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Chapter

Solid Waste Gasification: Comparison of Single- and Multi-Staged Reactors

Xianhui Zhao, Kai Li, Meghan E. Lamm, Serdar Celik, Lin Wei and Soydan Ozcan

Abstract

Interest in converting waste into renewable energy has increased recently due to concerns about sustainability and climate change. This solid waste is mainly derived from municipal solid waste (MSW), biomass residue, plastic waste, and their mixtures. Gasification is one commonly applied technology that can convert solid waste into usable gases, including H_2, CO, CH_4, and CO_2. Single- and multi-staged reactors have been utilized for solid waste gasification. Comparison in reactor dimensions, operating factors (e.g., gasification agent, temperature, and feed composition), performance (e.g., syngas yield and selectivity), advantages, and disadvantages are discussed and summarized. Additionally, discussion will include economic and advanced catalysts which have been developed for use in solid waste gasification. The multi-staged reactor can not only be applied for gasification, but also for pyrolysis and torrefaction.

Keywords: solid waste, gasification, single-staged reactor, multi-staged reactor, syngas, catalyst

1. Introduction

Solid waste can be derived from municipal solid waste (MSW), biomass residue, plastic waste, and their mixtures. For example, MSW management has become a big challenge all over the world. Based on a World Bank report [1], the world generates 0.74 kg of waste per capita per day, and the total MSW production is projected to grow to 3.40 billion tons by 2050. 37% of this MSW ends up in landfills and 33% is openly dumped worldwide [1]. Only 19% undergoes material recovery through recycling and composting, while the remaining 11% is treated through modern incineration. This creates serious environmental problems and a huge energy waste. One sustainable strategy for waste management is to reduce landfill disposal, thus minimizing the environmental impact. Meanwhile, utilizing solid waste resources to create value-added products has become one of the most attracting topics. The top 3 components of MSW are food and green waste (44%), paper and cardboard (17%), and rubber and leather (12%) [1]. Therefore, MSW contains a high content of organic material, which can be recovered through biochemical [2] and thermochemical processes [3]. Thermochemical processes are promising for dealing with a large quantity of MSW, especially from unsorted waste streams, as it can significantly reduce the waste in both

mass (about 70–80%) and volume (about 80–90%) with a high conversion rate. Other detailed advantages can be found in Arena's review on thermochemical processes [4].

Various thermochemical processes, such as incineration, pyrolysis, and gasification, have been developed to recover energy from the organic fraction in MSW [5]. Incineration is a full oxidation of the combustible materials in the waste and generates energy in the form of heat. Incineration has been traditionally used to treat waste. However, due to the production of flue gases (CO_2, H_2O, O_2, N_2) during the process and legislation enforcement regarding gas emission, new development of incineration is needed to reduce the environmental impact. Pyrolysis is the thermal degradation of waste, under a limit or total absence of an oxidizing agent. Pyrolysis can recover part of the organic fraction as liquid fuels (e.g., hydrocarbons, alcohols), while also generating a small amount of synthesis gas (syngas, a mixture of CO, H_2, CO_2, CH_4, etc.) and biochar. The generated syngas can be used to power gas engines or turbines to generate electricity. Although there may be some differences in yield, proportion, and exact composition, gasification is a partial oxidation of organic compounds and mainly produces syngas. Syngas can be converted into value products through processes such as the Fischer-Tropsch synthesis [6, 7], or used as a fuel for electricity and heat generation. Therefore, gasification can produce energy, energy carriers (such as H_2) and chemicals from the solid waste [8], all of which creates lots of research interest. Additionally, gasification has advantages including no limitations on the size and type of waste, different applications of the gaseous fuels, and a decrease in overall pollution.

Gasification of solid waste is a complex process, including different chemical and physical transformations at high temperature (e.g., >600 °C). Based on the oxidation medium, gasification can be classified into partial oxidation with air, oxygen-enriched air, pure oxygen, steam, and plasma gasification. Different gasification processes generate different gas compositions, heating values and byproduct yields. In general, there are four steps in gasification: vaporization, devolatilization/pyrolysis, secondary cracking of tars, and reactions/reduction/gasification [9]. Vaporization involves heating the waste at low temperature (ca. 160 °C) to remove water from the solid waste. Devolatilization/pyrolysis occurs at a higher temperature and generates char and volatiles, which include long chain hydrocarbon liquids and a small fraction of gases. Secondary cracking of tars (a mixture of condensable hydrocarbons) is used to further crack the tars and involves several homogeneous reactions in the gas phase and heterogeneous ones at the surface of the solid fuel or char particles. Reactions/ reduction/gasification is used to react the char with a gas species using heterogeneous reactions. The reactions which occur during gasification are complex, making it difficult to optimize the processing parameters to obtain the best quality and yield of syngas. These parameters include equivalence ratio, reactor temperature, residence time of gases and waste, waste composition and physical properties, and composition and inlet temperature of the gasifying medium. Park et al. [10] performed a two-staged gasification of high-density polyethylene (HDPE) and biomass blends, comprised of an oxidative pyrolysis reactor and a thermal plasma reactor. They found that, for higher biomass fractions, enhanced CO_2 yields were produced and reversely, an increased HDPE fraction yielded a higher content of hydrocarbons.

