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A Survey of the Gasification of Residual Household Waste

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Abstract

Solid waste is a promising renewable fuel that can substitute conventional fuel. According to the researchers, thermoconversion of solid waste such as municipal solid waste or residual household waste (RHW) is beneficial to society. However, due to its heterogeneity, the gasification of RHW is more complex. This review article discusses the steps that RHW must undergo before its thermoconversion and the state of the art of solid waste gasification. First, characterisation methods of RHW are surveyed. Second, the properties of RHW, the production lines of refuse derived fuel (RDF) from RHW, the influence of RDF composition and operating parameters such as equivalence ratio and temperature are reviewed. Moreover, RDF gasification products, scientific barriers and proposed solutions are evaluated. In conclusion, concerning emissions, costs and technical aspects related to each thermochemical process, it can be said that gasification is a promising technique for the recovery of RHW. However, studies on cogasification of waste and biomass on a pilot-industrial scale are still scarce and synergistic effects of this cogasification need to be clarified.

Keywords

Cogasification, Household Waste, Refuse-Derived Fuel, Waste to Energy, Waste Characterization

1. Introduction

The depletion of fossil resources is a great dilemma to which we will have to find solutions. Indeed, the energy transition is imperative and a sustainable alternative is needed for the years to come. Nowadays, studies on the effective and effi-

cient use of renewable resources are being developed. The development of renewable energies is crucial in order to mitigate the emission of greenhouse gases (GHG) which is related to the abusive use of fossil fuels [1]. The exploitation of fossil fuels is responsible for the emission of 10.65 billion tons of CO₂ per year [2]. Moreover, the dependence on conventional resources generates geopolitical tensions linked to the instability of oil prices and markets [2]. The international climate conference COP21 in Paris in 2015 encouraged countries to contribute to the mitigation of GHG emissions [3]. For the year 2020, the European Union (EU) is obliged to reduce by 20% the emission of GHG [4].

According to the literature, biomass is a promising source of carbon and liquid renewable fuels [5] [6] [7] to replace conventional hydrocarbon. The availability of biomass resource compared to fossil fuels and other intermittent renewables is one of the reasons why biomass energy conversion is very important.

In addition, an effective way to reduce CO₂ emissions and promote sustainable development is to recover waste. However, the waste (municipal solid waste, agricultural residues, etc.) conversion pathway is under-exploited. Waste management plays a major role in the implementation of the circular economy, which remains an overarching objective of the EU [8] [9]. Waste management, particularly municipal solid waste (MSW), is a major challenge on a global scale [10]. Currently, the annual global production of MSW is 2 billion tons [2] and this will rise to 2.5 billion tons by 2025 [11] [12]. Only 11% of MSW produced is recovered in the form of energy [2]. In the United States, 13% of MSW is recovered and 53% is landfilled [13] [14]. In Europe, in order to increase the share of renewable energy in energy production, a new principle on MSW management has been put in place. The principle is based on a waste management hierarchy such as reduction, re-use, recycling (mechanical or chemical), energy recovery and disposal [9] [15] [16]. In France, this principle is reflected in the LTECV law (Loi de Transition Énergétique pour la Croissance Verte) [17]. This law prioritises the modes of waste treatment: 1) favouring reuse and recycling of waste, 2) ensuring material and energy recovery of recoverable waste, and 3) eliminating non-recoverable final waste by landfill. The main objectives of the LTECV law are the use of SRF (Solid Recovery Fuel) to produce heat and electricity, *i.e.*, the recovery of waste sorting refusals while ensuring that this is not done to the detriment of the prevention of waste production and recovery in the form of materials, and energy recovery by pyro-gasification of waste that cannot be recycled according to the available channels.

The current means of waste treatment are not efficient from energy, economic and environmental point of view. Most of the solid waste is landfilled and this technique remains the most widespread one [11] [18]. Landfilling is associated with many disadvantages such as the emission of methane gas due to the anaerobic digestion of solid waste, the land occupation, the inability to manage a large quantity of waste and the pollution of groundwater [14] [19] [20]. Apart from landfilling, incineration is the most applied waste treatment worldwide [9] [12] [21]. However, the harmful emissions, hazardous products and other dis-

advantages of these two techniques do not allow them to effectively manage waste disposal [19]. Indeed, the development of thermochemical methods is imperative in order to eliminate and recover household waste in the form of energy. Pyrolysis and gasification are promising alternatives [19] [22]. These thermochemical methods are more efficient in terms of gas production and liquid fuels [19]. Currently, pyrolysis is at the heart of scientific research and has great potentials [12] [13]. In addition, gasification is a technology well adapted to the conversion of solid waste into syngas [23] [24] [25] and makes it possible to valorise waste of different natures at the same time [26].

Household waste (HW) consists of green and bulky waste, recyclable waste and RHW [27]. RHW is the mixed waste produced in households that remains after source separation of hazardous waste and recyclables, such as biological waste, paper, cardboard, metals, glass and wastes electrical and electronic equipment [28] [29]. Recently, the gasification of RHW has attracted the attention of researchers. RDF or SRF are auxiliary fuels formed from a mixture of non-hazardous wastes [30]. Generally, RDF formed from RHW is composed of: plastic, paper, cardboard, food residues, textiles, wood and other types of biomass. With a LHV (Lower Heating Value) greater than 10 MJ/kg, RDF from RHW has the potential to be used as a raw material for gasification [31] and may even substitute fossil fuels [20]. Because of its low production cost compared to biomass, the use of RDF from solid waste can launch the gasification sector [32] [33]. Like biomass, RDF can be simultaneously converted into syngas, biofuels and renewable solid fuel resources [34]. However, due to its heterogeneity, the gasification of RDF is more complex. The lack of understanding of the contribution of each of the RDF components on the aspects of the obtained products prevents extending the conclusion to other RDF with different components. In order to have an overview of the gasification of RHW, this paper presents in the second section the advantages and disadvantages of gasification compared to other processes. In the third section, the different methods of characterising RHW are discussed. Moreover, the next section highlights the properties of RHW. The fifth section discusses the production of RDF from solid waste and the gasification of RDF such as the influential parameters, the products, the scientific barriers and the suitable solutions according to the literature.

