

# Biomass. Incineration, Pyrolysis, Combustion and Gasification

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**Abstract:** *In this paper, biomass and its important properties most relevant to biomass gasification are discussed. To generate heat and/or electricity while save the environment, incineration, pyrolysis, combustion and gasification processes have all been tested mainly exploiting biomass. It is aimed in this paper, to discuss these processes with more attention on gasification process being the most efficient and economical process for hydrogen generation. It was found that biomass is a good candidate for gasification process although it has not been utilized enough. Gasification process in comparison to incineration, pyrolysis, combustion processes is the most practical while economical process if hydrogen production and protection of the environment are the main targets.*

**Keywords:** Biomass; incineration; pyrolysis; combustion; and gasification

## 1. Introduction

Nowadays, although biomass and other wastes, which when employed to generate electricity have given satisfactory results in terms of efficiency of electricity generation and effect on the environment, are ubiquitously available, emphasis on traditional, limited and environmental-harmful fossil fuels to generate electricity still seems a maximal. If not dealt with by some method, biomass and other wastes can be a burden to the environment. Available methods to process such wastes are: incineration, pyrolysis, combustion and gasification. With such methods not only energy can be generated from biomass or other wastes but also the environment becomes cleaner. Equally important, fossil fuels may become among several resources to generate electricity and that not the only available option as currently the case in most regions of the world. According to several studies, biomass has seen several gasification applications. To this end in this paper; therefore, biomass and its important properties most relevant to biomass gasification are discussed. This is; then, followed by the main characteristics of incineration, pyrolysis, combustion and gasification processes. Through out the paper, gasification process, in particular, has been given more focus for been widely used for the purpose of heat and/or power generation while little focus was paid to incineration process.

Centuries ago, fossil fuels, which include: coal, oil and natural gas, have been the only available source of energy worldwide. Initially were life standards were simpler, they had met people's demand, perhaps, due to their reserves availability and little consumption. Currently; however, they are not only considered un-sustainable but also, when consumed through combustion, pollutants of a great concern to the environment. In terms of sustainability, fossil fuels reserves may be susceptible to depletion in three generations, if the existing consumption rate of fossil fuels has not been retarded (Boyel, 2004; Kaygusuz, K, 2012). In nearly two decades, early 1980s to early 2000s, in Asia/Oceania region, generation of electricity based on fossil fuels was increased four- fold while it doubled worldwide (Takeharu, 2010). In another aspect, in terms of environment pollution, if improperly contained, a huge

amount of greenhouse gas emissions annually ejected to the environment is mainly linked to fossil fuels consumption through combustion (Le, et al., 2009; Davis and Caldeira, 2010; Street and Yu, 2011). According to Cassedy, this amount of emissions is estimated at more than 20 billion metric tons per annum (Cassedy, 2000). Increase of fossil fuels prices whether due to geographical, economical, operational or political issues is also an issue. Studies, that highlight the severe dependency of people's daily life on consumption of fossil fuels (Luis, 2007; Jorge, et al., 2008; Ajay, et al., 2009; Andrés, et al., 2009; Abrar, et al., 2010; Hengfu, et al., 2010; Takeharu, 2010; Chawdhury, and Mahkamov, 2011; Ihsan, 2012; Jorge, et al., 2012; Niclas and Claus, 2012; Brandon, 2013; Sharmina, et al., 2013; Thanasit, et al., 2013; Xu, Q., 2013; Chad, 2014; Onursal, et al., 2015, etc.) and emphasize depletion of reserves of such fuels (Venkata, et al., 2008; Jorge, et al., 2012; Sharmina, et al., 2013; Park, et al., 2014; Onursal, et al., 2015, etc.) as well as warn of its environmental burdens (Luis, 2007; Abrar, et al., 2010; Isack, 2012; Niclas and Claus, 2012; Sheng and Ying, 2012; Nicholas, 2013; Wu, H., 2013; Chunfei, et al., 2014; Reem, et al., 2014; Zhengfeng, et al., 2014; etc.) are enormous. Taking this into account, looking for sustainable while environmentally-clean energy source(s) becomes an inevitable option.