Different reactors, including single-staged and multi-staged gasifiers, have been developed for gasification [5]. For a single-staged reactor, the pyrolysis and gasification zones are packed into one reactor (**Figure 1a**). A single-staged gasifier includes a fixed bed gasifier [11, 12], fluidized bed gasifier [13, 14], and entrained flow gasifier [15, 16]. A multi-staged reactor system is configured in two ways: a single reactor with separate, controlled pyrolysis and gasification zones, and separate pyrolysis and gasification reactors connected in series (**Figure 1b**). The multi-staged gasification technology allows for optimization of reaction conditions
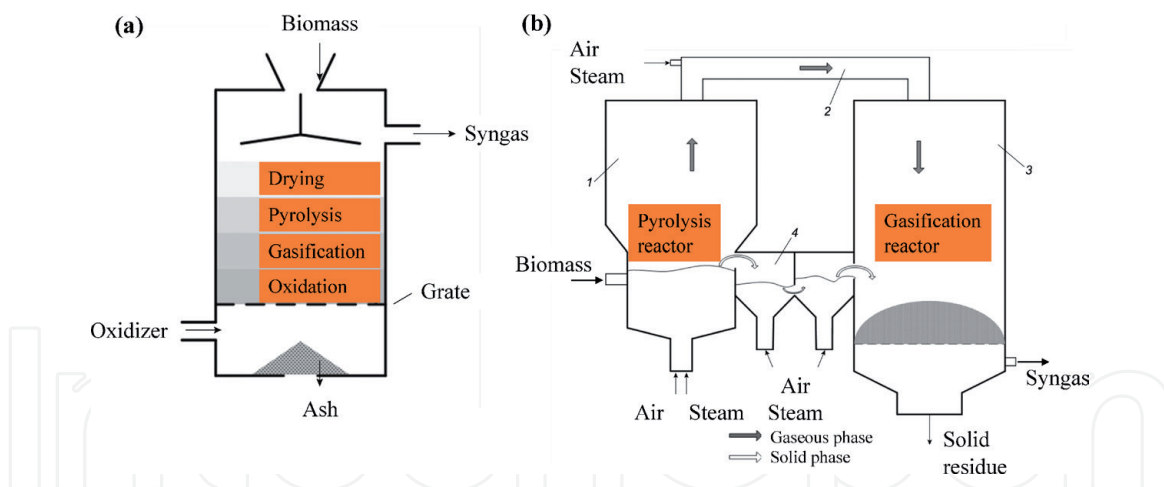
Figure 1.
Schematic of a single-staged reactor (a, fixed bed gasifier) and multi-staged reactor (b, 1: first stage [pyrolysis], 2: second stage [thermal decomposition of tar], 3: third stage [gasification], 4: fluidized bed) [21]. Reproduced with permission from [21].

for the conversion of biomass at every separate stage. Both single- and multi-staged reactors have been utilized for solid waste gasification. Single- and multi-staged reactors are illustrated in **Figure 1**. Chan et al. [17] studied the single-staged gasification of MSW, finding that the tar content in syngas could reach 7.8 g/Nm^3. Bhoi et al. [18] investigated the co-gasification of a MSW and switchgrass mixture in a single-staged reactor, producing 9.9–26 g/Nm^3 of tar. Compared with a single-staged reactor, a multi-staged reactor system can reduce the tar yield, which is beneficial because generated tar can cause failure of gasification projects [19]. Gómez-Barea et al. [20] developed a three-staged, fluidized bed based gasification reactor and found that this three-staged system depicted a higher gasification efficiency (14%) and lower tar content, compared to a regular single-staged fluidized bed reactor. However, literature providing a comparison between single- and multi-staged reactors for solid waste gasification remains sparse. The analysis of reactor dimensions, operating factors, and performance of these reactors has not been studied systematically. It is the goal of this review to present current literature comparing these reactor types and analyzing their relevant processing parameters.

This chapter focuses on the comparison of single- and multi-staged reactors used for solid waste gasification. Solid waste resources such as MSW, biomass residue, plastic waste, and their mixtures are discussed. The reactor dimensions, operating factors (e.g., temperature, gasification agent, and feed composition), performance (e.g., syngas yield), advantages, and disadvantages of single- and multi-staged reactors are discussed and summarized. Additionally, discussion includes economic and advanced catalysts (e.g., Ni-CaO-C and Ni/Al$_2$O$_3$) which have been developed for use in solid waste gasification. These Ni based catalysts are promising for solid waste gasification at high conversion efficiency. The multi-staged reactor can not only be applied for gasification, but also for pyrolysis and torrefaction.

2. Solid waste gasification

2.1 Single-staged reactor

2.1.1 Reactor dimensions

Different reactor scales, including bench, lab, and pilot scale, have been developed for solid waste gasification. The inside diameter and length of the reactor

are typically in the range of 3–800 mm and 200–3500 mm, respectively, as shown in **Table 1**. Selection of the appropriate reactor dimensions is helpful for the solid waste gasification performance. For example, Xiong et al. [22] found that the reactor diameter had a negligible effect on gasification performance, but an increase in bed height (0.6–1.2 m) caused an increased heating value and carbon conversion efficiency. Basha et al. [23] found that a difference in the hydrocarbon content and methane concentration of the product gas depends on the reactor size and design. Larger reactors can increase the residence time of the product gas in the reactor, so that lighter hydrocarbons have more time to decompose or undergo oxidization into smaller molecules such as H_2 and CO [23]. There are various types of reactors developed for solid waste gasification, including bubbling fluidized bed, downdraft fluidized bed, updraft fluidized bed, downdraft fixed bed, updraft fixed bed, batch, and entrained-flow reactors, some of which are shown in **Figures 2**–**4**. Different types of reactors are applicable for specific types of solid waste. For example, steam gasification of waste with a high moisture content occurs well in a bubbling fluidized bed reactor.

Other designs, such as adding a stirrer or using sorbents, have been developed to improve the solid waste gasification performance. In a study, Indrawan et al. [34] utilized a stirrer in a downdraft reactor system to create a uniform mixing feed and prevent bridging inside the reactor; a rotating ash scrapper to unload ash from the reactor and prevent ash accumulation inside the reactor; and an inclined ash screw conveyor to transport the ash into the ash drum. Pinto et al. [32] used water to cool the feeding system and avoid clogging inside, which can arise from the feedstock pyrolysis (prior to entry into the reactor). N_2 was blown through the feeding system to help transfer the feedstock smoothly, avoid plugging, and prevent gas backflow. Lastly, the gas product passed through a cyclone to remove particulates [32]. Salaudeen et al. [42] used calcined eggshell as the bed material and CO_2 sorbent for the steam gasification of sawdust, in a bubbling fluidized bed reactor, to improve the hydrogen content in the syngas. The sorbent-enhanced gasification enabled the reactor operation at comparatively lower temperatures, and required less equipment [42]. In summary, the reactor design and size (inside diameter of 3–800 mm and length of 200–3500 mm) need to be optimized to maximize the solid waste gasification performance.