2. Gasification

Gasification is a decomposition reaction of carbonaceous matrices at high temperature for a short residence time and with a quantity of oxygen lower than the stoichiometric value [19] [35]. Generally, the gasification temperatures are higher than 800°C and can reach more than 1300°C depending on the solid used and the process employed [36]. If the gasification temperature reaches 1400°C, the process no longer requires an external heat source, the combustion of part of the raw material provides heat to facilitate gasification [24]. The products obtained are: syngas composed of H₂, CO, CH₄ and CO₂, coal, liquid fuels and ash. The stages of the gasification process are: drying, pyrolysis, oxidation and reduction

[36] [37] [38]. The oxidation reactions are exothermic reactions while gasification is an overall endothermic reaction [37]. The gases produced are used to produce heat or electricity [39].

Advantages: Gasification does not record a GHG emission. It is a sustainable solution for waste management [2]. The low presence of oxygen slows down the formation of dioxins, furans and NO_x and prevents the oxidation of metals [13] [25] [37]. Apart from mercury and cadmium, alkalis and heavy metals are retained in the fly ash [25] [37]. Gasification is a process that produces 65% less toxic residues than incineration [13]. Consequently, the cost of eliminating the residues is reduced. This process is cost-effective [35] and has a higher conversion efficiency [14]. Secondly, one of the advantages of gasification over pyrolysis is that all kinds of waste, whether organic waste, plastics of different composition or even plastics mixed with other feedstocks can be co-valorised in a gasifier [2] [38] [40]. This technology can be developed on a large scale and can eliminate up to 90% of the volume of MSW [2]. Furthermore, through the Fischer-Tropsch process, clean syngas can be transformed into liquid fuels that can be used to produce electrical or mechanical energy [13] [26].

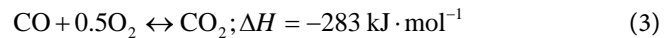
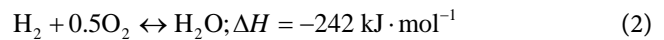
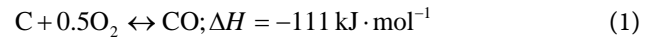
Disadvantages: Gasification faces many technical barriers [13]. The presence of tar, coal and ash in the syngas implies a long series of syngas purification processes [2] [13] [15] [20] [40]. Secondly, this technology requires a pre-treatment of the waste such as sorting, drying and grinding [2]. Indeed, this process consumes a significant amount of energy [2] [13]. In addition, the treatment of waste by gasification requires a high operational and management cost that varies between 40 and 100\$ per ton of MSW [13]. Also, the high quantities of coal, metals and organic pollutants in the ash and coals pose a problem especially to human health [15]. All these issues are related to the experimental and testing phases, therefore, a lot of information is missing for the implementation of a large-scale gasification project.

There is not a big difference between the investment costs of plasma gasification, conventional gasification and pyrolysis in economic terms [13]. The total investment cost of Lahti Energia's Kymijärvi II power plant in Finland, the world's first and largest power plant that runs solely on syngas from RDF/SRF is 160 M€. The RDF/SRF from industrial, commercial and household waste processed in this gasification power plant in operation produces 50 MW of electricity and 90 MW of heat. Moreover, the Vaskiluoto power plant in Vaasa, Finland, based on a fluidized bed reactor has a total investment cost of 40 M€ for 140 MW [41]. The major differences between the three types of processes appear in the operating and maintenance costs. The operating and maintenance cost of pyrolysis is 7 times higher compared to the other treatment methods [19].

In general, the main gasification reactions are:

- 1) Drying: This is the reduction of the moisture content at low temperature.
- 2) Pyrolysis: This is the production of syngas, biochar and liquid tar from the condensation of pyrolysis steam.

3) Oxidation: This is the partial combustion of carbon (Equation (1)), hydrogen (Equation (2)) and carbon monoxide formed from the oxidation of carbon (Equation (3)). The products obtained are CO, H₂O and CO₂. An oxidation reaction is an exothermic reaction that occurs at a temperature above 500°C [42]. The heat generated by these reactions ensures the rapid heating of the reactor [43] [44].



4) Reduction: This is the gasification reaction of char with the products of combustion, *i.e.* reactions with steam, H₂ and CO₂ [11] [25] [35]. Indeed, the reduction reaction occurs in the absence of oxygen. The reduction reaction includes: the Boudouard reaction (Equation (4)), water-gas reaction (Equation (5)), water-gas shift reaction (Equation (6)) and methane steam reforming reaction (Equation (7)) [37]. In addition, steam and dry reforming of hydrocarbons are described by Equation (8) and Equation (9) respectively.

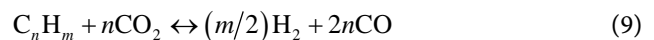
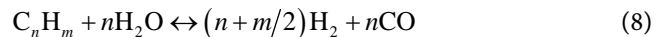
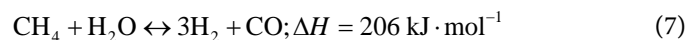
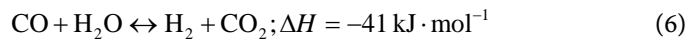
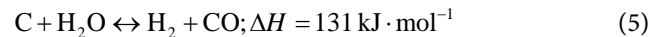
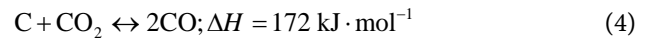


Table 1 shows the succession of these different types of reactions which depends on the configuration of the reactor used.

