Experimental Observation on Downdraft Gasification for Different Biomass Feedstocks

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Abstract

With the need for developing a more sustainable world, there is a desire to shift from fossil fuels to biofuels, produced using the concept of biorefineries. Within the last few decades, thermochemical conversion technologies have gained a great deal of attention for producing advanced biofuels. In this context, this chapter elaborates different aspects of biomass gasification technology, as a representative of thermochemical pathways, and suggested potential solutions to enhance the efficacy of the process. To fulfill this goal, different types of biomass feedstock are employed to examine the potential of each in bioenergy production through gasification process. The chapter is consisting of a series of dependent studies to investigate the path for advancements in the gasification process. The first study investigates the parametric effect of experimental conditions during gasification of individual biomass feedstocks to select the best biomass feedstock for next study. It is also demonstrated that how the variation in the syngas composition interacts with H_2/CO ratio. The other study investigates the potential of composite feedstocks based on the results from the first study. The last study investigates the potential failure scenarios and the likelihood of their occurrence are explored.

Keywords: biomass, plastic waste, gasification, downdraft, syngas, bridging, clinker

1. Introduction

Sustainable development is a multi-aspect concept which demands a variety of decision makers from different sectors to play a role in saving the resources for future generations. Environment, Economy and Society are three key elements in Sustainable development. There are a variety of environmental issues, such as air pollution, water pollution, waste and land contamination and climate change, which threaten both the natural resources and the human.

To a great extent, fossil fuels consumption is the cause of the environmental issues. The context of sustainability, as it relates to energy, requires considering potential replacements for the fossil fuels. Renewable resources of energy are the solution for solving this problem. The renewable resources do not interfere the carbon balance and therefore are so-called "carbon neutral" resources (**Figure 1**).

Owing to the depletion of fossil resources and the increasing demand on fuels, it is important to develop renewable resources to produce fuels and chemicals for energy security. Biobased materials, including biomass and wood pellets, are one of the most promising sustainable energy resources to replace expensive fossil fuels, which are threatening our environment and global climate. Biobased residues and waste, as renewable multifunctional resources, can not only be used for heating and power generation but also for greenhouse carbon dioxide enrichment and the improvement of soil structure or soil aeration via biochar production.

Bio-based materials have been introduced as one of the energy resources for producing advanced biofuels. Advanced biofuels are technically referred to non-food biomass materials which can potentially be used for producing bioenergy. Advanced biofuels derived from biomass feedstock, such as agroforestry, municipal and industrial residues, each of which has the biological source for bioenergy production purposes [1]. The definition of advanced biofuels as defined in European Union (EU) Commission is "every type of biomass typically derived from plant material which does not have an alternative use as food; they can be based on waste biomass, cereal stalks, other dry plant matter, or crops grown especially for fermentation into biofuels (algae, Miscanthus)" [2].

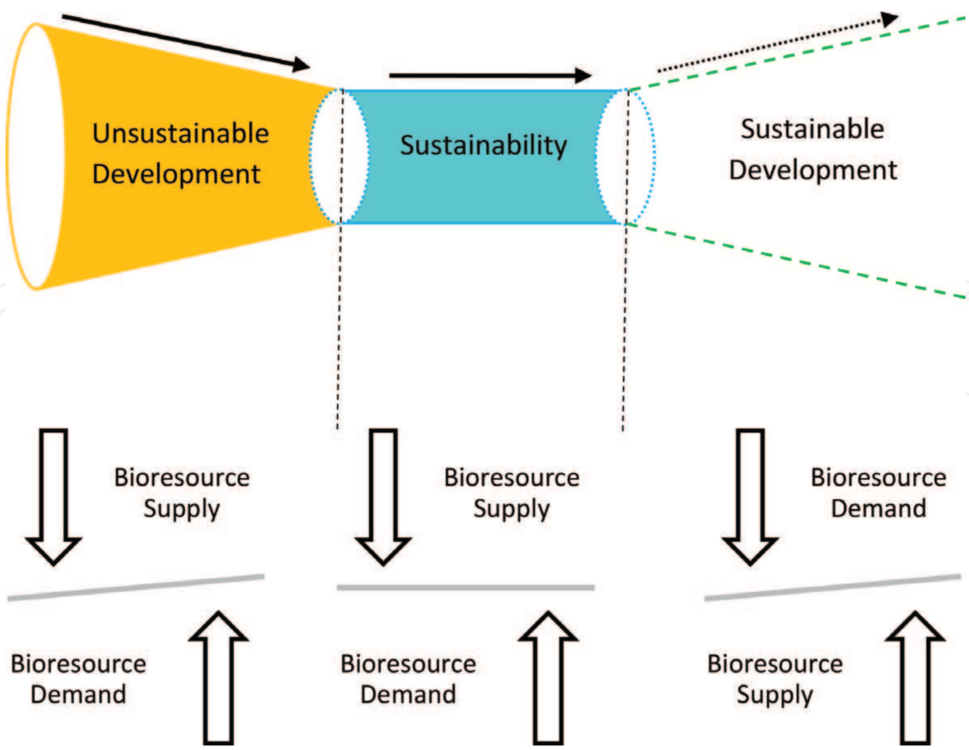

Figure 1. A developmental perspective on the transition from unsustainable era to sustainable era and sustainable development.

