment, assessing the properties of waste-derived char provides useful information on its applicability. The chemical and physical properties potentially relevant to waste-derived char applications include carbon and ash content, calorific value, inorganic elements, functional groups, aromatization, pH, pore volume and size, and specific surface area [73]. Table 5 shows the properties of different waste-derived chars produced from similar types of heterogeneous solid waste using the four thermochemical processes discussed in this work.

Table 5. Characteristic properties of waste-derived chars produced through different thermochemical processes.

	Torrefaction		Pyrolysis		Gasification		HTC	
Feedstock	**MSW**	**RDF from ISW**	**RDF from MSW**	**CDW**	**SRF from MSW**	**RDF from MSW**	**RDF from ISW**	**SRF from CDW and MSW**
Process conditions	300 °C 1 h	300 °C 30 min	400 °C 30 min	500 °C 1 h	700 °C	850 °C	250 °C 30 min	300 °C 30 min
Sample composition	59% polymers, 17% lignocellulosic material	22.9% plastic, 17.9% paper/cardboard, 7.9% textiles, 5% wood, 0.5% aluminum, 0.2% glass, 42.5% miscellaneous components	66% textiles, 17.1% paper, 16.9% plastics	39.1% paper, 32.2% wood, 11.8% plastics, 9.2% glass, 7.6% miscellaneous components	80% plastics, 10% HDPE, 10% paper and chopstick wood	n.d	22.9% plastic, 17.9% paper/cardboard, 7.9% textiles, 5% wood, 0.5% aluminum, 0.2% glass, 42.5% miscellaneous components	65.87% wood, 17.27% plastics, 16.85% paper/cardboard
Ash wt.%, db	28.7	22.8	20.1	41.9	88.5 [b]	66.8	4.8	3.0
Volatile matter wt.%, db	58.3	56.3	69.8	26.5	4.9 [b]	n.d	81.8	48.7
Fixed carbon wt.%, db	13.0	20.9	10.1	31.6	2.5 [b]	n.d	13.4	51.4
HHV (MJ/kg, db)	16.0	19.9	28.1	16.28	2.6	n.d	26.1	28.4
C wt.%, daf	61.3	61.0	77.2	40.5 [a]	8.1 [a]	18.5 [a]	61.9	73.0
H wt.%, daf	5.8	6.2	8.9	2.3 [a]	n.d	0.7 [a]	7.9	4.6
N wt.%, daf	0.5	1.3	2.1	0.6 [a]	n.d	0.2 [a]	1.8	0.8
S wt.%, daf	0.0	0.3	0.6	1.9 [a]	0.003 [a]	0.0 [a]	0.0	0.0
O wt.%, daf	32.4	31.2	11.2	n.d	n.d	13.8 [a]	28.4	21.6
Cl wt.%, db	8.5	1.8	n.d	4.9	0.2	n.d	1.27	2.4
K wt.%, db	0.02	4.0	n.d	0.1	n.d	n.d	n.d	0.6
Zn wt.%, db	0.05	6.8	n.d	0.2	n.d	n.d	n.d	n.d
Ca wt.%, db	13.2	34.1	n.d	9.1	n.d	n.d	n.d	7.6
BET surface area (m^2/g)	n.d	n.d	0.7	n.d	10.4	12.0	n.d	n.d
Ref.	[8]	[11]	[54,74]	[12]	[75]	[76]	[11,68]	[69]

[a] dry basis; [b] as received; n.d—no data.

Notably, there is a lack of information on the properties of heterogeneous solid waste gasification char. According to Table 5, this process was responsible for producing gasification char with high amounts of ash (66.8% and 88.53%), and its exploitation as a secondary feedstock for value-added products may be limited. The ash content of gasification char was generally higher than that of the feedstock owing to the loss of volatile matter and enrichment of inorganic components. A high mineral content can decrease the specific surface area of the gasification char by blocking its pores [73]. Nonetheless, the ash content of char from the gasification of heterogeneous solid waste is recognized as an active part of the char [13]. The presence of inorganics with catalytic effects allows it to have potential applications as catalysts, as well as other interesting applications such as additives in construction materials, road surface coating, and others [66,76].