Table 1. Chemical reactions in reactor.

Type of reactor	Chemical reactions	Reference
Downdraft reactor	- Drying	[10] [35]
	- Pyrolysis	
	- Combustion and tar cracking	
	- Reduction	
Updraft reactor	- Drying	[25]
	- Pyrolysis	
	- Char gasification or reduction	
	- Combustion	
Plasma reactor	- Oxidation reaction with oxygen	[11]
	- Reduction with steam, H ₂ and CO ₂	
	- Decomposition of tar and hydrocarbons	

3. Residual Household Waste Characterization

The characterisation of waste is a primordial action for its treatment, it allows it to be managed in an efficient and sustainable manner [16] [45]. In addition, it is essential for the modelling of environmental impacts [46] and the evaluation of waste qualities [10] [47]. The identification of the physico-chemical properties of a material fraction yields useful information in relation to the treatment, recycling of waste and the design of equipment necessary for treatment [16]. In addition, characterisation allows the sources of chemical components present in the waste to be recognised and thus to improve the conditions for thermal treatment or energy recovery of the latter [28] [48]. Furthermore, it is of great importance to make the immediate and ultimate analysis, to determine the calorific values of the waste in order to evaluate the feasibility of an energy recovery [49] [50]. Worldwide, there is very little data on the chemical composition of the material fractions present in household waste. This is probably due to the difficulty and cost of waste characterisation procedures which face numerous barriers [51].

In the literature, no work mentions the existence of a conventional method for waste characterisation [16] [46]. According to Brunner *et al.* [48], there are 3 methods of waste characterisation and the choice of methods depends on the objective of the study: direct waste analysis, analysis of products by incineration or composting and the analysis of market products.

Direct Analysis of Waste

Direct analysis of waste is the most common method used by scientists to study waste management. Recently, the European Commission has stated its intention to increase the recycling rate to 70% by 2030 and to strengthen the circular economy [28]. To reach its objective, Europe has implemented source separation systems at household level to easily separate recyclable and non-recyclable materials [46]. The reinforcement of waste recycling needs information on the composition of the waste to properly develop a solid recovery system [52]. In general, the method of characterisation varies according to the means of a collection of the parent samples. Collection is either at the household level [53], or with vehicle loads [54] or in landfills [16]. The steps of the direct analysis are: stratification, sampling and physico-chemical analysis. Stratification consists of dividing the study area according to the following factors: the season (winter and summer), the location (urban and rural areas), the standard of living, the custom, the type of dwelling (single-family and multi-family), the size of the property and the holiday periods [16] [52] [55] [56] [57]. In practice, the decision on the number of strata to consider depends on the objective of the survey [28] [54]. According to Parfitt *et al.* [28] the maximum number of strata should be 5 in order to avoid a large total sample size. Due to the stratification, fewer samples are needed, which increases the precision of the results [28]. The quality of the data on waste composition is strongly influenced by the sampling procedure [53]. The absence of international standards for waste characterisation means that

there are several sampling procedures in the literature [29] [53] [54]. **Table 2** shows the different stages of waste sampling.

4. Properties of RHW

RHW is composed of recyclable and non-recyclable materials. The Waste to Energy (WTE) process consists of converting non-recyclable waste (excluding glass and metal) into heat, electricity or liquid fuel [2]. The non-recyclable waste consists of organic materials such as plastics, food residues, textiles and wood, rubbers and inorganic materials such as minerals and metals. The composition of Wastes varies from region to region and non-organic wastes are abundant in developed countries [13]. Then, the calorific value of RHW depends on its chemical composition. Wastes containing more plastics have a high calorific value due to the high C (above 60%) and H content and the low O content (between 0% - 4%). In contrast

Table 2. The sampling steps.

Steps	Description
Collect of mother sample	<ul style="list-style-type: none"> From waste storage site: <ul style="list-style-type: none"> - Use the amount of load from a waste transporter truck [60] - It should represent at least a whole week [28] [58] At household level: <ul style="list-style-type: none"> - Collect wastes from 40 to 857 households [10] - IEA: the weight varies from 0.5 to 12 tonnes [54] - EU: collect a minimum of six samples from each stratum [28] or 45 m³ of waste sample in total [54]
Sub-sampling	<ul style="list-style-type: none"> - Hand sorting of mother sample into multiple categories [16] [28] [50] [52] [54] [56] - Weight: 100 kg [28] - IEA: 9 to 19 categories (kitchen and garden waste, paper and cardboard, plastics, metals, textiles, fuels, non-fuels, fine fractions and glass) with 2 or 3 levels of categories [28] [54]
Prepare sample for the laboratory	<ul style="list-style-type: none"> Mass reduction by: coning and quartering [45] [50] [54] and the flat pile [45] [52] [53] - Sample weight: 2 - 4 kg for each category [52]
Drying and shredding	<ul style="list-style-type: none"> - Drying for 1 or 2 days (biowaste: in a laboratory oven at 105°C for 24 hours [47] [51] [52] [56], other categories: twice at 80°C for 24 hours until constant weight [52]) - Shredding of dry samples by Retsch SM300 or SM400 or SM2000 chipper [52] or the ARP CS 2000 shredder [45] - Shredding of non-combustible waste and glass by Jaw crusher and a vibrating disc mill, respectively - Mass reduction by the Riffle splitter: 5-10 g sample for each category [45] [52]
Proximate and ultimate analysis	<ul style="list-style-type: none"> - Proximate analysis: 1 g of sample - Ultimate analysis: 1-5 g of sample [49] [53]

to plastic waste, waste formed by food residues, garden waste and biomasses has a low calorific value due to the excess of oxygen and moisture content [12] [13] [59].