Biofuels have emerged as one of the most strategically important sustainable fuel sources and are considered an important way of progress for limiting greenhouse gas emissions, improving air quality and finding new energy resources. Advanced biofuels are referred to as liquid, gas and solid fuels predominantly produced from biomass, which are not in conflict with food security. A variety of fuels can be produced from biomass such as ethanol, methanol, biodiesel, Fischer-Tropsch diesel, hydrogen and methane. Renewable and carbon neutral biofuels are necessary for environmental and economic sustainability. Gasification is an environmentally friendly method which enables producing a wider range of products depending on the ultimate application.

There has been a great deal of attention from different authorities devoted to enhancing the share of advanced biofuels in the next decade. For instance, the Renewable Energy Directive (RED) stablished overall policy for the advancement of energy from renewable sources in the European Union (EU) which requires deployment of renewable energy for the share of 20% of the total energy needs of the union. RED also requires that all the members of the union to ensure use of renewable sources in the transport sector upward of 10% by 2020 which is twice of its share in 2009 [3]. Moreover, the U.S. Environment Protection Agency (EPA) mandates the increment in the share of biofuels in transportation sector from 41.9 (in 2009) to 136 billion liters (in 2022) under Renewable Fuel Standard (RFS2) [4, 5].

There are two major processes which can be served for converting biomass into useful forms of energy. The choice of conversion process could be performed by considering different parameters such as type and quantity of feedstock, the end-use applications, the local and national environmental regulations and the financial and economic conditions. Thermochemical and biochemical conversion pathways are categorized as the most well-known techniques for producing the desired form of the energy from biomass feedstocks [6, 7]. An overview of different technologies which falls under thermochemical and biochemical conversion pathways is presented in **Figure 2**.

Gasification technology represents an effective thermochemical conversion method which converts carbonaceous into synthetic feedstock. Gasification technology has been receiving a great deal of attention in the past few decades. Gasification converts carbon-based materials into gaseous products using a gasifying agent such as air, oxygen, steam and carbon dioxide. When air is used as the oxidant, the gaseous product is usually called producer gas, and when oxygen or steam is used, the product is termed synthesis gas (syngas). Syngas is an important feedstock for the chemical and energy industries, along with hydrocarbons traditionally produced from petroleum oil that can also be produced from syngas [1, 8]. During gasification, feedstock is partially oxidized. A gas medium—air, pure oxygen, steam or a mixture of these gases—is required to maintain the process. Biomass feedstock and gasification reactants, which accelerate ignition of the feedstock, typically enter the gasifier at the top and travel in the same direction down the gasifier. It should be noted that feeding points for biomass gasifiers can be from the top or from the side depending on the process.

Compared to combustion, gasification has higher efficiency due to exergy (i.e. the energy that is available to be used) losses, mainly from lower internal thermal energy exchange of expended exergy. The losses due to internal thermal energy exchange may be lowered by changing the

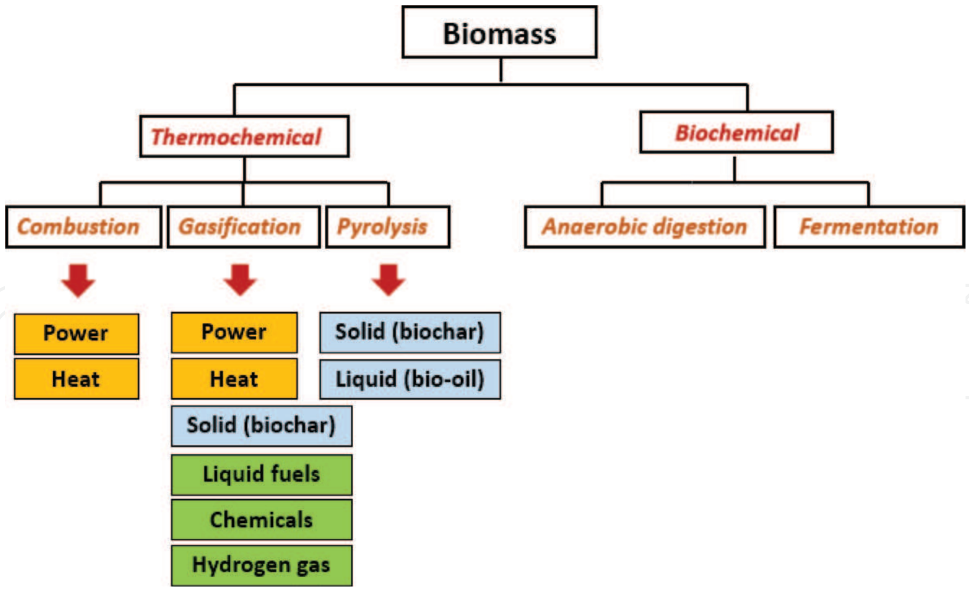

Figure 2. Biomass conversion pathways for producing bioenergy.

gasifying agent [9]. The gas composition evolved from biomass gasification strongly depends on the gasification process, the gasifying agent, and the feedstock composition [9].

The production of renewable energy from biomass using a gasification system is an environmentally friendly method that helps reduce dependence on fossil fuels. Biomass gasification offers advantages over the direct burning of biomass in a boiler. The sustainability of biomass utilization will greatly increase the overall sustainability of biomass management. In this chapter, the technical aspects of sustainable biomass management, with specific focus on recycling and energy recovery via gasification technology, are investigated. The Chapter is consisting of four interconnected studies to examine the basics towards advancements in the gasification process.