The specific surface areas of the gasification chars shown in Table 5 are very low, suggesting that the measurement was largely affected by the high ash content. Temperature also influences the surface area of gasification chars. Han et al. (2022) found that the surface area and pore volume of SRF gasification char, derived from MSW, peaked at 700 °C before declining beyond 800 °C. The authors attributed the rise in surface area at higher temperatures to the formation of micropores post-devolatilization and gasification. However, they observed that the porous structure of the char collapsed as the pore walls were destroyed, leading to a subsequent reduction in surface area and pore volume [75]. In the study conducted by You et al. (2017), gasification-derived chars exhibited lower specific surface areas and total pore volumes compared to those obtained from slow and fast pyrolysis. Additionally, gasification chars demonstrated higher ash content and pH levels. Nevertheless, the utilization of pure oxygen and steam as gasifying agents was found to yield gasification chars with twice the specific surface area of pyrolysis-derived chars. It is noteworthy that char resulting from gasification typically exhibits an alkaline pH ($7 < pH < 12$), which is likely attributed to its content of metal salts and ash. In contrast, although the pH of char from HTC and pyrolysis varies between acidic and alkaline, they are usually acidic, with pH values close to neutral [73].

Waste-derived char from the HTC process has low ash contents (3% and 4.8%), caused by the migration of mineral elements to the liquid phase of the process [69]. These chars showed better combustible characteristics, not only regarding ash content but also presenting high calorific values (26.1 MJ/kg and 28.4 MJ/kg). The low inorganic content of HTC waste-derived char suggests its application as a fuel or feedstock for thermochemical recovery processes since it would not create problems of fouling, corrosion, and radiative heat transfer that occur with chars with high ash content [22,77]. Also, chlorine content is relatively low (1.27% and 2.4%) compared to waste-derived char from the other processes in the discussion. As a relevant parameter for thermochemical technologies, chlorine is subjected to specifications that depend on the energy conversion process. Based on the specifications that determine the quality and classes of SRF, HTC waste-derived char would belong to classes 4 and 5 [78]. Although Table 5 does not report the surface area data for these chars, according to Escudero-Curiel et al. (2023), HTC chars do not have as great a specific surface area as the other chars, but they do have a significant abundance of functional groups on their surface [79]. The presence of functional groups, such as carboxyl and hydroxyl groups, enables waste-derived HTC char to retain cationic contaminants found in effluents via adsorption mechanisms, including ion exchange and surface complexation. Consequently, waste-derived HTC char holds promise for application in effluent decontamination processes [14,69].

Torrefaction and pyrolysis seem to produce waste-derived chars with relatively high ash contents, in the range of 20–42%, good heating values in the range of 16–28 MJ/kg, and chlorine contents in the range of 1.8–8.5%, with higher chlorine values being found in feedstock with a greater presence of polymers and plastics in its composition. The ash content found in these chars would allow most of them to be used, for example, in gasification to produce syngas and other value-added products. According to Arena (2012), the recommended ash content in feedstock for gasification can be up to 25% for fluidized reactors and up to 40% for rotary kiln reactors [77]. In addition, waste-derived char with high ash (nutrient) and carbon content (>75%), such as the RDF pyrolysis char from ISW at 400 °C for 30 min produced in the work of Nobre et al. (2019), that could have applications such as soil correction and improvement, filtration, and remediation of contaminated land [11,15].

Waste-derived char exhibits different functional groups on the surface. For the application of these waste-derived chars, some properties are extremely important and the presence of functional groups on the surface is one of them. For example, for application in soil, the waste-derived chars must have good cation exchange capacity, which depends on the functional groups present on the surface of the char [80]. Table 6 summarizes the surface functional groups on different waste-derived char samples.

Table 6. FT-IR characterization of waste-derived char surface functional groups.

Sample	Functionality	Wavenumber (cm^{-1})	Ref.
Pyrolysis RDF (from MSW) char (500 °C for 90 min)	O-H stretch (phenol and alcohols)	3700–3500	[80]
	Aromatic C–H functional group	2365	
	N–H functional group	2319	
	C–H stretching vibration and conjugated aromatic carbonyl	1690	
	Inorganic compounds (lumino-silicate, calcium oxide, or metal oxide)	1500–1300	