The production of plastic waste continues to increase and will reach 13% of global MSW production by 2025 [2]. Nearly 8% of conventional crude oil is used to produce plastics, which are generally used for packaging [5] [38]. Currently, between 26% - 36% of plastic waste is recycled or incinerated, the rest is land-filled [5] [26]. Due to its low thermal conductivity, sticky nature and high volatile content leading to the remarkable formation of tar, the thermochemical conversion of plastics has scientific barriers [38]. However, chlorine-free plastics have a HHV of 43 MJ/kg [2]. Furthermore, the pyrolysis of industrial plastic waste is attracting more attention from researchers [60]. The products obtained from the thermochemical conversion of plastics can be used for electricity generation, transportation and heating. Indeed, the components of RHW are all good candidates for syngas production [59]. For successful conversion of plastics, a high heat transfer rate, resolution of operational issues related to its sticky nature, accurate residence time to promote tar cracking and the use of an in-situ catalyst are required [38]. Paper has a low calorific value (less than 10 MJ/kg), high moisture content (above 60 wt%) and an ash content above 45 wt%. Therefore, the process of converting paper into syngas is a challenge [18].

5. Gasification of RDF from Solid Waste

5.1. The Production of RDF from Solid Waste

Recently, the production of RDF is being advocated by waste management planners and governments [31]. RDF is an auxiliary fuel made from the sorting or mixing of solid waste such as MSW and RHW and accepted in most waste combustion systems [31] [61]. Indeed, RDF is made up of plastic films, paper, non-recoverable soiled cardboard, residues unsuitable for reuse, wood, rubber and textiles [30] [62]. The production of SRF is more complex and costly than that of RDF and takes into account regulations imposed by the government. For example, for France, according to article R541-8-1 decree of 23 May 2016, an SRF must be prepared from non-hazardous waste, have a LHV on raw SRF greater than or equal to 12 MJ/kg, be sorted, free of ferrous and non-ferrous metals as well as inert materials and have the following properties: mercury (Hg): 3 mg/kg dry matter/chlorine (Cl): 15 g/kg dry matter/bromine (Br): 15 g/kg dry matter/total halogens (bromine, chlorine, fluorine and iodine): 20 g/kg dry matter. Then, according to the European standard EN 15.359, the chlorine and mercury content, the size and the LHV of the SRF must be determined [30] [61]. The results of this complexity are: improved fuel quality (physico-chemical properties and calorific value), higher production cost compared to RDF and lower mass yield. The advantages of RDF production are: 1) the increase in the calorific value of the fuel guaranteeing a good heat transfer during gasification [15] [19] [31] [63], Milena *et al.* [64] found an increase in LHV of 33% compared to the

raw solid waste, 2) the homogeneity of the physico-chemical composition of the product [31] [32] [64] [65], 3) ease of storage, handling, transport and conveying of the biomass to the reactor [31] [32] [65] [66], 4) reduction of pollutant emissions during gasification [64].

In general, the stages of waste treatment (MSW or RHW) can be summarised as follows: waste separation, screening, shredding, size reduction, classification, drying and densification [31] [32] [61] [64] [67]. The sorting and sampling phase presented in **Table 2** give an overview of the SRF production line [24]. During the sorting of the collected waste, recyclable and non-combustible waste is not included in the sample but is sent to the manufacturing industries [19]. Thus, these types of waste, such as glasses and metals, are not favourable to gasification [14] and have a huge impact on the gasification process [19]. Then, each subsample related to each imposed category is crushed, sieved, mixed and blended according to the desired composition [19] [24]. The mixed waste is then densified into briquettes or pellets [12] [24] [63]. **Table 3** shows the different types of RDF production in the literature. In their work, Caputo *et al.* [31] studied the concept of an RDF production installation and found that the processes allowing for a high calorific value are: trommel screening, manual sorting, magnetic separation, shredding, trommel screening, crushing, trommel screening, densification/pelletisation. Indeed, mechanical operations alone are insufficient as manual intervention is always necessary during the production of RDF [73]. Seven different types of RDF have been classified by the American Society for Testing and Materials (ASTM) [74], the differences are in the RDF production line. The most common types used in the research are Type 3 and Type 5. Type 3 is defined by shredding of MSW, extraction of metals, glass and other inorganic materials while Type 5 is a densified fuel of more than 600 kg/m³ in the form of pellets or briquettes [31].

The choice of RDF composition is very important because the physico-chemical properties of the fuel and the quality of the syngas will depend on it. The

Table 3. RDF production line.

Type of production	Reference
classification, sorting, separation of ferrous, non-ferrous metals and heavyweight inert materials and confectioning of the fuel	Lorber <i>et al.</i> [76]
size screening, magnetic separation, coarse shredding, refining separation and pelletization	Barba <i>et al.</i> [67]
sorting, screening, shredding, size reduction, sieving, drying and densification	Milena <i>et al.</i> [64]
size reduction, drying, screening, sorting, metal and glass separation, pelletization	Aluri <i>et al.</i> [32]
trommel screen, hand sorting, magnetic separation, shredder, trommel screen, milling, trommel screen and densification	Caputo <i>et al.</i> [31]
refuse separation, shredding, densification	Khosasaeng <i>et al.</i> [75]

mixture of waste with a high calorific value is essential [31]. This implies a composition in which plastic occupies an important place [75]. However, a mixture in which plastic dominates is a mixture with a high volatile matter content. Therefore, the proportion of wood, paper, cardboard and food residues should not be neglected in order to have a balanced content of fixed carbon and ash [32] [65] [70]. The moisture content of the mixture varies mainly with the proportion of biomass such as food residues, wood, paper and cardboard and ranges from 1 - 25 wt%. However, the composition can vary depending on the origin of the waste, the season, the production technique and the sorting and sampling technique. **Table 4** shows the results of the proximate analysis of RDF.