2. Gasification of individual biomass feedstocks

The first study begins with the first set of experimental studies using a 10 kW energy output down-draft gasification system (**Figure 3**). The type and characteristics of biomass can significantly affect the performance of gasification process and consequently result in different reaction temperatures, synthesis gas high heating value and tar content [10–12].

As shown in **Figure 3**, the complete system for syngas production from the gasification unit is composed of six major parts: (1) feeding; (2) main reactor; (3) filtering system, (4) burner assembly, (5) calorimetric units, and (6) purification system.

Feeding consists of a cylindrical painted steel drum bolted to a double layer drying bucket for drying of raw material. The main purpose of the painted steel drum is to increase the biomass storage capacity of the gasifier which multiplies by 6 the continuous operational time in comparison of using only the storage capacity of the main reactor. The drying bucket is used

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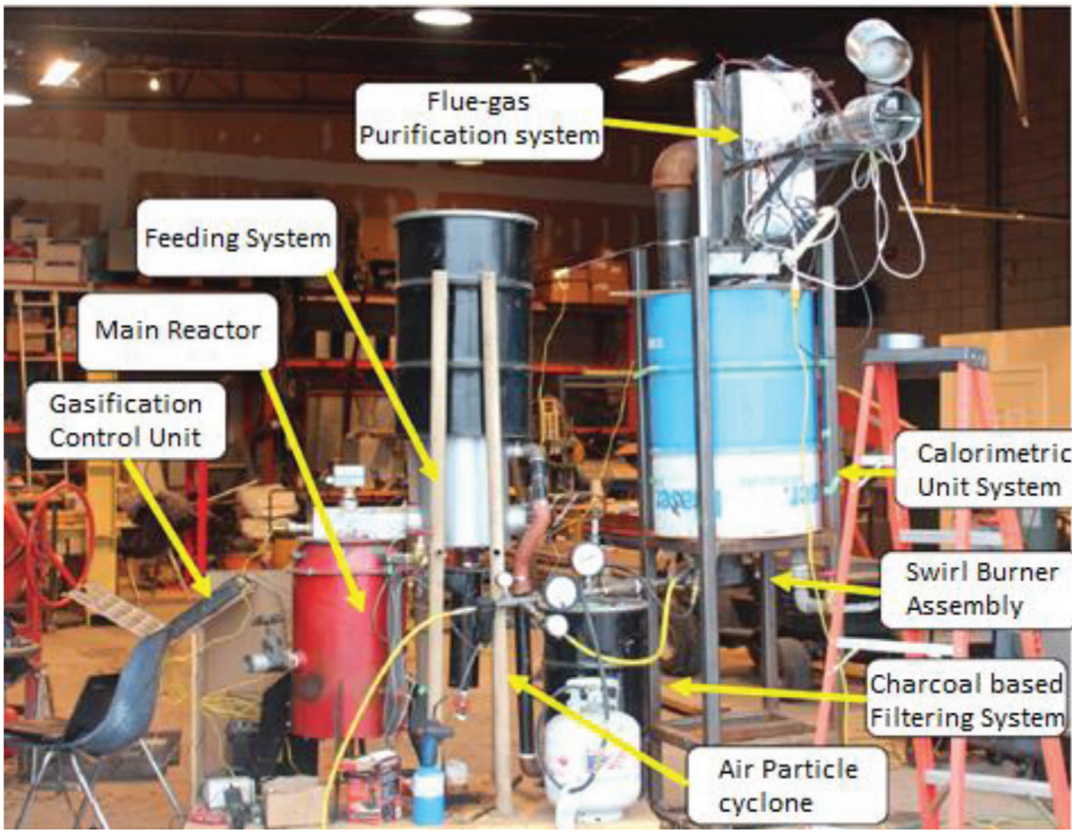

Figure 3. A downdraft gasification unit for producing advanced biofuels (McGill University, Canada).

to reduce the moisture content of the biomass that will enter the main reactor. The drying bucket is a double layer container with the biomass feedstock in the middle and hot syngas coming from the cyclone in a separate compartment surrounding the feedstock. From feeding point of view, the capacity of the employed mini-scale gasification system ranges averagely between 2.45 and 3.75 kg hr^{-1} of biomass. However, this range may change depending on the conditions of the reactor as well as the biomass feedstock.

The main reactor, which is a cylinder-shaped vessel, receives the gasifying medium (i.e. air, oxygen, steam or carbon dioxide) using internal pipes rolled around the reactor. These pipes are used to preheat the air prior the injection at the top of the reduction bell allowing a more stable gasification. Thermocouples are installed at different heights into the reactor to monitor the gasification process. An ignition port provides an access to introduce a flame directly at the top of the reduction bell to start the gasification process. The pressure into the reactor is maintained at atmospheric pressure by an ejector venturi located prior the swirl burner. This negative pressure siphons the syngas produced at the bottom of the reduction bell into the air particulate cyclone. There is a reticular grate under the reduction bell that allows the ash to be separated from the unprocessed feedstock. The ash accumulates under the grate and can be removed from the reactor by the ash trap. The compartment comprised between the reduction bell and the grate is filled with wood charcoal. A bed of pyrolysis materials facilitates the ignition of the system. The compartment between the lid and the reduction bed is filled with the biomass that will be gasified. A manometer is connected to the reactor frame to measure the vacuum pressure inside the reactor. A schematic view from cross section of the reactor along with the different zones during the gasification is shown in **Figure 4**.