Table 6. *Cont.*

Sample	Functionality	Wavenumber (cm^{-1})	Ref.
Pyrolysis MSW char (550 °C for 30 min)	Aliphatic O-H bond	3200–3500	[81]
	Saturated symmetric and asymmetric C-H stretching vibration (aliphatic C-H)	2875, 1935	
	C=C or/and saturated C-H bending vibration	1430	
	C-O/Si-O bond (inorganic oxide compounds, such as phosphorus and sulfur)	1101–1160	
	P-O-P bond	878	
	C=O or C-O bond (carbonate functional groups)	820	
	O-Si-O (calcite and sílica)	700	
Gasification SRF (from MSW) char (835 °C)	Hydrogen bonded O-H stretch	3405	[82]
	C-H asymmetric/symmetric stretch	2917, 2848	
	Alkenyl C=C stretch overlapped by an open chain imino (C=N)	1635	
	Methyl C-H asymmetric bend	1429	
	Aliphatic-phosphate stretch (P-O-C) stretch	1022	
	Polysulphide (S-S) stretch	536	
HTC waste textile (from MSW) char (230 and 280 °C for 30, 60, 90 min)	OH-stretching vibration bands of hydroxyl and carboxyl groups	3200–3600	[83]
	Aromatic benzene ring =C–H stretching	3000–3100	
	C=O functional group	1600–1800	
	Aromatic C-C stretching	1460–1600	
	Esters C-O-C stretching	1200–1360	
	Aliphatic ether C-O or alcohol C-O stretching	1100–1160	
	Aldehydes -CHO stretching	900–980	
	Aromatic out-of-plane C-H bending	750–875	

All waste-derived chars show characteristic peaks (3200–3700 cm^{-1}) indicative of oxygen-containing functional groups, especially the O-H stretch, possibly because of the presence of phenol and alcohols [80]. Increasing the temperature of the process leads to a reduction in the intensity of these peaks, due to the decrease in water content and aliphatic, hydroxyl, and carboxyl compounds [81]. Aromatic and aliphatic C-H stretching is also present in all the waste-derived chars. However, these aliphatic C-H bonds seem to lose their intensity as the severity of the process increases, in line with the decrease in H content in the chars with increasing severity [54]. On the other hand, Lin et al. (2016a), found that in waste-derived char obtained through HTC, the peaks indicative of aromatic benzene ring =C-H stretching, aromatic C-C stretching, and aromatic out-of-plane C-H bending increased as the temperature or residence time increased, especially for aromatic out-of-plane C-H bending [83]. For Bhatt et al. (2021) and Taherymoosavi et al. (2017), inorganic functional groups are also found on the surfaces of the waste-derived char [80,81]. This is in line with the proximate analysis data (Table 5), which indicate relatively high ash content in waste-derived chars, except for HTC.

Furthermore, as noted by You et al. (2017), during the gasification process, where elevated temperatures are reached, a significant reduction in functional groups such as hydroxyl, carboxyl, and carbonyl may occur. Consequently, waste-derived char from gasification typically possesses fewer functional groups compared to char produced from pyrolysis or HTC. This reduction in functional groups correlates with a higher degree of aromaticity in gasification char, which tends to increase with rising temperatures. The presence of aromatic functional groups and oxygen-rich groups can serve as potent active sites, enhancing the adsorption capacity of waste-derived char [73].

5. Different Applications for Waste-Derived Char

Waste-derived chars are regarded as cost-effective carbonaceous materials with a broad spectrum of applications, as seen in Figure 5.

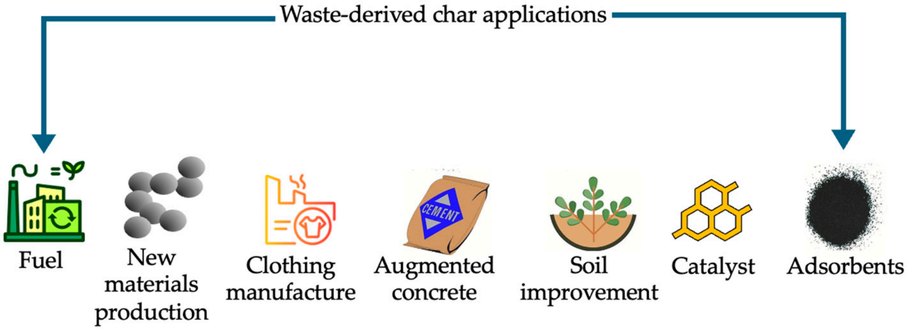


Figure 5. Different applications for waste-derived char.