If sufficiently available, renewable energy supplies have been widely proposed as an alternative to fossil fuels to tackle issues of sustainability and environmental pollution, associated with fossil fuels, or at least mitigate them. Among renewable energy supplies, in addition to biomass, are: tides, wind, solar, hydro, geothermal. Biomass accounts for more than two thirds of the world's renewable energy sources. Biomass is the fourth largest energy resource after the three fossil fuels mentioned previously (Onursal, et al., 2015). In Europe, 56% of energy renewable resources are biomass (Niclas and Claus, 2012). In the United States alone, more than 500 million tones of manure, that's biomass, are produced annually. In addition to this, there is also a huge amount of sewage sludge produced through municipal wastewater treatment units (Gerba and Smith, 2005; US Environmental Protection Agency, 2007). Both biomass and municipal solid waste are continuously and increasingly generated.

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## 2. Biomass

Biomass is a broad term; hence, to avoid confusion it might be useful to represent its definition with examples of biomass and some of its properties. Further, main analyses relevant to gasification process usually conducted on biomass along its annual demand and availability are discussed next. 'Any organic substances that are directly or indirectly derived from those plants that are able to conduct photosynthesis process are defined as biomass' (Boyel, 2004). The term biomass covers a broad range of materials that offer themselves as fuels or raw materials and that what they have in common is that they are all derived from recently living organisms. Whereas traditional fossil fuels which also have been driven from plant (coal) or animal (oil and gas) life, but it has taken millions of years to convert to their current forms (fossil fuels) (Higamn and Burgt, 2003). According to Prade (2011), there are two main biomass types: residues and energy carrier production. Residues biomass are those residual materials originate from agriculture and industrial processes. Energy carrier production, as the name implies, are biomasses merely cultivated for energy applications. Biomass is a renewable sustainable energy resource. Its renewability is facilitated by the ability of a plant to store and release carbon dioxide during photosynthesis process and during biomass-to-energy conversion process, respectively. Details of biomass photosynthesis process is available in (Carpentieri, et al., 2005; Demirbas, A, 2009). Depending on biomass type, its composition may differ notably. Typically, a biomass may comprise of the following constituents: cellulose, hemicelluloses, lignin, extractives, lipids, proteins, simple sugars, starches, water, in-organics (ashes) and other compounds. The main constituents of biomass are briefly described elsewhere (Hanaoka, et al., 2005; Gates, et al., 2008; Barneto, 2009). According to biomass origin, composition, production conditions and collection sites, different biomass classes can be identified, refer to Table (1) (Santoianni, et al., 2008; Marcin, et al., 2011; Wu, H., 2013).

**Table 1:** Main Classes of Biomass\*

No.	Class	Such as:
1-	Forest products	Wood, logging residues, trees, shrubs and wood residues, sawdust and bark, etc.
2-	Bio-renewable residues	Agricultural wastes, crop residues, mill wood wastes, urban wood wastes and urban organic wastes
3-	Energy crops	Short rotation woody crops, herbaceous woody crops, grasses, starch crops, sugar crops, forage crops and oil seed crops
4-	Aquatic plants	Algae, water weed, water hyacinth, reed and rushes
5-	Food crops	Grains and oil crops
6-	Sugar crops	Sugar cane, sugar beets, molasses and sorghum
7-	Landfill	Waste materials
8-	Industrial/ organic wastes	Chemical solvents, paper products, sandpaper, paints and industrial by-products
9-	Algae, kelps, lichens and mosses.	Algae, kelps, lichens and mosses

\*Adapted from: Marcin, et al., 2011.