The filtering system consists of an air particulate cyclone and a charcoal filtering system. The filtration process assists to remove particulates of larger diameters than 5–25 μm. The efficiency of the particulate removal varies between 50 and 90% depending on the conditions of the gaseous entered into the cyclone.

The burner assembly consists of an ejector venturi and a swirl burner. Compressed air is provided to the ejector venturi by a compressor capable of delivering an air flow between 10.2 and 13.6 $m^3 hr^{-1}$ at a pressure of 750 kPa as specified by the manufacturer's recommendations.

The calorimetric unit consists of an insulated drum filled with water in which a spiral chimney is installed. The swirl burner is connected at the bottom of the drum to the chimney. The flue gas produced by syngas-air combustion travels inside the spiral chimney and transfers its heat to the water surrounding the chimney. The calorific value of the syngas is calculated based on the calculation of the rejected heat from the flue gas and the change in temperature of the water [13].

Low energy density of biomass is a major restriction for using biomass which typically ranges from 60 to 400 kg m^{-3} for different feedstocks [10]. There are also two operational parameters bed temperature and pressure across the reactor which affects the process of gasification as well as ultimate heating values and the syngas composition. The pressure gradient, which is monitored using pressure sensors positioned at different levels across the reactor, is a function of system configuration, geometry, feedstock porosity, permeability and physical properties of the feedstock [14].

A variety of biomass feedstock is deployed for the gasification process. In the first step, pelletized woody biomass is selected as the primary biomass of interest to run in the reactor. Forests are a major source of wealth for Canadians, providing a wide range of economic, social and environmental benefits. Therefore, choosing woody biomass to run the gasifier for baseline tests matches with the available natural resources in Canada. This section elaborates

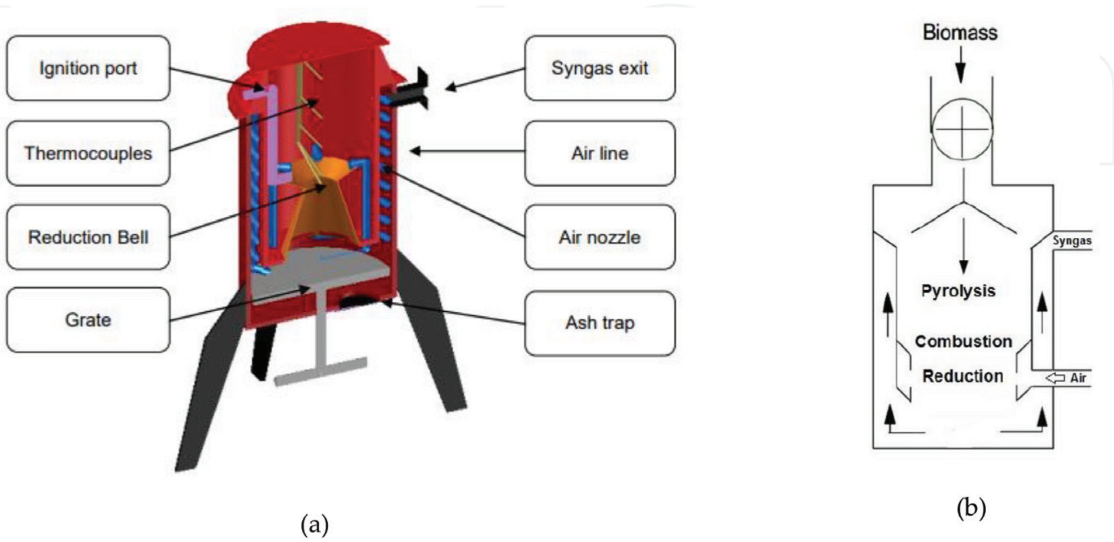

Figure 4. (a) Cross section view of the main reactor of the downdraft gasifier, (b) different zones across the gasifier [10].

the development, detailed technical aspects, and potential failure scenarios of the gasification process using woody biomass. The wood pellets are cylindrical in shape and are characterized according to American Society for Testing and Materials (ASTM) for finding out the proximate and ultimate analysis (**Table 1**).

The pressure fluctuations between the top and bottom pressure sensors cause material jamming such as bridging. Bridging of the feedstock results in a stopping of the downward flow of the pellet biomass inside the main reactor. A schematic of bridging scenario is depicted in **Figure 5a**. As can be seen, the bridging happens in the above-side zones of the reactor where only drying and pyrolysis take place. Bridging starts at early stage of gasification when the raw biomass is not yet influenced by the heat from the combustion zone (**Figure 5b**). The materials are however impacted by the gaseous products generated from the pyrolysis zone (**Figure 5c**). The pyrolysis does not take place completely due to the feedstock bridging. Therefore, the blocked materials do not allow an appropriate flow of heat towards drying and pyrolysis zones. As a result, the level of biomass does not change across the reactor in different times while the materials are slightly impacted by incomplete pyrolysis products and only transforms to darker color after a while. It should be noted that there is no chemical transformation happening under this scenario.