2.1.2 Operating factors and performance

During the solid waste gasification process, many parameters such as temperature, feed composition, gasification agent, and reaction time are investigated. **Table 2** shows the syngas yield (typically 1.2–2.2 Nm^3/kg) obtained from gasification under varying conditions. Temperature is a significant parameter that can affect the gasification performance and is usually in the range of 600–900 °C. For example, Bai et al. [36] studied the gasification of PP at 23 MPa and 500–800 °C, finding that an increase in temperature improved the gasification efficiency. Bai et al. [43] also studied the supercritical water gasification of polyethylene terephthalate (PET), finding that the gasification efficiency increased with an increase in temperature from 500 to 800 °C. The PET gasification reaction increased slowly with the temperature (500–700 °C). Based on the kinetics, the PET gasification reaction was complex and intense in the initial stage of gasification. Most active components gasified quickly, while inert components reacted slowly in the later stage of gasification [43]. Peng et al. [44] studied the gasification at various gasification temperatures (750, 825, and 900 °C), finding that high temperature (900 °C) was favorable for tar cracking. Xiong et al. [22] studied gasification at 400–800 °C, finding that an increase in temperature affected the heating value and improved the gasifier

Waste	Reactor type	Reactor dimension	Other	Ref.
MSW	Lab scale fixed bed	Inside diameter = 48 mm, length = 500 mm	—	[24]
Landfill waste	Lab-scale horizontal tube	Inside diameter = 25 mm, length = 1000 mm	—	[25]
Lignite coal and plastic mixture	Sealed quartz	Inside diameter = 3 mm, length = 200 mm	Plastic: PP[a], PE[b], or PC[c]	[26]
Poplar wood chips	Stainless steel batch (autoclave)	—	Supercritical water gasification	[27]
Rice husk	Bubbling fluidized bed	Diameter = 0.08 and 0.8 m, bed height = 0.6–1.2 m	—	[22]
MSW	Fixed bed	Outside diameter = 219 mm, length = 600 mm	—	[28]
Chicken manure and wood chip mixture	Fixed bed downdraft	—	Feedstock flow rate: 10 kg/h	[29]
Rural solid waste	Fixed bed updraft	—	Feedstock main composition: paper, plastic, and kitchen waste	[30]
Biomass	Fixed bed reverse downdraft	Inside diameter = 54 mm, length = 1.25 m	—	[31]
Rice production waste mixture	Bench scale bubbling fluidized bed	Inside diameter = 80 mm, length = 1.5 m	Feedstock flow rate: 5 g/min	[32]
Biomass	Fluidized bed	Outside diameter = 120 mm, length = 610 mm	—	[33]
MSW and switchgrass mixture	Downdraft	Length = 3.2 m	Feedstock flow rate: 100 kg/h	[34]
Food waste	Batch	Reactor volume = 200 mL	Supercritical water gasification; maximum operation temperature: 600 °C, maximum operation pressure: 35 MPa	[35]
PP	Quartz tube	Inside diameter = 3 mm, length = 200 mm	—	[36]
MSW	Drop quartz tube	Inside diameter = 19 mm, length = 1.8 m	Feedstock flow rate: 0.78 g/min	[37]
MSW and biomass mixture	Pilot-scale bubbling fluidized bed	Inside diameter = 0.25 m, length = 2.3 m	—	[38]
Sawdust	Pilot scale bubbling fluidized	Inside diameter = 0.2 m, length = 3.5 m	Reactor capacity: 50 kg/h	[39]

[a]*Polypropylene (PP).*
[b]*Polyethylene (PE).*
[c]*Polycarbonate (PC).*

Table 1.
The solid waste gasification, single-staged reactor type, and dimension.
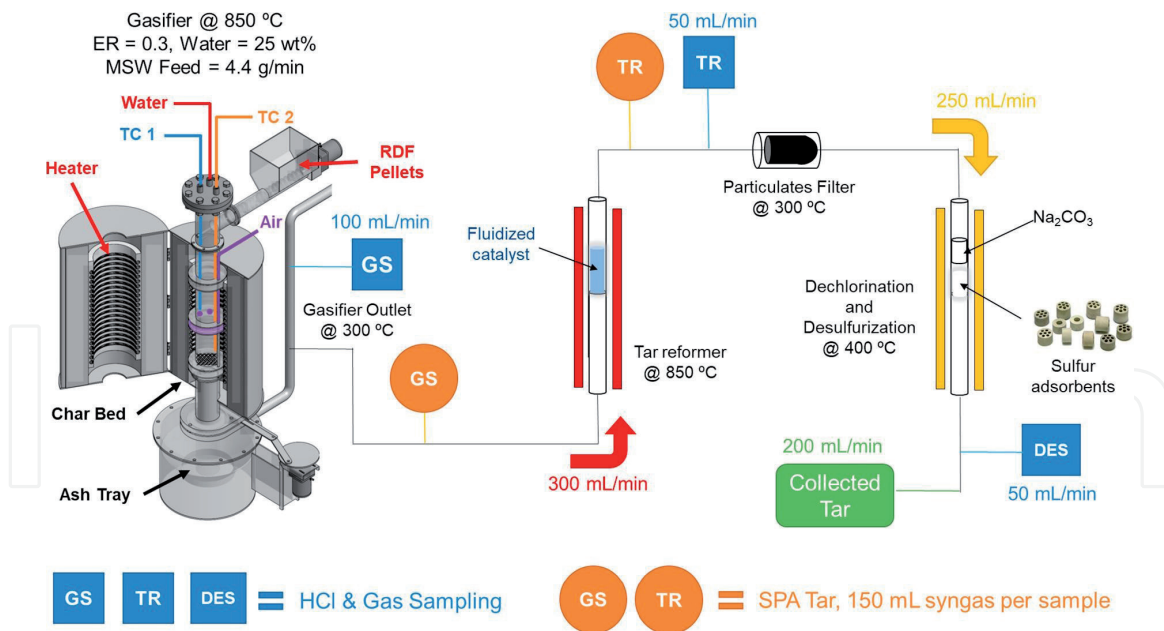
Figure 2.
Illustration of the downdraft gasification of MSW integrated with a hot syngas purification system. RDF pellets were gasified to produce syngas. Some of the syngas passed through a purification system (including a tar reformer, particulate filter, and dechlorination/desulfurization reactor) to remove impurities (tar, particulates, HCl, and sulfur species). (ER: equivalence air ratio, TC1: thermocouple 1, TC2: thermocouple 2, RDF: refuse derived fuel, TR: tar reformer, DES: desulfurization reactor, GS: gasifier, SPA: solid phase adsorption) [17]. Reproduced with permission from [17].
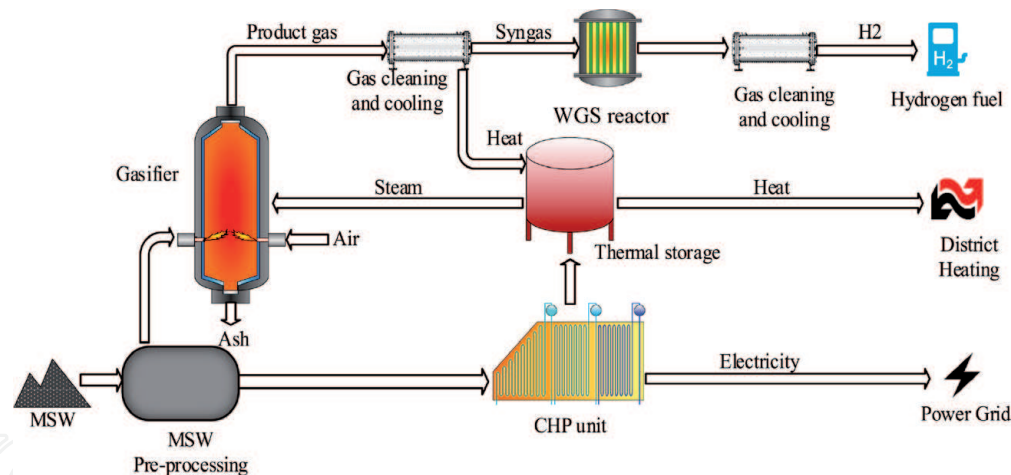