They have also found utility in polymer production, anaerobic digestion, composting, electrochemical applications, and other innovative uses. According to Abdelaal et al. (2023), the primary valorization pathways for char primarily revolve around adsorption (especially in water treatment, gas adsorption, and soil remediation), catalysis (for tar reforming and as catalyst support), and agricultural applications (such as soil amendment, fertilization, and remediation) [66,79].

5.1. Material Applications

5.1.1. Adsorbents

Demand for adsorbents to treat pollutants has seen a notable increase. Projections suggest that the production of activated carbon should increase by 9.3% per year, potentially reaching a market value of 8.5 billion dollars by 2026. Therefore, heterogeneous solid waste such as MSW, ISW, and CDW have the potential to be used in the manufacture of adsorbents [84]. In the last decade, there has been a growing interest in utilizing char as an adsorbent for wastewater treatment. Specific properties such as pH, relatively porous structure, functional groups, and mineral agglomerates on the surface of chars are properties that make them useful as adsorbents for pollutants [73]. According to Abbas et al. (2018), pH is one of the most critical characteristics in the adsorption of organic and inorganic contaminants, altering the degree of ionization of the adsorbate, and affecting the surface charge of waste-derived char. At low pH, the overall adsorption capacity of contaminants decreases as a result of competition between protons and metal ions for the binding site. Increasing the pH reduces the competition between metal ions and protons for the binding site, thus resulting in better adsorption of contaminants [85].

A few studies have emerged along these lines, trying to understand the applicability of waste-derived char as an adsorbent for various pollutants and contaminants. SRF from MSW was gasified, and the produced char presented a BET surface area of 11.4 m^2/g and an ash content of 54.54% and was used as an adsorbent to reduce chemical oxygen demand (COD) and color from textile wastewater enriched with crystal violet cationic dye. The COD removal efficiency was 61.7% and the color removal efficiency was 94.4%. The authors pointed out that this waste-derived char exhibited an adsorption capacity (49.7 mg/g) comparable to NaOH-modified rice husk char (44.9 mg/g) and apricot kernel activated char (32.9 mg/g). Overall, the results suggested that MSW-derived char obtained from gasification had great potential as a potent adsorbent for practical wastewater treatment scenarios and could potentially act as an economically viable adsorbent for environmental applications [82]. Some studies have validated that char derived from MSW can effectively eliminate volatile organic compounds (VOCs) from water. Hoslett et al. (2019) studied the application of MSW pyrolysis char produced at 300 °C for 12 h as an adsorbent in the removal of copper ions (Cu^{2+}) from aqueous solution. In solutions with an initial copper concentration of 100 mg/L and pH of 5, the MSW-derived char exhibited an adsorption capacity of 6.28 mg/g, a higher adsorption capacity compared to that observed with walnut shell pyrolysis char (600 °C/2 h), where starting from the same initial copper concentration, the observed adsorption capacity was 2.64 mg/g. The results showed that MSW can be a precursor of char for effective Cu^{2+} adsorption below an initial concentration of 100 mg/L with a pH solution >4.5 and can be effectively used to reduce the concentration of Cu^{2+} [86]. Li et al. (2015) used MSW pyrolysis chars produced at 600 °C for 2 h to remove elemental mercury (Hg^0) from combustion gases. The MSW char had 53.8% ash and 4.0 m^2/g surface area and presented an adsorption capacity of 26.8 μg/g. After activation with 5% NH_4Cl (surface area of 12.4 m^2/g), the char was able to reach an adsorption capacity of 157.7 μg/g. The Hg^0 removal efficiency of MSW char was 12.8% and that of activated MSW char was 65.9%. The authors concluded that activated MSW pyrolysis char showed a Hg^0 removal efficiency comparable to that of commercial activated carbon or its modified counterparts. Furthermore, it exhibited significantly higher Hg^0 removal efficiency compared to inorganic adsorbents or other chars, such as mulberry twig char. As MSW pyrolysis char is cheaper than commercial activated carbon, it turns out to be an economical adsorbent for removing contaminants such as Hg^0 [87]. Specifically concerning waste-derived char, usually they do not have a large surface area and porous structure given their high ash content. Therefore, physical, chemical, and biological methods have been used to modify and improve these adsorption properties [14]. For example, char from the gasification of solid recovered fuel (SRF) was physically activated and used as a sorbent to remove mercury (Hg) from combustion flue gas. Physical activation increased the specific surface area of the char by 31.6% and the Hg removal efficiency by 41.9% compared to non-activated char [88].