The gasification temperature controls the equilibrium of the chemical reactions [15, 16]. The results for five different types of feedstocks including switchgrass (representative of energy crops), woody materials (representative of agro-forestry), chicken manure (representative of animal waste) and fiber and cardboard (representative of municipal solid waste) are presented in **Figure 6** [17]. The gas compositions are recorded at five different instant temperatures of 600, 700, 800, 900 and 1000°C during the operation and at an air-biomass ratio of 0.3. All the feedstock reached instantaneous temperature over 1000°C while the average bed temperature measured is different for each feedstock. It is of worth mentioning that depending on the type of the feedstock and the conditions of the reactor in the time of operation, the producer gas flow into the swirl burner rate was recorded averagely in the range of 9.6–11.4 $Nm^3\ hr^{-1}$.

The desired element in the syngas composition is producing hydrogen (first preference) and then carbon monoxide (second preference). The production of hydrogen is so appropriate for using in the secondary combustion chamber downstream to the gasification unit for conditioning the syngas and producing ultimate end-products. This, however, never happens in practice to have only these two elements in the syngas. There have been numerous studies working on the composition of syngas [17–21] at which there are always four components hydrogen, carbon monoxide, carbon dioxide and methane reported. Majority

Properties (%)	Value	Properties (%)	Value
Moisture content	5.2	Carbon	42.64
Ash content	1.2	Hydrogen	8.5
Fixed carbon content	21.1	Oxygen	42.40
Volatile matter	72.45	Nitrogen	0.06

Table 1. Proximate and ultimate analysis of pelletized woody biomass.

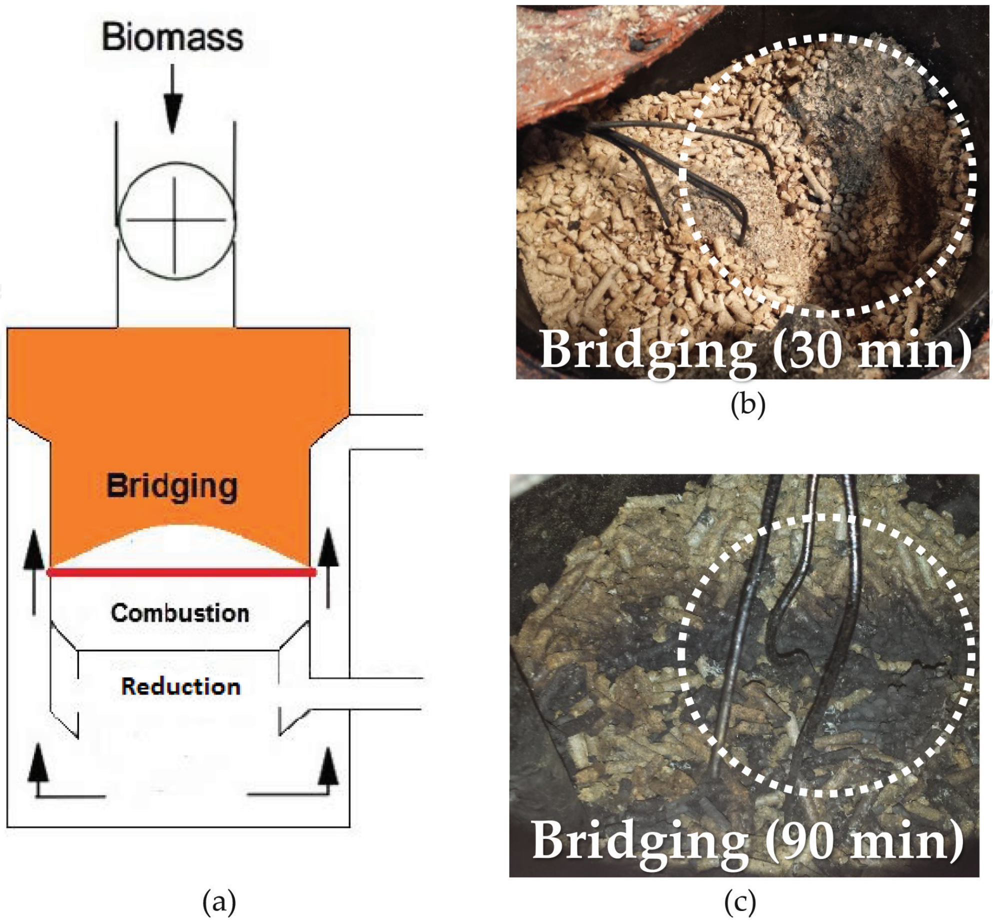

Figure 5. (a) Schematic of bridging formation across the reactor [10], (b) bridging after 30 minutes from beginning of the gasification process, (c) bridging after 90 minutes from beginning of the gasification process.

of studies have shown only up to 50% of the syngas composition filled with hydrogen and carbon monoxide, and the rest is contaminated with the other elements. As can be seen in **Figure 6**, energy crops (switchgrass) along with municipal solid waste (fiber and cardboard) showed promising performance in hydrogen and carbon monoxide. It should be also noted that the ratio of hydrogen to carbon monoxide is an important factor for condition the syngas. Madadian et al. reported that a higher percentage of hydrogen to carbon monoxide does not necessarily indicated a rich syngas [17]. This could be the main reason that the gas needs a secondary conditioning after production. Furthermore, the syngas heating values measured using the calorimetric unit fell in the range 16.84–9.24 MJ kg^{-1} which belongs to switchgrass and chicken manure, respectively. The heating values of the other biomass were recorded at 15.7, 14.45, 14.19 and 13.94 MJ kg^{-1} for hardwood, cardboard, softwood and fiber. The values may be found to some extent lower from what is reported in literature which is mainly attributed to the calorimetric unit errors which was developed by the author.