## 3. Properties of Biomass Relevant to Gasification

Owing to its wide range, properties of biomass are different from a biomass to another (Higamn and Burgt, 2003). Accordingly, performance of a certain biomass as a fuel in a gasification process could vary from that performance of another different biomass. In biomass gasification, important biomass properties are: i-moisture content; that is the quantity of the contained water molecules that physico-chemically bond to solid fuel material (biomass) (Xu, Q., 2013). It ranges from 10% up to 50-70% for cereal grain straws and forest residues, respectively (Alok D. and Gupt .V.K., 2014). Maximum allowed moisture content of a biomass differs with respect to the gasifier type used for gasification. For instance, although a downdraft gasifier can give a satisfactory result when the moisture content of the biomass gasified is no higher than 30-40% on a dry basis, an updraft gasifier can cope with quite higher moisture contents (Dogru, et al., 2002; Venkata , et al., 2008). Entrained-bed gasifiers are sensitive to moisture content in a biomass as moisture may inhibit the overall gasification reactions (Robert, et al., 1992). High moisture content of a biomass can be a problematic property and may disqualify it from been economically gasifiable. With excessive biomass moisture content, energy required for drying and that energy of the produced syn gas may be comparable rendering gasification process is not economically feasible (Maker, T. M., 2004; Onursal, et al., 2015). High moisture content in a biomass (more than 40 wt%) reduces the thermal efficiency of gasification system (Hosseini, et al., 2012). Loss of heat is as a result of using available gasification heat to heat up the moisture down from ambient temperature up to the required temperature for drying (around 100 °C), to heat up the steam generated following drying up to the high temperatures required for gasification. Latent heat of vaporization can also be lost from the gasification system (Singh RN., 2004). A make up heat to the gasification system is; then, required, of-course at an additional cost. It should not be understood; however, that complete drying, in order to avoid heat loss(es) during gasification, is desirable. In fact, a minimum amount of no more than 40 wt% of moisture content in biomass is beneficial to the gasification system as will be briefly explained next and also to avoid or at least minimize costs associated with drying (Xu, et al. 2008; Dong, et al., 2010). Cost of drying includes cost of drying equipment as well as cost of energy (heat) used for drying (Asadullah, M., 2014). Remaining moisture within biomass following its drying can be converted into steam by the aid of heat generated while gasification. This steam can act as a gasification agent which can react with volatiles generated during gasification as well as with char to produce syn gas and also it can enhance the production of hydrogen that produced through water-gas shift reaction (Lv, et al., 2007; Yan, et al., 2010), ii-an important property of biomass in gasification processes is the ash content. This ash is the solid residue produced in a gasification process by combustion. This ash; however, is undesirable and its formation through gasification should be avoided. Formation of ash reduces the energy content of biomass, the fuel to gasification. Exposing to high temperatures near its melting point followed by cooling, ash can react forming slag. Downdraft gasifiers, in particular, are sensitive to slag formation as slag can obstruct the flow of

fuel (biomass) and formed char. Hence, throughput of a gasification plant may be affected while increasing operating and handling costs. Formation of slag depends on reaction temperature, composition of fuel ash formed as well as its percentage (Kaupp, and Goss, 1981). To reduce formation of ash, temperature of the gasifier should be reduced, although this might not be possible in a downdraft gasifier where large reductions in gasifier's temperature are impossible. This is because in a downdraft gasifier, higher temperatures are desired to produce a better and cleaner syn gas (George, et al., 1995), iii-volatile matter and fixed carbon content: volatile matter (VM) of a solid biomass is that total (gas plus moisture) obtained when heating that biomass. Whereas fixed carbon (FC) is the mass that remains subsequent to the release of volatiles without ash and moisture contents. Usually, energy stored in solid fuels is measured by VM as well as FC, iv-calorific value (CV): it is an expression of energy content/heat value of a material/fuel when burnt in air. A fraction of C, H and S in a biomass governs the value of its CV. It is measured in Jules per unit mass, mole or volume of the material/fuel (J/kg), (J/kmol) or (J/m<sup>3</sup>), respectively. In the literature, there are two forms that a CV is expressed with. These forms are: gross calorific value (GCV) or higher heating value (HHV) and net calorific value (NCV) or lower heating value (LHV). HHV represents the utmost amount of energy that can be recovered from a material/fuel when burnt in air plus the latent heat that might be contained in water vapour (Reed, T. B., 1988). Since this latent heat cannot be effectively measured nor used, LHV is the most used form of CV. Experimentally, a heating value of a syn gas can be obtained through combustion in a calorimeter. Otherwise, it can be calculated using some formal that are available elsewhere (Higman and Burgt, 2003). The heating value of a syn gas produced partly depends on the moisture content of the biomass gasified. High moisture content is associated with a low heating value of its corresponding syn gas, and v-bulk density: this property of biomass gives information on biomass handling, transportation and storage. The bulk density of a biomass that is the weight per unit volume of loosely tipped waste (biomass) is usually low due to internal and intravoids spaces of biomass particles.