5.1.2. Catalyst

It is estimated that 95% of industrial products are produced through catalytic processes, that more than 35% of global GDP is associated with these processes, and that the global catalyst market is worth around 15 billion dollars. Several carbon-based materials have been used in heterogeneous catalysis reactions, both as catalyst support and direct catalysts in industrial applications. Waste-derived char, as a carbon-rich material, is a promising alternative to support or replace conventional solid catalysts, presenting advantages regarding costs and environmental friendliness [89].

Recently, waste-derived char has attracted more attention in the field of tar reforming due to its low preparation cost and sustainable supply. The focus on waste gasification char as a catalyst, especially in tar reforming, is due to the neutral or weak base nature (largely due to its high ash content) of this char, which makes it highly resistant to the deposition of coke and heavy metals [66,73]. In the work by Assima et al. (2018), char derived from MSW gasification was used as a catalyst for tar reforming and the tar content was reduced from 65 g/Nm^3 to 90 mg/Nm^3 [13]. On another work from Assima et al. (2019), tar conversion of 85% at 871 °C was achieved using MSW gasification char as a catalyst in tar reforming, compared to 56% conversion achieved without using char. Furthermore, the presence of MSW gasification char in the reformer allowed a complete conversion of phenolic compounds and the disappearance of styrene, methylindene, and methylnaphthalene, while the only persistent tars were xylene and naphthalene. Thus, a simple process of washing the syngas with water and subsequent liquid–liquid phase separation could be used to recover the naphthalene from the water, obtaining tar-free syngas. Using MSW-derived char as a catalyst to remove tar from syngas could present a highly promising opportunity for the industry [90]. Although waste-derived char is a carbonaceous and relatively porous material, the morphology and porosity of unactivated char exhibit very poor catalytic properties. So as to improve catalytic performance, research can be directed to modify the morphology and porosity of waste-derived char through several treatments [89]. For example, Mei et al. (2024) studied the catalytic performance of MSW char produced through pyrolysis and gasification and supported with nickel (Ni) in the production of syngas, H_2, CH_4, and tars. MSW pyrolysis char (P-MSWC) produced at 600 °C for 30 min was used as a catalyst in the MSW pyrogasification process at 800 °C. P-MSWC led to the lowest tar yield and the highest gas production, and at the same time the highest concentration of H_2. A syngas yield of 1.3 L/g MSW and an H_2 fraction of 56.6 vol.% were obtained when the steam/MSW ratio was 0.4. For comparison, the same authors used pyrolysis char from the biomass fraction of MSW as a catalyst and found that it had the lowest catalytic activity, as evidenced by its minimum gas yield and high tar yield. The authors concluded that the presence of plastics in MSW contributed to increasing the catalytic activity of P-MSWC. Furthermore, the same work also studied the effect of MSW pyrolysis char (P-MSWC) and MSW gasification char (G-MSWC), supported with Ni in the methanation of syngas. The authors assessed that both waste-derived char performed well catalytically, showing better performance in CH_4 production compared to not using Ni-supported char. For both catalysts, the Ni-supported G-MSWC proved to have better catalytic activities in the methanation process, with the gas reaching a CH_4 concentration of 52.9 vol.%. Thus, the results demonstrate the feasibility of the complete route from MSW to CH_4 and provide valuable guidelines for the valorization of MSW based on pyrolysis and gasification technology [9].