For the abovementioned biomass feedstocks in this section, the ratio of hydrogen to carbon monoxide is presented in the range of 0.15–1.5 under different temperatures. As shown in **Figure 6**, there is a proportional relationship between the value of hydrogen to carbon monoxide and the temperature profile within the reactor. In higher temperature, the

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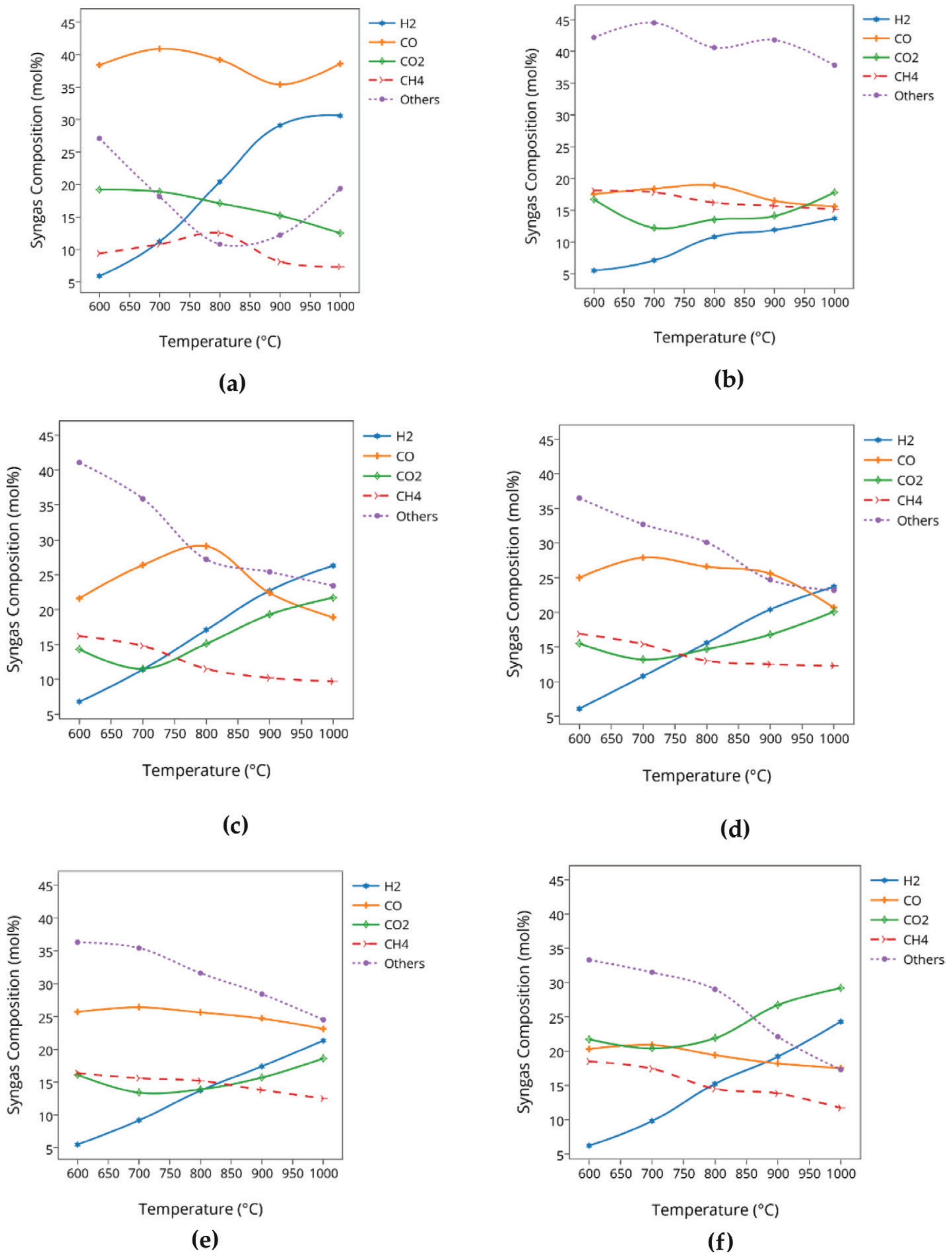

Figure 6. The recorded variations in syngas composition with respect to temperature profile during gasification of (a) switchgrass, (b) chicken manure, (c) soft wood, (d) hardwood, (e) fiber, and (f) cardboard [17].

amount of carbon monoxide drops which can be related to the reduced environment at higher elevation within the reactor. The step-by-step procedure under which this observed phenomenon took place is explain below:

a. By increasing the elevation across the reactor (from top to bottom), the temperature initially rises particularly in combustion zone where the reduction bell and air nozzles are positioned. At this step, a rich combustion process happens due to excess of air.

b. Over the time, and by controlling the amount of air getting into the reactor, oxygen-starved environment forms in higher elevation where the air enters the reactor. The immediate impact of reduced environment is an increment in the level of carbon monoxide.

c. However, the value of carbon monoxide drops gradually as the formed gaseous products react with the generated steam and/or moisture from the biomass and produce higher amount of hydrogen and carbon dioxide.