Figure 3.
Schematic diagram of an H_2 production plant with gasification of MSW. MSW was pre-processed and then gasified to produce syngas, which passed through a WGS reactor to produce H_2. Partial MSW combustion provided heat for district heating and power grid. (WGS: water gas shift, CHP: combined heat and power) [40]. Reproduced with permission from [40].

efficiency. Xiang et al. [28] studied the steam gasification at temperatures of 600–1000 °C, finding that the increase in temperature increased the total volume fraction of H_2 and CO from 56% to 66%. From all the above studies, an appropriate temperature (e.g., 800–900 °C) should be selected for solid waste gasification based on high gasification performance and low energy consumption.

Feed composition is also a significant parameter for gasification. For example, Pio et al. [38] studied gasification using a refuse-derived fuel (from MSW) and biomass (pine chips or pine pellets) mixture. 0, 10, 20, 50, and 100 wt% of refuse-derived fuel content in the mixture was studied. An increase in the refuse-derived fuel content increased both the CH_4 concentration and lower heating value (LHV) of the product gas. Therefore, the addition of refuse-derived fuel to biomass may improve
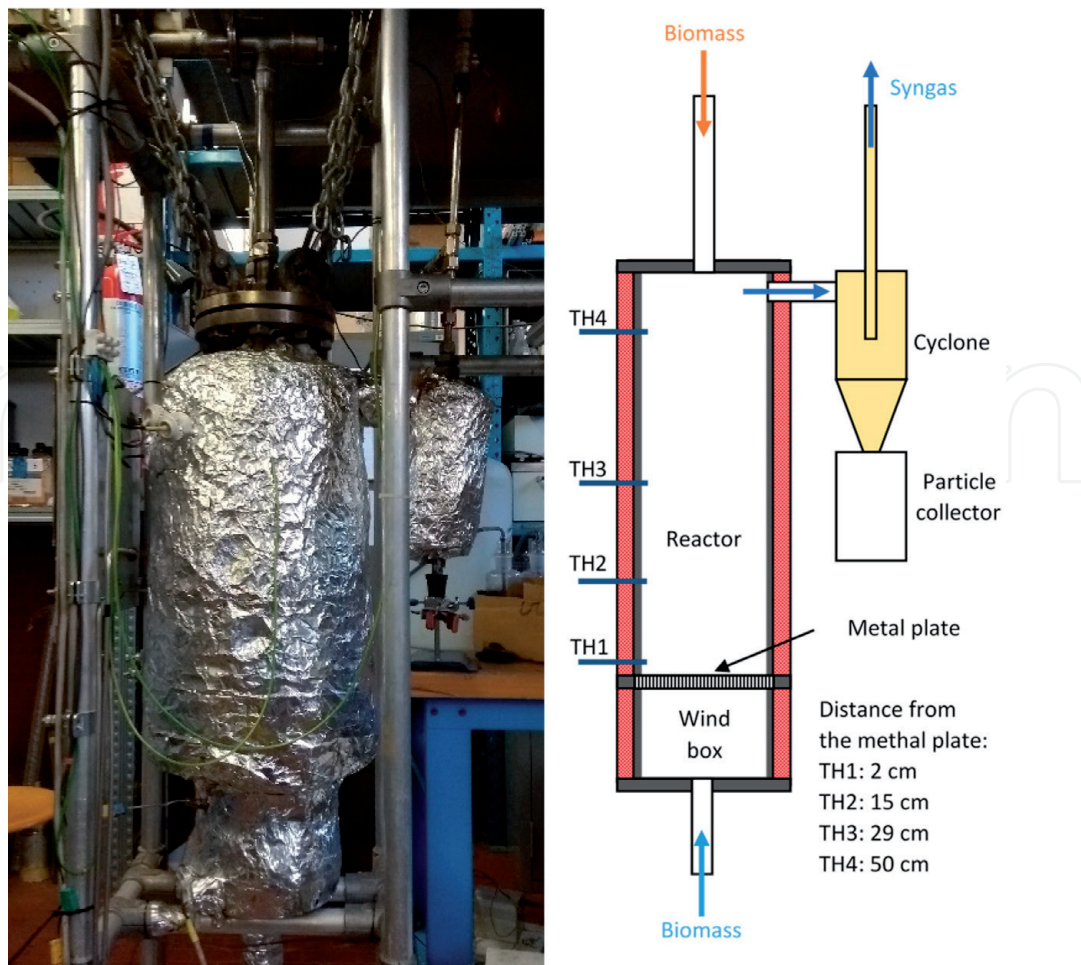
Figure 4.
An updraft gasification reactor (left) and a schematic diagram of the reactor interior (right). The reactor consisted of a stainless-steel cylinder with a height of 59 cm and a diameter of 8.3 cm. Biomass was transported through a feeding cochlea at the top. Four thermocouples (TH1–TH4) were used to monitor the temperature evolution during the gasification process. A perforated metal plate was used as a support for the gasification bed to allow the oxidant to flow through. A wind box was used to preheat the oxidant agent. The produced syngas was cleaned using a cyclone and a ceramic filter for particle removal. Reproduced with permission from [41].