5.2. Influential Parameters of RDF Gasification

Apart from the gasifier parameters, the physical and chemical characteristics of the feedstock influence the quality of the syngas. The mass composition of the waste is important, therefore an ultimate analysis of the RDF is necessary prior to gasification [19]. Next, the moisture content of the feedstock affects the gasification process, high moisture content reduces the syngas quality and cold gas efficiency [37] [77] which is an important factor in determining the performance

Table 4. RDF proximate analysis.

RDF Composition	LHV of RDF [MJ/kg]	Ash [wt%]	FC [wt%]	VM [wt%]	Moisture [wt%]	Reference
Plastic 20.5%						
Paper 16%						
Cardboard 22.5%	19.6	1.59	15.47	78.04	4.9	[67]
Textiles 31%						
RDF	15.2	6	26.3	67.6	12	[64]
RDF	11.9	19.1	6.4	59.6	14.9	[68]
RDF	16.03	22.92	9.35	58.57	9.16	[69]
Plastics paper and food wastes	24.8 (HHV)	3.44	-	-	4	[32]
Paper and fiber 50%						
Wood 28%						
Plastics 9%	17.9	12.9	10.4	76.7	-	[70]
Food waste 7%						
Incombustibles 6%						
Paper 70%						
Plastics 30%	24.6	7.9	5.4	86.7	-	[70]
MSW 50%						
Commercial and industrial wastes 50%	21	12.1	11.6	64.8	11.5	[71]
RDF	18.6	1.1	16.3	82.6	25	[72]

of the gasifier [44]. The cold gas efficiency of RDF gasification can reach a value of more than 70% [14] [37] [78] [79]. Then, the size of the raw material plays a major role, a size of 2 mm ensures a good heat transfer facilitating the thermal decomposition of the waste [77]. In addition, the LHV which is relative to the composition of the biomass is often used as a parameter indicating the potential of the raw material [19].

Then, the type of reactor used and the operating conditions of the gasifier such as the mass flow rate [4] [19], the oxidant used, the temperature inside the reactor, the equivalence ratio (ER), the residence time [4] [80] and the catalyst [26] influence the quality of the gasification products. The ER is a more important parameter than the bed height and the fluidisation speed [37]. An ER that is too high (above 0.4) leads to the dilution of the syngas, the CO₂ content of the gas increases whereas the H₂, CH₄ and CO decrease. On the other hand, an ER that is too low (below 0.2) means an incomplete gasification process [81]. Indeed, an appropriate ER (0.2 - 0.4) should be used to improve the production rate of combustible gases (CO, H₂ and CH₄) [44]. An increase in ER is accompanied by a rise in temperature in the gasification zone [24]. According to Boudouard's reaction 4 and le Chatelier's principle, this temperature rise will lead to an increase in the CO content and a reduction in the CO₂ content [24] [37] [38] [40] [81]. Then, if the ER is gradually increased, the amount of H₂ and CH₄ produced will decrease. These phenomena are explained by the oxidation reaction of H₂ 2 and the steam reforming reaction of methane 7 [24]. An optimal ER is defined by optimal CO, H₂ and CH₄ contents resulting in an optimal LHV of the syngas [24] [25]. Moreover, temperature is the most influencing parameters in gasification process, it influences the composition of the syngas and the product distribution [81]. The increase in temperature favours the production of CO and H₂ and reduces the production of CO₂ and CH₄ [38]. High CO and H₂ contents mean high LHV values, cold gas efficiency and carbon conversion efficiency [13] [37] [44]. Therefore, a higher temperature is favourable to the production of H₂ rich gas [14] and CO [43] [44] and to the increase of energy efficiency [24]. The H₂/CO molar ratio increases with increasing temperature in air, oxygen and CO₂-gasification and decreases in steam-gasification [82]. Hence, it can be said that higher temperatures combined with moderate ER favours the production of H₂ and CO. Furthermore, a low temperature is selective in the types of raw materials [14].

5.3. The Products of RDF Gasification

Generally, the products of RDF gasification are: syngas, condensable organics (tars and water vapour) [22] [83] and solid products (char and ash) [35]. RDF gasification shows a positive effect on H₂ gas concentration, syngas yield and LHV of the gas [38]. A high quality syngas has a high content of H₂ and CO and a low content of CH₄, CO₂ and gaseous hydrocarbons such as C₂H₄ and C₂H₆ [4] [19] [43] [83]. The aspect of the RDF gasification results is a contribution from each of the RDF components [32]. The results show that gasification of plastic

produces more C1 - C4 hydrocarbons due to high volatile content, low fixed carbon content and low or no oxygen content. Indeed, plastic gasification produces more tar than coal. The syngas produced by the gasification of plastic-rich RDF has a high LHV [84] and is predominantly composed of: CH₄ and C₂H₄. Also, gasification of high oxygen biomass such as food waste, paper and wood produces more CO and CO₂ and less hydrocarbons. At a temperature of around 900°C or with a high ER, the ash in biomass acts as a catalyst in the gasification of RDF and leads to the rapid cracking of the plastic polymers [70]. Therefore, plastic-biomass co-gasification will be able to produce good quality syngas, *i.e.*, low tar content and high LHV [32] [65] [70]. **Table 5** shows the results of RDF gasification of different composition.