Among the terminologies that well describe biomass gasification process and widely used in gasification studies are proximate and ultimate analyses. To evaluate a solid fuel, e.g. a biomass waste, proximate and ultimate analyses must be carried out. Proximate analysis of a solid fuel provides information about its moisture content, volatile matters, fixed carbon and ash content in mass percentage (wt %). Amount of volatile matter and fixed carbon in a solid fuel along with the content of oxygen reflects the reactivity of that solid fuel (van Krevelen, 1993; Xu, Q., 2013; Alok D. and Gupt .V.K., 2014). Where as the ultimate analysis provides information about the elemental constitution of a solid fuel in mass percentage (Xu, Q., 2013). A main elemental composition of different kinds of biomasses is available at (Hein and Karl, 2006). Within this paper, experimental details of both analyses are not discussed further. They can be found elsewhere (Xu, Q., 2013).

In accordance to the recent statistics, shown in Table (2), made by Sims and others in 2007 on the energy demand and availability of main renewable resources on an annual basis in the year 2005, implementation of renewable energy resources for energy production applications seems limited in spite of their wealthy availability (Sims, et al., 2007). On the contrary; however, their traditional cooking and heating applications are otherwise. This applies not only on hydro, wind, geothermal and solar but also on biomass, part of the focus of this paper. Current total demand of these renewables in 2005 was not more than 6.5 % of the estimated total available. Estimated biomass availability was 250 EJ while the rate of use for energy production purposes was surprisingly only 9 EJ while rate of use of biomass for traditional cooking and heating applications was nearly fourfold, at 37 EJ. In another more recent separate study, it was reported that energy production in the Czech Republic was 4 % based on renewables. Biomass alone was the most renewable resource used (Marek, et al., 2012).

#### 4. Incineration, Pyrolysis, Combustion and Gasification

Traditionally, these wastes (biomass and other wastes) have been mainly dealt with through landfilling. With landfilling; however, a number of environmental problems have been reported. In a study by Wu ,H. (2013), these environmental problems were: pollution of surface water with phosphate compounds, nitrogen and phosphorus originally contained in the animal waste, pollution of the surroundings through generated odours, greenhouse emissions and some metals such as copper, zinc and arsenic (Otero et al., 2010). Further, excessive landfilling results in soil, water and air quality degradation (Larney and Hao, 2007). In one line, to save the environment and in another line due to depletion of fossil fuels, alternative strategies for power generation were; therefore, a necessity. Among these strategies were processes including: thermo-chemical, bio-chemical, and physicochemical pathways (Brunner et al., 2004; Porteous, 2005; Psomopoulos et al., 2009, Huang et al., 2011, Marek and Tomasz, 2012; Xu, Q., 2013). Apart from the thermo-chemical processes, no other process is further considered throughout this paper.

**Table 2:** Energy Demand and Availability of Main Renewable Resources on Annual Basis: Adapted from: Sims, et al., 2007

Renewable resource	Estimated availability, EJ	Rate of use (2005), EJ
Hydro	62	25.8
Wind	600	0.95
Biomass	250	46*
Geothermal	5000	2
Solar (PV)	1600	0.2
Total	7512	75
Current demand	490	

\*= including 37 EJ of traditional biomass use (heating and cooking)