the economic viability and environmental benefits for gasification plants. There was no agglomeration, slag, or defluidization observed during the experiment [38]. Ng et al. [29] studied the gasification of a chicken manure and wood chip mixture. The co-gasification of this chicken manure and wood chip mixture (30 wt% chicken manure) produced a syngas of similar quality (in terms of LHV) compared to that of gasification of pure wood chip. The chicken manure was found to be a compatible feedstock for gasification in the presence of wood chips [29]. Su et al. [48] studied the gasification of food waste at a food waste concentration of 10–30 wt%. When the food waste concentration increased from 10 to 30 wt%, the H_2 yield largely decreased from 1.1 to 0.6 mol/kg, while the CH_4 yield increased. However, higher food waste concentrations may cause the reactor to plug and catalyst to deactivate [48].

More researchers have studied the effect of feed composition on gasification performance. For example, Bian et al. [26] studied the supercritical water co-gasification of a lignite coal and plastic (PP, PE, or PC) mixture at concentrations of 5–35 wt%. The co-gasification of lignite coal and plastic improved the gasification efficiency of each other, indicating a synergistic effect. This was also observed in other studies. Zaini et al. [25] studied the gasification of landfill waste and a landfill waste and biochar mixture. Co-gasification of landfill waste with biochar was beneficial to improve the H_2 concentration in the syngas. At 800 °C, the addition of 35 wt% biochar enhanced the H_2 concentration from 38 to 54 vol%, and reduced the tar yield from 0.05 to 0.01 g/g-fuel-daf (daf: dry-ash-free weight basis) [25]. It was

Waste	Reactor type	Reaction conditions	Performance	Other	Ref.
MSW	Downdraft fixed-bed	850 °C, equivalence air ratio of 0.3	Syngas yield: ~12 L/min	MSW feed rate: 4.4 g/min; MSW moisture content: 25 wt%	[17]
Food waste	Batch	420 °C, 23 MPa, reaction time of 30 min	Gas yield: 8.4 mol/kg; H_2 yield: 3.1 mol/kg	Reactor volume: 200 mL; heat rate: 10 °C/min	[45]
Biomass	Bubbling fluidized bed	700–854 °C, equivalence ratio of 0.17–0.36	Syngas yield: 1.2–2.2 Nm^3/kg; carbon conversion efficiency: 60–88%	Biomass feed rate: 7–15 kg/h	[13]
MSW and switchgrass mixture	Fixed bed downdraft	~800 °C	Syngas yield: 1.5 Nm^3/kg	20% MSW in the feed mixture	[18]
Palm kernel shell and PS[a] mixture	Downdraft	800 °C, air flow rate of 2.5 L/min	Solid yield: ~17 wt%; liquid yield: ~18 wt%; tar yield: ~5 wt%; gas yield: ~60 wt%	20 wt% PS in the feed mixture	[23]
PE and soda lignin mixture	Batch	700 °C, reaction time of 30 min	Gas yield: 75 mol/kg	Internal volume: 10 mL; 50% PE in the feed mixture	[46]
MSW	Drop-tube	900 °C	Syngas yield: 17.5 mol/kg	CO_2 gasification; MSW feed rate: 0.8 g/min	[47]
PET	Quartz tube	800 °C, reaction time of 10 min	Carbon conversion: 98 wt%	Supercritical water gasification	[43]

[a]*Polystyrene (PS).*

Table 2.
The solid waste single-staged gasification factor and performance.

also determined that an increase in feedstock concentration could cause problems with reactor operations, such as reactor plugging and damage, thus reducing the gasification efficiency. A suitable feedstock concentration should be selected to balance the gasification efficiency and industrial application [26].

During solid waste gasification, different gasification agents such as O_2 and air can be used. For example, Pinto et al. [32] studied the gasification of rice husk, rice straw and PE at ~850 °C using different gasification agents, such as a mixture of steam, air, oxygen, and CO_2. At this temperature, the heavier gaseous hydrocarbons and tar contents can be minimized, while steam can promote steam reforming reactions, thus resulting in a gas enriched in H_2 and lower tar content. The use of steam and O_2 was also a good gasification agent option, especially since it lacked N_2 and prevented any diluting effects. The combination produces a larger gas HHV (around 42% higher) and greater energy conversion than those obtained when air was used instead of O_2. However, the cost of O_2 is still a disadvantage and limits its use [32].

Meng et al. [39] studied the effect of gasifying agents such as air, air–steam, oxygen-steam, and oxygen-enriched air, on sawdust gasification. Compared to sawdust gasification using air, oxygen-enriched air increased LHV due to a reduction in N_2 dilution, while air–steam favored H_2 production due to water gas shift reaction enhancement [39]. Zheng et al. [37] studied the steam gasification of MSW using recycled CO_2 at 1000 °C with a CO_2/steam ratio of 0.5–3.0, and found that increasing the CO_2/steam ratio from 0.5 to 2.5 increased both H_2 and CO molar yields.

In order to further improve the gasification performance, various catalysts have been developed and explored. For example, Wang et al. [49] studied the CO_2-assisted gasification of PP at 900 °C, and discovered the catalytic (Ni/Al_2O_3 catalyst) gasification improved the gas evolution rate and syngas yield significantly compared to non-catalytic gasification. Irfan et al. [24] studied the catalytic gasification of MSW at 1 atm, finding that the use of waste marble powder as a catalyst was helpful to increase the H_2 concentration and decrease the CO_2 concentration in the gas product, compared to non-catalytic tests. Tian et al. [33] studied the gasification at 800–1000 °C, finding that the use of a catalyst (olivine) enhanced the syngas yield and reduced the cracked tar content. Peng et al. [44] studied gasification over a $Ni/CeO_2/Al_2O_3$ catalyst at different Ni loadings (20, 30, and 40%), finding that a high catalyst loading (40%) was favorable for high-purity H_2 production and tar cracking. The above research demonstrates that the use of an appropriate catalyst can improve product yield and selectivity.