For air gasification, half the volume of syngas produced is formed by nitrogen. At high temperatures (above 900°C), the use of air as an oxidising agent shows little improvement in the calorific value of the syngas [37]. Then, the gasification using CO₂ as gasifying agent yields more CO and CH₄ and produces syngas with higher LHV compared to other gasifying agent [82]. Moreover, steam gasification produces high quality syngas free of nitrogen and its oxides and with a very high concentration of H₂ [14] [26] [37]. Currently, steam is the most widely used gasification agent [25]. The injection of steam into the reactor favours the production of H₂ and CO₂ while decreasing the CO yield. Moreover, the steam decreases slightly the heating value and the cold gas efficiency (CGE) by decreasing the process temperature [85]. At a temperature equal to or higher than 900°C, the production of H₂ and CO₂ intensifies and the LHV and the syngas yield improve [25]. Furthermore, the composition of the syngas produced by plasma gasification depends on the source of the plasma gas. Plasma with N₂ produces more H₂ gas while plasma from steam produces syngas formed mainly by CO and H₂. The combination of plasma and steam gasification has a positive effect on the LHV of the syngas, the syngas yield and the conversion of char [11]. With plasma gasification, inorganic materials such as minerals and metals in the ash are transformed into harmless, vitrified slag consisting of: Silicon dioxide (SiO₂), Aluminium oxide (Al₂O₃), Calcium oxide (CaO), Iron (III) oxide (Fe₂O₃), Sodium oxide (Na₂O) and Magnesium oxide (MgO) [23] [25] [43]. Following the US EPA (United States Environmental Protection Agency) leech tests, the vitrified slag can be used for construction purposes [86].

5.4. The Scientific Barriers to RDF Gasification

The gasification of RDF is more difficult due to its heterogeneous nature. Indeed, all available technologies have been developed to work on pure biomass [68]. The barriers to solid waste gasification are: the presence of tars, chars, particulates, NH₃, H₂S, HCl, Cl₂ and chlorinated organics in the syngas [13] [33] [87]. The high content of chlorine (NaCl and PVC) in the waste is the cause of the formation of certain chlorinated products and a source of emission of toxic dioxins and furans [13]. Moreover, chlorine, cadmium and lead are often concentrated in the fuels produced [73]. However, polyvinyl chloride (PVC), a source

Table 5. Results of RDF gasification.

RDF Composition	Proximate analysis [wt%]	LHV of syngas [MJ/Nm ³]	CGE [%]	ER	Temperature [°C]	H ₂ /CO [%]	References
RDF from MSW (Plastics)	FC: 9.73						
	VM: 81.47						
	Ash: 4.8	5.87	73.04	0.35	-	CO: 14.72 for ER = 0.35 H ₂ : 8.82 for ER = 0.25	[75]
	Moisture: 4 dry basis						
PET: 75% Paper: 25%	FC: 2.18						
	VM: 94.01						
	Ash: 2.33	4.39	-	-	-	CO: 22.02 H ₂ : 10.43	[65]
	Moisture: 1.48 dry basis						
RDF from MSW	FC: 26.3						
	VM: 67.6						
	Ash: 6	5.8	57 - 60	0.25 - 0.3	680 - 700	CO: 15 - 25 H ₂ : 12 - 20	[64]
	Moisture: 12 dry basis						
RDF from MSW	FC: 6.4						
	VM: 59.6						
	Ash: 19.1	11.9 MJ/kg	78.2	0.37	770	H ₂ /CO: 1.62	[68]
	Moisture: 14.9 as received						
Paper 70% Plastics 30%	FC: 5.4						
	VM: 86.7						
	Ash: 7.9	17.9	-	0.2 - 0.4	-	-	[70]
	Moisture: - dry basis						
Paper and fiber 50% Wood 28% Plastics 9% Food waste 7% Incombustibles 6%	FC: 10.4						
	VM: 76.7						
	Ash: 12.9	14.1	-	0.2 - 0.4	900	-	[70]
	Moisture: 4 dry basis						

Continued

MSW 50% Commercial and industrial waste 50%	FC: 11.6						
	VM: 64.8						
	Ash: 12.1	8	55	-	750	CO: 24 H ₂ : 35	[71]
	Moisture: 11.5 dry basis						
RDF from MSW	FC: 16.3						
	VM: 82.6						
	Ash: 1.1	-	-	-	700 - 1000	CO: 28.5 H ₂ : 19	[72]
	Moisture: 25 dry basis						
MSW	FC: 8.5						
	VM: 60.28						
	Ash: 26.53	9.33 - 12.48	-	0.25 - 0.3	800 - 900	0.45 - 0.93	[81]
	Moisture: 4.69 dry basis						

of Cl, constitutes the majority of polymers produced and distributed worldwide. In the case of Europe, after polypropylene (PP) and polyethylene (PE), PVC constitutes 10% of polymer production in 2017 [38]. According to Rotter *et al.* [73] the presence of these elements in most waste streams limits the ability to reduce pollution associated with the gasification of the fuels produced. Furthermore, the nitrogen in the biomass used in RDF, for example, wood is the source of NH₃ formation in the syngas [87]. Due to a high percentage of plastics in RDF, the high amount of volatile matter in RDF leads to the formation of tars [68]. The obstacles to the valorisation of plastics by gasification are: the presence of inorganic materials in the plastic, the chemical characteristics of the plastics, the high content of volatile matter [38]. Therefore, efficient gas cleaning is recommended to reduce the amount of these impurities in the syngas [33] [38] [83] [87]. The tar causes the blockage of the reaction vessel [88] [89] and the reduction of the calorific value and the syngas yield [80]. Moreover, the ash produced by the gasification of RDF, composed of alkali and alkaline earth metals, heavy metals and non-toxic organic compounds, contaminates water and soil. At high concentrations, bottom ash from RDF gasification has toxic effects on human HepG2 and MRC-5 cells [35] [68]. Besides, the gasification of plastics remains a challenge despite its high calorific value. However, on a regional or national scale, the mixture introduced into the gasifier contains at least 10% plastics [2]. Nevertheless, high plastic content in RDF can generate a high temperature and damage the gasifier [65].