3. Gasification of composite biomass feedstocks

In this part, gasification of composite biomass feedstock is investigated. The blending of biofuels is one of the solutions for the suppliers of conventional fuel to alleviate the greenhouse gas intensity originated from the fossil fuels. As an example, a composite biomass composed of paper fiber and plastic waste originating from a municipal waste stream is tested to investigate the role of adding dissimilar agents on the productivity of the gasification technology. The study also elaborates the failure scenario of "Clinkering" and investigates the thermo-chemical properties of the generated by-products through gasification of composite fiber and plastic.

To date, experimental indices based on feedstock composition have been used to predict ash deposition and slagging potential [22]. Ash deposits or agglomerates are a major problem in the continuous operation of a thermo-chemical conversion reactor such as a gasification and combustion system [23]. There are several major factors in the bed representative agglomeration phenomenon such as particle size, feeding mode, reaction environment (oxidation/reduction), temperature, fluidization velocity, and contents of alkaline earth and alkali mineral [23]. Although downdraft gasifiers are known to have their limitations such as a feed size requirement, low ash content, decreased scale-up potential and increased risk for bridging and clinkering, this technology normally produces less tars and is less complex which could be applied for smaller scale systems [24].

The composition of the current experimental biomass includes a blend of the fibrous and plastic portions of post-consumer solid waste in Montreal, Quebec, Canada. The majority of the feedstock (90–100%) is comprised of fiber, which includes newspaper, cardboard, office paper, flyers, etc. Plastics are included as the remainder and consists of a blend of mixed polymers that include HDPE, LDPE, PET, trace PVC, etc. The plastics portion combined with fiber does not account for the level of plastic contamination that already exists in recycled municipal solid waste fiber. This portion may be as high as 2–5 wt%.

The proximate and ultimate analysis to understand the elemental matters in the individual and composite biomass feedstock is listed in **Table 2**.

As shown in **Table 2**, the ash content of plastic is much less than paper fiber waste which causes a lower ash content in the matrix of the composite pellets. Furthermore, the higher

	Testing item (%)	Plastic waste	Paper waste	Composite biomass*
Proximate analysis	Moisture content	4.78	6.27	6.12
	Volatile matter	94.19	85.78	86.62
	Fixed carbon content	<0.01	3.45	3.11
	Ash content	1.03	4.5	4.15
Ultimate analysis	Carbon	77	44.95	48.16
	Hydrogen	13.97	5.92	6.73
	Nitrogen	0.29	0.18	0.19
	Sulfur	0.19	0.19	0.19
	Oxygen	2.93	38.18	34.66
	Higher heating value (MJ kg^{-1})	40.01	17.09	19.38

*Ratio 1:10 for plastic to paper.

Table 2. Proximate and ultimate analysis of composite pelletized paper and plastic waste [25].

heating value of plastic waste is notably higher (over double) than the one for paper waste which also adds value to the composite pellet. Therefore, the lower ash content and higher heating value of plastic waste show the promising potential of making their composite pellets for producing biofuels [26]. The lower heating values of plastic waste and paper waste were calculated at 36.91 and 15.38 MJ kg^{-1}. It should be noted that gasifying the plastic is not practical as single biomass despite its high heating value. Hence, it is inevitable to blend the plastic waste with other biomass to reduce its potential emissions.

The excess of plastic content in the composition of composite matrix results in production of contamination in different forms. In the case of composite pellet, the plastic content was mixed in the ratio of 10% and resulted in producing metallic chunks of semi-burnt pellet mixed with some other elements called as clinker. The clinkering or so called "agglomeration" happens after ash is generated within the reactor when ash sintering begins at higher temperatures. The clinker forms initially in combustion zone where the highest temperature resides. By increasing clinker formation, some move downward with the help of biomass flow and deposit on top of the bed material. Therefore, the developed clinker is less porous compared to the original one formed in combustion zone. This can be due to longer distance in which they travel resulting in increased retention time in a high temperature zone which would lead to more viscous slag, along with lower heat transfer when entering the reduction zone. At the highest plastic levels tested (10%) one big ball of aluminum slag with an average of around 912 g was generated from a 15 kg start sample. The clinkers are shown in **Figure 7** [25]. One possible source of aluminum component can be from the coated plastic, however, other small contaminants during the experiment and from the fibrous feedstock might be another reason for observing contamination in the clinker. The detailed analysis of the clinker is explained in the next two paragraphs.

The organic content and minerals of the biomass feedstock have different level of persistency in leaving the matrix of the composite pellets at different temperatures. Organic content of biomass has fairly lower resistance against high temperature gasification and is fully consumed in the combustion region of the reactor where highest temperature takes place. At higher temperature, the mineral content of the biomass transforms into ash and prepares the ash sintering process at which liquid and viscous slag is generated. The formation of slag is due to the interactive reaction between the melted ash and the mineral matter content of the ash matrix. This process continues until the generated molten ash accumulates and makes the chunk of clinkers which deposits in the bottom part of the reactor. It is also reported that liquid slag flows under the force of gravity and out of the bottom of the gasifier into a water quenching system which is not the case for the current system [25].