Other parameters such as reaction time, waste pretreatment, and feed dimension have also been investigated for their influence on gasification performance. For example, Bai et al. [36] studied the gasification of PP at a reaction time of 2–60 min, finding that an increase in reaction time had a positive effect on the gasification efficiency. In another study, Bai et al. [43] studied the supercritical water gasification of PET, finding that gasification efficiency increased with the increase in reaction time from 2 to 60 min. Bai et al. [43] also found that the reaction pressure (21–29 MPa) had little impact on the gasification efficiency because the properties of the supercritical water did not change significantly at these different pressures. Su et al. [35] found that waste sorting is helpful to improve the H_2-rich syngas production (or syngas yield) and gasification efficiency compared to unsorted waste. Xiang et al. [28] studied the steam gasification of MSW with two different MSW particle sizes (20 < diameter < 30 mm and 80 < diameter < 100 mm), finding that the increase of particle size decreased the total volume fraction of H_2 and CO from 52% to 50%. Basha et al. [23] selected a feedstock size of 2–4 mm because a larger particle size prevented a compact fuel bed, while a smaller particle size blocked the reactor and plugged the gas outlet.

2.1.3 Advantages and disadvantages

In single-staged reactor systems, different types of reactors have been utilized based on their advantages and disadvantages. The common reactors used for solid waste gasification include fixed bed, fluidized bed, and entrained flow reactors [50]. A fixed bed reactor has simple construction and operation. However, a fixed bed reactor is typically used for small size reactions with limited loading/processing flexibility because of the poor adaptability for heterogeneous materials. A fluidized bed reactor can provide high mixing and solid–gas contact, promote heat and mass transfer, increase the reaction rate and conversion efficiency, and improve the process flexibility, compared to a fixed bed reactor. However, for both fixed bed and fluidized bed reactors, tar formation is a major problem, while entrained flow reactors have a high cost and poor biomass adaptability [50].

Indrawan et al. [34] studied the gasification of a MSW and switchgrass mixture, finding that the downdraft reactor (patented design) system design was selected due

to low tar content (< 0.5 g/Nm^3), compared to a circulating fluidized bed (up to 12 g/Nm^3), fluidized bed (up to 40 g/Nm^3), and updraft fixed-bed reactor (up to 150 g/Nm^3). Bian et al. [26] used a sealed quartz reactor system in their study and determined that a fluidized bed reactor might be better for enhancing the mass transfer of the reactant and reducing reactor plugging problems. The fluidized bed gasifier has excellent solid–gas contact efficiency, uniform and controllable temperature distribution, and broad feedstock feasibility [51]. Based on this data, the downdraft fluidized bed is a promising reactor choice for solid waste gasification.

2.2 Multi-staged reactor

2.2.1 Reactor dimensions

The inside diameter and length of a multi-staged reactor is typically in the range of 3–750 mm and 150–3500 mm, respectively, shown in **Table 3**. These dimensions are similar to those of the single-staged reactor. Likewise, selection of appropriate reactor dimensions will be helpful for the solid waste gasification performance in a multi-staged reactor. There are multiple stages in a multi-staged reactor system such as pyrolysis, reforming, tar cracking, and water-gas shift. **Figure 5** shows a diagram of a two-staged gasification process. Different stages are developed for specified reactions. Parameters in each stage can be operated individually for optimization. In addition, using high temperatures in the tar cracking stage can be helpful to largely reduce tar [50].

Kuba and Hofbauer [63] studied the gasification in a dual fluid bed gasifier, where heat is supplied by the bed material circulating between the gasifier and the combustion reactor. The reactor design and the fluidization nozzle position had a significant effect on the tar formation and reduction. For example, an increase in the bed height of the gasifier can increase the residence time, leading to an overall decrease in tar. Additional fluidization nozzles in the inclined wall, located in the bubbling bed where the feedstock enters the gasifier via a conveyer screw, can improve the mixing of feedstock and bed material. A moving bed section above the inclined wall (no fluidization) can be used to reduce the tar formation. Additional fluidization nozzles can also be installed to reduce the influence of the inclined wall [63]. Chai et al. [54] studied the two-staged gasification of a mixture of LDPE and pine sawdust over catalysts, finding that N$_2$ can be introduced into the gasifier to prevent oxidation of the catalyst in the bottom stage.

2.2.2 Operating factors and performance

Table 4 shows the syngas yield (typically 0.7–3.0 Nm^3/kg) obtained from different gasification processes, depending on feedstock species, reactor types, and operating conditions. Temperature is one operating parameter that has a significant influence on the solid waste gasification performance in a multi-staged reactor. For example, Bai et al. [52] studied the two-staged gasification kinetics of PC in supercritical water at different temperatures (500–800 °C). An increase in temperature improved the free radical and cracking reactions of PC. The gasification reaction of PC was intense and underwent a cracking reaction, forming gas phase products and many small molecular fragments in the first stage. The gasification reaction was slow, but kept increasing in the second phase [52]. Xiao et al. [55] found the pyrolysis/gasification of pine sawdust was largely improved by increasing the reactor temperature from 700 to 850 °C. Prasertcharoensuk et al. [57] found that pyrolysis temperature significantly influenced char properties, specifically, the surface area and pore size increased with an increase in temperature from 600 to 900 °C. Liu et al. [60] studied the gasification at temperatures of 600–800 °C, finding that a higher temperature was helpful to