5.5. Solutions from Literature

The co-gasification of RDF and biomass is a promising pathway to produce

high-quality syngas from solid waste [69] [90]. The addition of biomass or coal leads to an increase in the fraction of fixed carbon in the mixture and promotes the maintenance of the gasification reaction (Equations (4) and (5)). The formation of char from the pyrolysis reaction is very important in order to accelerate the water-gas reaction (Equation (5)) which produces hydrogen and carbon monoxide [30] [70]. Therefore, the addition of biomass improves the quality of the gas produced and optimises the temperature distribution inside the reactor [30] [65]. Moreover, biomass ash is rich in alkali and alkaline earth metals (sodium, potassium, magnesium and calcium) and has effectively catalytic effects during co-gasification with other fuels [91]. Indeed, co-gasification with RDF is also beneficial for biomass because this technology has the potential to reduce ash melting at high gasification temperatures [69]. However, the lack of understanding of phenomena such as the synergistic effects of biomass-RDF co-gasification and the lack of published data on biomass-RDF co-gasification remain barriers that require attention [69] [92].

On the other hand, the gasification of the coal-biomass mix is a new challenge. The mastery of a clean fossil fuel technology is very promising and advantageous because of the abundance and stability of coal prices [4]. At the laboratory scale, co-gasification of coal/biomass mixtures is promising compared to individual gasification of coal and biomass [93] [94]. The existence of the synergistic effect obtained by jointly feeding biomass and coal into a gasifier may improve the conversion process and the quality of the products obtained. Generally, the syngas obtained from the co-gasification of the coal/biomass mixture is composed of H_2 , CO, CO_2 and CH_4 [40] [94] [95]. The distribution of the products and the composition of the syngas depend on the following parameters: the temperature of the gasifier, the ER, the composition of the raw materials, the heating rate and the gasification agent used [40] [94]. There are different types of coal/biomass blends in the literature, such as coal/plastic blend, plastic/wood/coal blend and wood/coal blend. According to the literature:

- Increasing the ratio of biomass in the biomass/coal mixture leads to an increase in the CO, H_2 , hydrocarbon and tar content of the syngas [94]. Then, the increase of the wood ratio in the wood/coal mixture leads to the production of cleaner syngas with a low LHV due to the production of coal, the reduction of the presence of hydrocarbons and the absence of tar [95].
- The gasification of coal is associated with the production of tar, which constitutes 15% to 20% of the total production of energy [83], and with the formation of NH_3 and H_2S because of the presence of S and N in the coal. Then, the presence of SiO_2 in the coal participates in the reduction of the tar, the SiO_2 acts as an in-situ catalyst [94].
- A mixture with a high plastic content produces syngas with a high LHV. The syngas yield is low. However, a mixture with a high coal content has a high syngas yield and produces syngas with a low LHV [40].

Moreover, pre-treatment of RDF by carbonisation at $300^\circ C$ - $400^\circ C$ for 15 - 60 mn has been shown to be effective. The advantages of carbonisation of RDF

before gasification are: reduction of the emission of hazardous pollutants due to the elimination of some inorganic components such as calcium or chlorine, an increase of density, calorific value, carbon, ash and fixed carbon content of the RDF [96]. According to Goncalves *et al.* [96] the HHV of RDF after carbonisation is between 20.1 - 26.2 MJ/kg.

Then, modifying the reactor design to increase the temperature inside, or gasification in two or more stages, can reduce and increase the tar and H₂ content of the syngas respectively. As in the case of gasification, higher temperature and ER favour the syngas yield during co-gasification [69]. Saleh *et al.* [24] showed that the creation of an air inlet in a zone between pyrolysis and oxidation leads to an increase in temperature and consequently to a reduction of 30% - 50% in tar content and a 20% increase in H₂ production. Additionally, two-stage gasification, *i.e.* the use of two different reactors, is an efficient way of producing H₂ and tar-free syngas. The combination of a conventional gasification reactor with a plasma reactor gives a good result. In this case, the cracking of the tars and vitrification of the inorganic ash fraction takes place in the plasma reactor. According to Mukherjee *et al.* [13], fluidised bed plasma gasification of solid waste is a promising technology. By combining a fluidised bed gasifier with a plasma gasifier, Ray *et al.* [15] found high energy conversion (74% - 90%) and carbon conversion (95% ± 1.6%). Then, the use of 2 reactors, one for pyrolysis and the other for catalytic reforming of the volatiles produced by pyrolysis, allows to enhance the production of H₂ and to obtain a tar-free syngas [38].

Furthermore, the use of a catalyst is important in order to increase the efficiency of gasification, improve the gas yield by decreasing the production of liquid and char, reduce the tar content and avoid the thermodynamic restriction of the gas to water displacement reaction (Equation (6)) due to a high-temperature [38]. In fact, the catalyst enhances the production of H₂ and CO and decreases the production of tar, coal, CO₂, C₂H₄ and C₂H₆ [26]. Nickel is the catalyst generally used [70] [97]. The Nickel-based catalyst ensures the elimination of tar, accelerates the methane reforming reaction and the gas-to-water conversion reaction [80].