The inductively coupled plasma (ICP) mass spectrometry analysis of individual and composite paper and plastic waste indicates presence of six major elements in the matrix of the composite pellet including sodium (Na), magnesium (Mg), aluminum (Al), potassium (K), calcium (Ca) and silicon (Si). The majority of the contaminants (i.e. Na, Mg, Al, K and Ca) originates from paper fiber existed in the municipal waste stream, and silicon is derived from plastic wastes. It is reported that these elements could be detected in typical paper waste such as brown toilet paper, cardboard, industrial paper towel, magazine paper and printer papers. The use of these elements is for the purpose of grading and sizing of the papers [25, 27]. Characteristics of the clinker are also a function of degradation mechanism depending on the composition of volatiles and consequently the gaseous phased products are affected. The thermal degradation of polymers and plastics typically begins with random scission followed

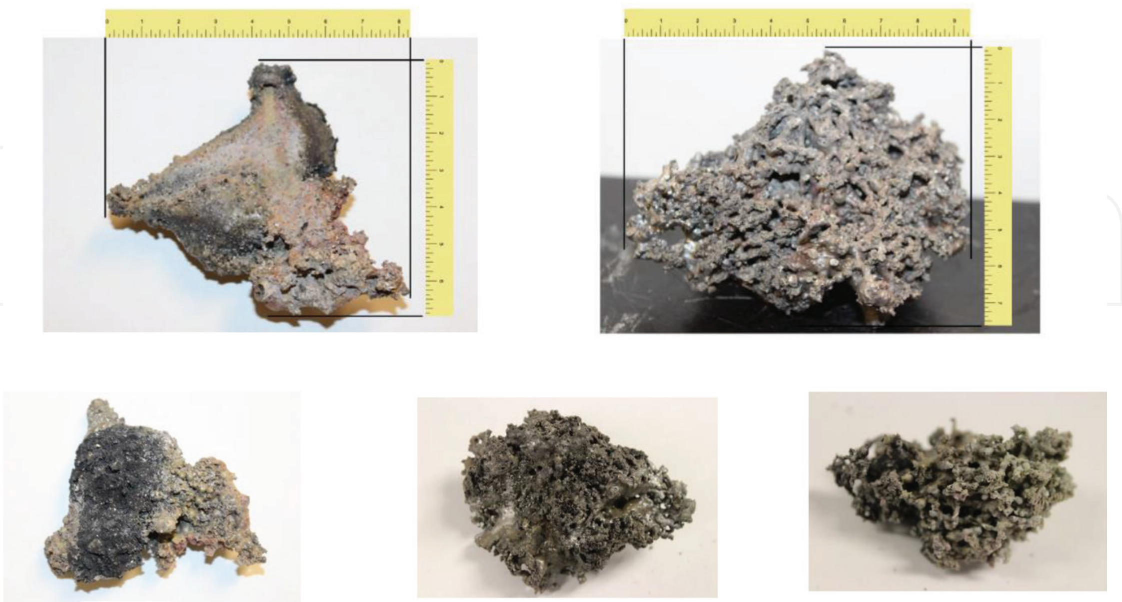

Figure 7. Clinkering during gasification of composite pellet of fiber and plastic (unit: cm) [25].

by direct scission, 1,5-radical transfer scission, and multiple step-radical transfer scissions as temperature climbs over 800°C [27].

4. Conclusion

In this chapter, the potential of bioenergy production from each of which was investigated. The failure scenario of "bridging" was observed in this stage. Next, multiple feedstocks were examined for seeking the possible improvement in the quantity and quality of the produced gas. This chapter also aimed to find how the increase in plastic specifically in the recycled fiber stream would affect the performance of a downdraft gasifier. The failure scenario of "clinkering" was observed in this stage which could be considered as an individual project to work on. The chapter also showed that a mixture of silicon with aluminum, calcium and sodium under high temperatures would result in the generation of a solid clinker that ultimately moves through the reactor and is deposited at the bottom of the reactor. It may be concluded that due to the presence of plastic, the generated ash is superheated and melts into glass-like materials causing formation of metallic chunk. The chunk is cooled down through partially endothermic nature of the gasification and results in generation of clinker. This chapter presented informative tools for improving advanced biofuel production through gasification technology and using different types of biomass feedstock which can be continued in further researches.

This study also focused on the development of gasification technology to enhance the efficiency of biomass conversion within the process. In a nutshell, the following recommendations are offered for future research:

1. Although this study worked on gasification of different types of biomass feedstock and identified the potential failure scenarios, it is still essential to elaborate the post-gasification process for syngas conditioning to produce enriched gas. This will have a significant contribution to approaching integrated gasification combined cycle (IGCC) concept.
2. Developing/re-designing the down-draft gasification unit is recommended to examine the possibility of process optimization. The new design might apply a coupled reactor in which one produces the syngas and the other one works as a downstream unit to condition the produced gas.
3. Designing a burner is recommended to enhance the efficiency of the process where the syngas comes out. A good burning process helps to preserve the syngas produced in the reactor and boost the performance of the technology.
4. Developing a feeding system which is independent of the physical properties of feedstock is strongly recommended. This will help to reduce the cost related to supply chain.
5. A detailed investigation of tar and char modeling through different types of reactor configurations could help to understand the formation process and minimize the detrimental effects of by-products.

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