5.1.3. Soil Improvement

There are many chemical reactions that occur during the implementation of waste-derived char in soils, causing the pH of soils to change from an acidic range to a neutral range. As well as increasing the pH of the soil, it increases the cation exchange capacity, electrical conductivity, and nutrient and water retention, which makes waste-derived char suitable for applications in acidic and arid soils [91]. Moreover, as char is a porous material, it absorbs and retains water and minerals, thus reducing dependence on irrigation and preventing water from running off into the sandy soil. This makes it very efficient and attractive for hot, water-scarce areas such as deserts and arid regions or in cases of drought [3]. In essence, to be applied in soils, char must have properties such as water retention capacity, a good amount of nutrients and cation exchange capacity. The cation exchange capacity depends on the functional groups present on the surface of the char. Bhatt et al. (2021) produced char from the pyrolysis of RDF between 400–500 °C for 90 min and the char presented different functional groups such as -OH and -COOH, along with micronutrients such as K, Mg, and P, with pH in the range of 7.8 to 9.5, consequently making them suitable for soil applications [80]. However, when it comes to applying waste-derived char to soils, there are also concerns about PAHs and heavy metals. The application of waste-derived chars to soil can be limited by regulatory authorities such as the International Char Initiative (IBI), with limits pertaining to heavy metals such as cadmium (Cd), molybdenum (Mo), zinc (Zn), and others. The accumulation of heavy metals can result in various environmental and health issues when they migrate to groundwater and soil. Additionally, polycyclic aromatic hydrocarbons (PAHs), known for their carcinogenic and persistent nature, can be generated during the production of waste-derived char. These PAHs may adhere to the hydrophobic surface of the waste-derived char and later leach into the environment upon application of the produced char. In the study by Taherymoosavi et al. (2017), MSW pyrolysis char produced between 450–650 °C showed low concentrations of potentially toxic elements such as heavy metals and PAHs, which were within the standard limits set by IBI, although their derivatives and phenolic compounds were recorded in high concentrations. These waste-derived chars could improve soil fertility; however, the impact of these chars on the soil's PAH levels depends on several factors, including the initial PAH content in the soil, the quantity of char incorporated into the soil, and the influence of natural environmental processes. Therefore, the authors indicated that further research would be essential to determine the accumulation of PAHs in soil modified with waste-derived char and that it was necessary to have strict control over the type of MSW and properties of its derived char to significantly reduce the risk of soil contamination [81].

5.1.4. Other Material Applications

Waste-derived char, being a low-cost carbonaceous material, has sparked interest in a series of material applications, in addition to the best-known ones already covered in the previous sections. Studies have been carried out on the use of waste-derived char in concrete [92], epoxy composites [93], and clothing manufacture [6]. The feasibility of char from the pyrolysis of MSW at 600 °C as an additive in the production of concrete was studied by Jia et al., and the substitution of char increased flexural and breaking strength and promoted the formation of calcium carbonate. With less than 5% of cement replaced, the concrete's compressive strength increased by 9.2%. The authors concluded that the application of MSW char as an alternative cement offers a sustainable solution for waste management and the construction of low-carbon buildings [92]. Lee et al. (2023) showed that the use of char derived from plastic waste as an additive in the production of epoxy compounds leads to an improvement in various properties, such as tensile strength, hardness, electrical conductivity, and Young's modulus [93]. Furthermore, Çay et al. (2020) converted MSW textile waste into char by the torrefaction process at 350 °C for 1 h and investigated its application in cotton textiles to improve the performance of clothing and confer functional properties to textile materials. No PAHs were detected in the produced chars, which showed that there is no disadvantage in using these waste-derived chars for clothing. Incorporating textile waste char imparted a mild hydrophobic effect to the printed side of cotton textiles, enhancing moisture transfer, expediting drying, and augmenting water vapor permeability. Also, the char-printed textiles exhibited odor-masking properties. The authors concluded that these textiles could be particularly advantageous for summer clothing and sportswear and that the application of char from textile waste could be a convenient and positive route for the recovery of this waste stream [6].