The reduction of the tar content of the syngas is of primary importance. Apart from the Nickel catalyst, other types of catalysts such as zeolites, dolomites [13] [80], gasification and pyrolysis chars [88] and alkaline minerals in gasification bottom ash [18] could be used as adsorbent or catalyst for tar decomposition. The use of bottom ash and fly ash as a catalyst both improves the quality of the syngas and treats the highly toxic residues [43]. Ash from biomass gasification contains C, O, Si, alkali metals, alkaline earth metals, non-metals, metalloids and a significant amount of Ca (above 40%). A good catalyst such as calcium oxide (CaO) can be obtained by open thermal calcination of the Ca present in these residues for the production of biodiesel from vegetable oil [89]. Moreover, the use of olivine as a bed material is effective in removing tar [4] [80] [93]. The latter acts both as a heat carrier, catalyst, and increases gas production [4]. **Figure 1** shows a schematic diagram of input and output of the gasification system. The

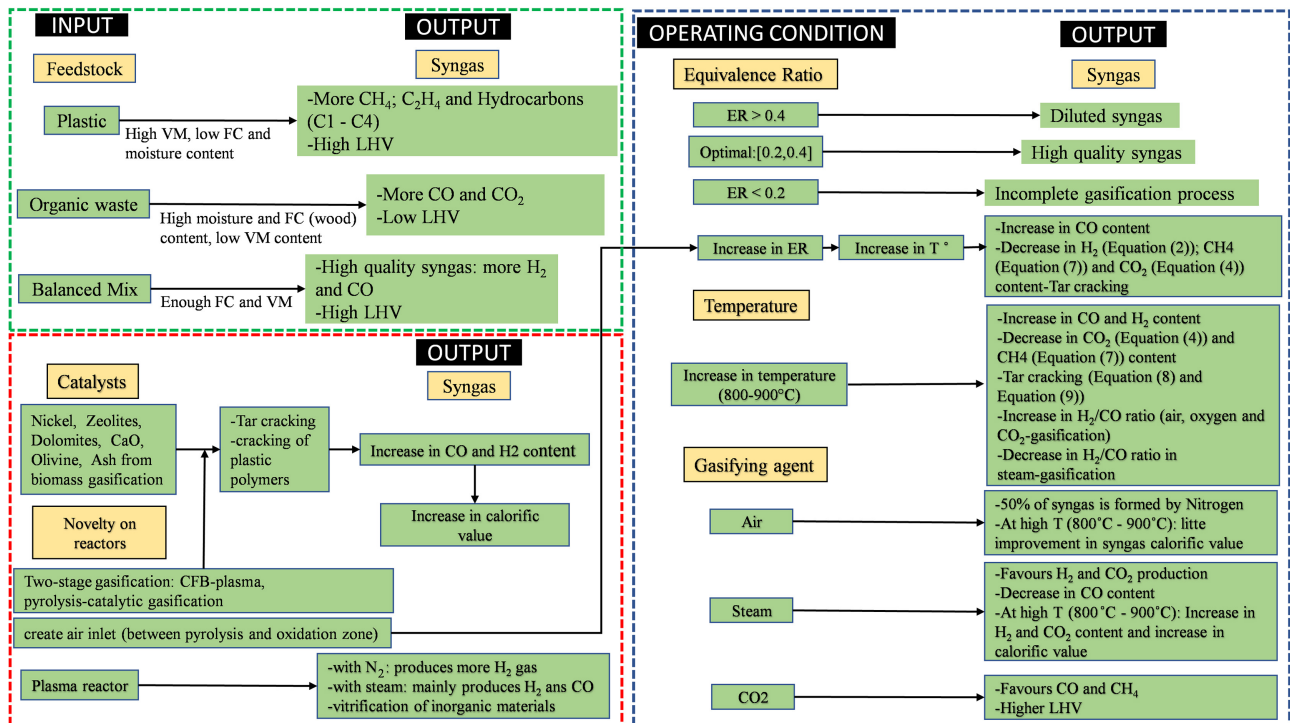


Figure 1. Schematic diagram: Input and output of the gasification system.

diagram summarizes the state of the art in solid waste gasification and highlights the variation in gasification products as a function of waste composition, catalysts and reactor type used and operating conditions such as temperature, gasification agent and equivalence ratio.

6. Conclusions and Suggestions

Gasification is ideal for the production of syngas from RHW because all kinds of waste can be recovered from this process. The aspect of the result of the gasification of RDF is a contribution from each of the RDF components. The gasification of plastic produces more C1 - C4 hydrocarbons due to a high volatile content, low fixed carbon content and low or no oxygen content. Plastics readily decompose into tar rather than char. In addition, gasification of high oxygen biomass such as food waste, paper and wood produces more CO and CO₂ and less hydrocarbons. Indeed, the plastic: biomass ratio is an important parameter in the gasification of RDF. A plastic-rich RDF has a low syngas yield while a biomass-rich RDF produces a low calorific value syngas. Plastic-biomass co-gasification produces good quality syngas, *i.e.*, low tar content and high calorific value. In short, to have a better quality of gas produced, an RDF must have a high calorific value and a sufficient amount of fixed carbon and ash. The latter has a catalytic effect on the decomposition of RDF. Plastic and biomass provide the calorific value and the fixed carbon and ash content of RDF respectively. However, the quality of the syngas produced depends not only on the composition of the RDF but also on the operating conditions of the reactor, the type of

reactor and the type of gasification agent used.

In addition, solid waste gasification has a higher cold gas efficiency than 70% and a higher conversion efficiency. Steam and plasma gasification produce syngas with a high calorific value and low tar content. By removing tars, coals and ash from the syngas, it can be used for electricity generation in small power plants below 10 MW. However, the high amounts of char, metals and organic pollutants in the ash and char are concerns especially with human health.

Taking into account the emissions, costs and technical aspects of each process, it can be said that gasification is a promising technique for the valorisation of RHW. However, studies on co-gasification of waste and biomass and gasification on a pilot-industrial scale are still scarce in the literature. So far, the synergistic effect of co-gasification of biomass and RDF is not entirely clear.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Acronyms

CGE: Cold Gas Efficiency

ER: Equivalence Ratio

GHG: Green House Gases

HHV: Higher Heating Value

HW: Household Waste

LHV: Lower Heating Value

LTECV: Loi de Transition Energetique pour la Croissance Verte

MSW: Municipal Solid Waste

RDF: Refuse-Derived Fuel

RHW: Residual Household Waste

SRF: Solid Recovery Fuel

TOC: Total Organic Carbon