Waste	Reactor type	Reactor configuration	Other	Ref.
PC	Quartz two-staged tube	Inside diameter = 3 mm, length = 200 mm	Two stages: 500–700 °C, and 700–800 °C	[52]
Oat hull pellet	Two-staged fixed bed	—	Steam gasification	[53]
LDPE[a] and pine sawdust mixture	Two-staged fixed bed	Central diameter = 30 mm, length = 150 mm	Pyrolysis (feedstock loaded, 700 °C) and gasification (catalyst loaded, 600 °C)	[54]
Pine sawdust	Three-staged	First stage: inside diameter = 80 mm, length = 200 mm, second stage: inside diameter = 136 mm, length = 400 mm, and third stage: inside diameter = 26 mm, length = 2500 mm	First stage: pyrolysis/gasification, second stage: reformer for tar cracked, and third stage: combustor with air	[55]
Olive oil mill residue	Two-staged	Inside diameter = 0.75 m, length = 2 m	Pyrolysis and char gasification	[56]
Waste biomass	Two-staged fixed bed	Center diameter = 33 mm, length = 830 mm	—	[57]
Biomass	—	Inside diameter = 22 mm, length = 160 mm	—	[58]
Rice husk and PE mixture	Bench-scale two-staged fixed bed	First stage: diameter = 38 mm, length = 300 mm, and second stage: diameter = 25 mm, length = 300 mm	First stage: pyrolysis at 600 °C, and second stage: reforming at 800 °C	[59]
Rice husk	Two-staged downdraft fixed bed	First stage: inside diameter = 44 mm, length = 250 mm; second stage: inside diameter = 44 mm, length = 530 mm	First stage: pyrolysis, and second stage: tar cracking	[19]
Rice straw	Two-staged bubbling fluidized bed	Inside diameter = 50 mm, length = 1.2 m	—	[60]
Wood pellet or manure	Dual fluidized bed	Inside diameter = 150 mm, length = 3.5 m	—	[61]

[a]Low-density polyethylene (LDPE).

Table 3.
The solid waste gasification, multi-staged reactor type, and dimension.

enhance gasification performance. Khonde and Chaurasia [19] studied the two-staged gasification at different second-stage temperatures (700–900 °C). The tar yield decreased with increasing temperature, while tar cracking at higher temperatures led to hydrogen rich syngas production (or gas yield) [19].

Feed concentration and catalyst are important factors that have been investigated for solid waste gasification. For example, Bai et al. [52] studied the gasification kinetics of PC in supercritical water at different PC concentrations (5–25 wt%), finding that a decrease in PC concentration improved the gasification level of the unit feedstock. Chai et al. [54] studied the two-staged gasification of a mixture of
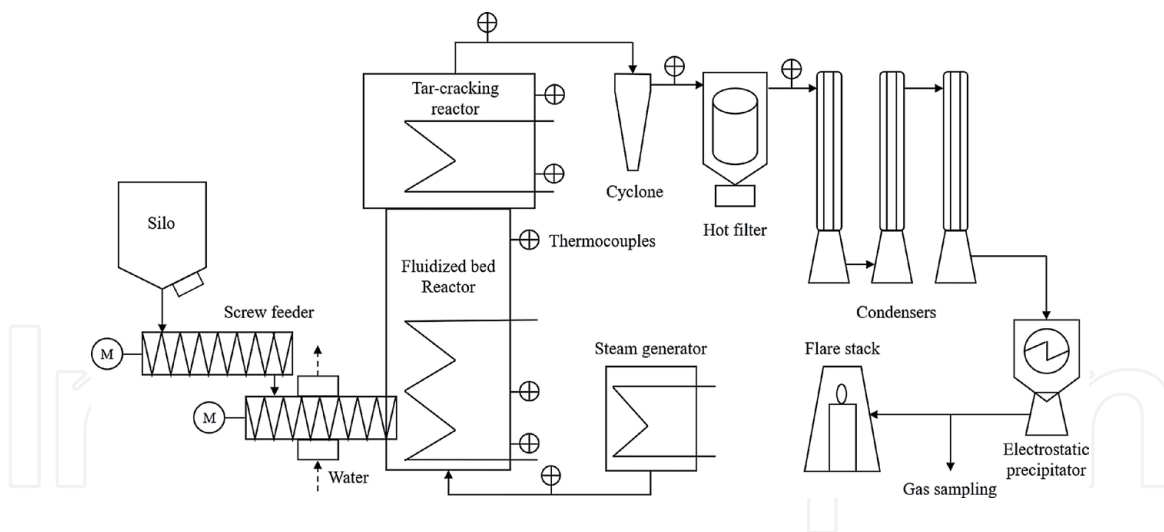
Figure 5.
Diagram of a two-staged gasification process, which mainly consists of a feeding system, two reaction zones (fluidized bed reactor and tar-cracking reactor), a char separation system (cyclone and hot filter), and a quenching system (water-cooled condensers) [62]. Reproduced with permission from [62].

Waste	Reactor type	Conditions	Performance	Other	Ref.
Biomass briquette	Two-staged (fluidized bed and swirl-melting furnace)	First stage: 695 °C; second stage: 1280 °C	Gas yield: ~1.5 Nm^3/kg	Biomass contains rice straw, plastic and paper; Biomass feed rate: 25 kg/h	[50]
Pine sawdust	Three-staged (pyrolyzer, reformer, and combustor)	Pyrolyzer: 700 °C; reformer: 850 °C; combustor: 850 °C	Gas yield: 1.6 Nm^3/kg; tar yield: 1.0 g/kg	Biomass feed rate: 200 g/h	[64]
Pine sawdust	Three-staged (pyrolysis/gasification, reformer, and combustor)	Pyrolysis/gasification: 800 °C; reformer: 850 °C; combustor: 850 °C	Gas yield: 1.0 Nm^3/kg	Biomass feed rate: 200 g/h	[55]
Wood sawdust and HDPE mixture	Two-staged (plasma gasification and folded plate)	Input power of 18 kW	Gas yield: ~2.2 Nm^3/kg	40 wt% HDPE in the feed mixture	[65]
MSW	Two-staged (gasification and reforming)	Gasification: 850 °C; reforming: 850 °C	Syngas yield: 0.7 m^3/kg	—	[66]
PE	Two-staged (fluidized bed gasifying and tar cracking)	Gasifying: 792 °C; cracking: 852 °C	Syngas yield: 3 Nm^3/kg; char yield: 271 g/kg; tar yield: 68 g/kg	Steam gasification	[62]

Table 4.
The solid waste multi-staged gasification factor and performance.

LDPE and pine sawdust, finding that the use of a Ni-CaO-C catalyst was helpful to improve the gas yield, compared with non-catalyst. Additionally, it was determined that the heat recovered from the catalyst regeneration can be used for heating

feedstocks in the reactor [54]. Al-Rahbi and Williams [58] studied a two-staged pyrolysis-reforming gasification, finding that the H_2 production increased largely with the use of a tyre pyrolysis char as the catalyst, compared to non-catalytic test.