5.2. Energy Applications

Some studies have shown that using heterogeneous waste char instead of the original waste as feedstock in waste-to-energy processes (WtE) such as gasification and combustion can be a suitable solution for economic and viable waste management and energy recovery. CO_2 gasification of MSW HTC char was evaluated in a work by Lin et al. (2016). The char was produced at temperatures between 210 and 280 °C and residence times between 30 and 90 min and the char gasification test was conducted at 1000 °C for 1 h. Overall, the hydrothermal carbonization (HTC) treatment enhanced the gasification reactivity of MSW char and reduced the carbon conversion time. Specifically, MSW char produced at 280 °C for 30 min exhibited reactivity up to three times higher than that of the original MSW. The authors noted that nearly 95% carbon conversion of MSW char could be attained with a residence time of 30 min at 1000 °C. However, for the original MSW, almost 90% carbon conversion was achieved with a residence time of 1 h. Therefore, the gasification of MSW char could be completed in a relatively shorter time. The authors stated that this result was of particular interest as it demonstrated the possibility of reducing energy consumption in the gasification process when combined with HTC [94]. Nobre et al. (2019) produced char using RDF from ISW at 300 °C for 30 min, used it as an additive to biomass pellets in the gasification process, and evaluated its influence on the quality of the produced syngas. The results showed that, in tests at 850 °C and an equivalence ratio of 0.25, the addition of 10% RDF char resulted in a syngas with 5.3 MJ/m^3 (LHV) and 92.3% of carbon conversion efficiency, compared to 5.4 MJ/m^3 and 81.8% of biomass pellets. The addition of 10% RDF char led to a lower production of N_2 and CO_2 but produced a higher concentration of tars and heavy PAHs compared to biomass pellet gasification. The authors concluded that RDF char can be used as a gasification additive in moderate incorporation proportions, which could be a viable path for energy recovery [95]. Castro et al. (2023) investigated the gasification of slow pyrolysis RDF char produced at 400 °C for 30 min. The syngas obtained in the RDF char gasification test at 700 °C with an equivalence ratio of 0.15 had an HHV of 5 MJ/Nm^3 and contained 78.7 L CH_4/kg and 30.3 L CO/kg. The authors indicated that this composition was sufficient to use this gas as a fuel to produce useful energy (heat or electricity) [96]. Plastic-free RDF pyrolysis char produced from MSW was evaluated as a feedstock for combustion in the work by Guo et al., (2024). The authors found that RDF char was capable of combustion without any auxiliary fuel and could be a potential alternative to conventional solid fuel (fossil char). As for gaseous emissions, it was observed that only particulate matter (215 mg/m^3) and NOx (210 mg/m^3) exceeded the limit values set by the US EPA standard. SO_2 and CO values were well below the standardized limit values. HCl and Hg values were also lower, suggesting that no additional treatment was required regarding SO_2, CO, HCl, and Hg emissions. Thus, with an additional process to remove particulate matter and NO_X, RDF char could be a potential feedstock to replace conventional fuels in combustion plants for energy production [10].

6. Conclusions and Prospects

In recent years, the production of heterogeneous solid waste such as MSW, ISW, and CDW has increased significantly, and its poor management has made clear the need to define new paths for sustainable and economic management. Making full use of heterogeneous solid waste to reduce environmental pollution issues and recover energy or value has received increasing emphasis from government entities and scientists, and studies corresponding to the valorization of this waste have been conducted. The use of MSW, ISW, and CDW as feedstock for char production was investigated in this study, as well as the main thermochemical processes applied, the properties of waste-derived chars, and their main application routes. Torrefaction, pyrolysis, gasification, and HTC are the four main processes used to produce waste-derived char. Few studies address the production and use of waste-derived char produced through the gasification process. Most works are focused on the pyrolysis process. Currently, most gasification studies focus on syngas or tar removal, so more studies on the characterization and potential applications of waste-derived char from gasification should be carried out since at least 10% of the feedstock entering the gasifier is converted into the char by-product. The relationship between the thermochemical production processes, the properties of waste-derived char, and the results of several applications need to be further explored.

Studies have shown that waste-derived char can act as a catalyst in the gasification process, increasing syngas yield and H_2 production, and as a methanation catalyst to facilitate a low-cost methanation strategy. As a soil improver, waste-derived chars need to meet the limit requirements established in terms of heavy metal and PAH content. They can also be used as additives in construction materials or in the manufacture of textiles for clothing production, as adsorbents of environmental pollutants (Hg^0 from combustion gases, COD, Cu^{2+}), and as fuels for energy production and renewable gases, reducing the total time to achieve complete conversion.

One of the main advantages of using waste-derived char is its ability to divert heterogeneous solid waste and effluents from the environment or landfills, reduce the use of virgin materials, and promote the circular economy. However, the viability of a waste-derived char production process is crucial to its integration into waste management systems. The use of MSW, ISW, and CDW as feedstock for char production could substantially reduce the cost of feedstock, potentially reducing the selling price of waste-derived char and increasing the viability and sustainability of the process, especially if waste-derived char production is integrated with bioenergy systems. This integration would make it possible to obtain more than one product, which could offer additional income streams and energy diversification. Future projects should therefore be considered along these lines.

Although waste-derived char has good potential for several applications, it has some limitations, owing to its heterogeneous composition, high ash content, relatively low specific surface area, presence of heavy metals, and PAHs. These characteristics can affect its performance and limit its application. As such, rigorous quality control measures are necessary and crucial to ensure the safe and effective use of waste-derived char.

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