Other parameters such as reaction time and pressure have also been investigated for gasification. For example, Bai et al. [52] studied the gasification kinetic of PC in supercritical water at different reaction time (5–60 min), finding that the increase in reaction time improved the gasification efficiency. Bai et al. [52] also studied the gasification at different pressures (21–29 MPa), finding that the pressure had no significant impact on gasification. This is likely because the properties of the supercritical water do not change significantly at these different pressures.

2.2.3 Advantages and disadvantages

Compared to single-staged reactor systems, the use of multi-staged reactor systems for solid waste gasification has some advantages and disadvantages. A two-staged reactor system is convenient to investigate the specific effect of temperature at different stages [54]. The multi-staged reactor tends to be more promising and reliable in technique development [50]. For example, Al-Rahbi and Williams [58] studied two-staged pyrolysis-reforming gasification. The first stage was pyrolysis at 500 °C, and the second stage was reforming at 700–900 °C. The two-staged pyrolysis-reforming reactor was found to increase the total gas yield, compared to a single-staged reactor. One aim of this combination approach of pyrolysis and reforming is to improve the gas yield and obtain an optimum syngas ratio via shifting the reaction from exothermic to endothermic [58].

In a single reactor, it is difficult to control the different gasification reactions, such as pyrolysis, char gasification, tar cracking, and water-gas shift reaction, individually [64]. Multiple reactions can occur in one reactor, making it difficult to correlate feedstock properties and downstream utilization of the gas product. Multi-staged reactors can be helpful to improve gasification performance [64]. In a three-staged reactor system, the reactions can be optimized, individually, under appropriate conditions. This can also achieve efficient tar removal [55]. However, the multi-staged reactor is significantly more complex and has a higher capital cost, compared to a single-staged reactor [67]. Furthermore, a long and steady gasification operation needs to be developed for commercial scale H_2 production [62].

2.2.4 Applications of a multi-staged reactor

Multi-staged reactors have some advantages, as discussed previously. They have been applied not only in gasification, but also in other technologies such as pyrolysis and torrefaction. For example, we previously studied the pyrolysis of alkali lignin to biofuel using a two-staged reactor (pyrolysis and catalytic reactor) [68]. The alkali lignin and catalyst were individually loaded into the pyrolysis and catalytic reactor, respectively. The alkali lignin was successfully converted into biofuel at a biofuel yield of 28 wt% [68]. Guzelciftci et al. [69] studied the pyrolysis of wood using a two-staged reactor system (auger and fluidized bed reactors). The auger reactor temperature varied between room temperature and 290 °C, while the fluidized bed reactor temperature varied between 500 and 700 °C. The obtained bio-oil yield varied largely between 24 and 52 wt% [69].

Granados et al. [70] used a two-staged rotary reactor system for torrefaction of poplar wood residues. The two-staged rotary reactor system consists of two in-series rotary drums for continuous drying (115 °C) and torrefaction (300 °C) processes. The HHV of the torrefied poplar wood residues reached 26 MJ/kg, which

was a much higher value than that of the raw poplar wood residues (18 MJ/kg) [70]. Nhuchhen et al. [71] studied the torrefaction of yellow poplar in a two-staged reactor system at an angular speed of 4 rpm. Three different torrefaction temperatures (260, 290, and 320 °C) were investigated. An increase in the torrefaction temperature resulted in a decrease in solid mass yield from 93 wt% to 81 wt%. The HHV of the torrefied poplar increased from 20 to 23 MJ/kg with an increase in the torrefaction temperature from 260 to 320 °C [71]. However, further torrefaction studies on the comparison of single- and multi-staged reactors will be needed.

3. Conclusion

Solid waste, including MSW, biomass residue, plastic waste, and their mixtures, has accumulated fast in recent years, leading to solid waste gasification gaining great attention. However, no systematic study has been performed to compare single-staged and multi-staged reactors. This book chapter systematically reviewed state-of-the-art research for both single- and multi-staged reactors. Discussion included analysis of the reactor dimensions, operating factors and performance, advantages, and disadvantages of these reactors. The yield of syngas generated from solid waste gasification is mainly in the range of 0.7–3.0 Nm^3/kg. Multi-staged reactors are a convenient approach to investigate the specific effect of parameters at different stages, and the reactions can be optimized individually under appropriate conditions. Additionally, a multi-staged reactor can be helpful to improve gasification performance, but is more complex and has higher capital cost, compared to a single-staged reactor.

Solid waste gasification is affected by several factors including temperature, reaction time, feed composition, and catalyst activity. An appropriate temperature (e.g., 800–900 °C) can be selected for solid waste gasification based on the elevated gasification performance and low energy consumption. A suitable feedstock concentration and reaction time should be selected to balance gasification efficiency and industrial application. Higher feedstock concentration can cause the reactor to plug and subsequent catalyst deactivation, while a longer reaction time may cause greater energy consumption. The use of a steam and O_2 mixture as the gasification agent is helpful for gasification efficiency because it produces steam reforming reactions and has a lack of N_2 dilution. Waste sorting is helpful to improve the gasification efficiency compared to unsorted waste. Moreover, an appropriate waste feed size should be selected because larger feed size can cause a loose bed and smaller feed size can lead to reactor blockage. The co-gasification of waste mixtures over Ni based catalysts is a promising technology due to the improved gasification efficiency derived from the synergistic effect of the feed mixture.

Additionally, multi-staged reactors have many unique advantages, which make them useful in other applications such as pyrolysis and torrefaction. However, reducing the processing cost of converting solid waste to syngas remains a major technical challenge. Pretreating solid waste, such as MSW, to remove the impurities, high energy consumption at elevated temperatures, and the use of catalysts remain the most expensive aspects of this process. In the future, a better understanding of the gasification reactions, reactor design, and catalyst development needs to be investigated to improve syngas yield and avoid tar formation.

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Conflict of interest

The authors declare no conflict of interest.

Appendices and nomenclature

MSW	Municipal solid waste
HDPE	High density polyethylene
PP	Polypropylene
PC	Polycarbonate
PE	Polyethylene
HHV	Higher heating value
LHV	Lower heating value
S/C	Steam to carbon ratio
ER	Equivalence air ratio
TC1	Thermocouple 1
TC2	Thermocouple 2
RDF	Refuse derived fuel
TR	Tar reformer
DES	Desulfurization reactor
GS	Gasifier
SPA	Solid phase adsorption
WGS	Water gas shift
CHP	Combined heat and power

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