In general, thermo-chemical processes employ higher temperatures than those employed in bio-chemical or physicochemical processes. Also, thermo-chemical processes can efficiently handle different types of solid wastes as well

biomasses with a sound higher conversion rates than that may be obtained via another conversion process. A list of most important advantages of thermo-chemical processes is included within this review. Thermo-chemical processes include: incineration, combustion (full oxidation) (Overview of DOE's Gasification Program, U.S. Department of Energy, 2009), pyrolysis (partial gasification) (Basu, P., 2006), and gasification (Xu, Q., 2013) (partial oxidation) (Overview of DOE's Gasification Program, U.S. Department of Energy, 2009). Incineration which perhaps due to lower thermal efficiencies and higher greenhouse gas emissions than combustion has not found a worldwide application. Of these greenhouse gas emissions that may generate from an incinerator are: SO<sub>x</sub>, NO<sub>x</sub>, HCl, HF, polyaromatic hydrocarbons (PAH), polychlorinated biphenyls (PCB), dioxins and furans with a wide range of heavy metals (Jaeger and Mayer, 2000; Jorge, et al., 2008) which are carcinogenic and toxic chemicals. In fact, in some developed countries like United States incineration has been banned. Although with newer incinerators, emissions may be lower; however, gas cleaning system is too costly (Jorge, et al., 2008). In response to this and to the public concern over incineration process due to its risky emissions, incineration process has been limited in use and scarce information in the literature is available on it; thus, will not be considered further through this article. In a thermo-chemical process, one or more process of these three processes, excluding incineration, is used as the case with gasification process in which combustion, pyrolysis, and gasification are all used, although the process is totally termed gasification. In combustion process, in the presence of an excess air more than what's chemically required, chemical energy is converted into heat along with CO<sub>2</sub> and H<sub>2</sub>O as by-products while reducing the volume of the original waste (Otero et al., 2010). In combustion, excess air is required to boost the fuel efficiency and to avoid the formation of very toxic carbon monoxide and soot (Alok D. and Gupta .V.K., 2014). In a pyrolysis process, a biomass is decomposed thermally but in no oxygen environment. Gasification process sits in the middle between these two processes as it involves using a limited rather controlled amount of an oxidant of many available oxidants such as: air, oxygen, steam or a combination of air with steam or a combination of air with oxygen, at different air compositions (Mansaray and Ghaly, 1999; Thiruchitrabalam, 2004; Ro et al.; 2009; Wang et al.; 2011; Sharmina, et al., 2014). Gasification technology goes back to nearly 200 years ago (Wu, H., 2013). It has been in use since the World War II (WWII) where millions of vehicles in Europe, in particular, were equipped with gasifiers as a source of fuel by means of a synthetic gas (Egloff, 1943; Marcin, et al., 2011; Wu, H., 2013). Further historic details on gasification process can be found in a study by Gert Hendrik Coetzee (Gert Hendrik Coetzee, 2011). This; however, as a result of fossil fuel prices decrease at a time, did not last where fossil fuels took over from gasification. Later, due to various reasons some of which were geographical, economical, operational and not surprisingly political, prices of fossil fuels increased again. Further, due to concerns over depletion of fossil fuels as well as concerns over their associated greenhouse gases emissions, gasification process is currently turned out to be prevalent yet again. Gasification utilizes the chemical

energy held in a biomass waste converting it into chemical product(s) and sensible energy of its produced gas. In terms of carbon content, a pyrolysis process produces much more carbon than gasification process (Kezhen, et al., 2013). Deciding a suitable process among pyrolysis, combustion, or gasification for a certain biomass is mainly determined by the components of the biomass (McKendry, P., 2002).

Main advantages of thermo-chemical processes together (pyrolysis, combustion and gasification) are: i- great reductions of waste, preserving a landfill space. Reductions of 70-80% in mass and 80-90% in volume of waste have been reported (Consonni et al., 2005), ii- huge savings in land use compared to landfilling. A piece of land required to construct a thermo-chemical plant to process a certain quantity of waste is drastically smaller than that required for landfilling of similar quantity of waste. It has been estimated that to process 1 Mt/y of waste for a 30 years period of time, in a waste-to-energy plant, less than 100000 m<sup>2</sup> of land is required. Landfilling of 30 Mt of the same waste; however, requires 3000000 m<sup>2</sup> (Psomopoulos et al., 2009), iii- instead of releasing organic pollutants, e.g. halogenated hydrocarbons into the atmosphere or into the earth as the case with landfilling, in gasification; nevertheless, they are destructed and disposed of (McKay, 2002). Alternatively, they can be safely used through concentration and immobilization (ISWA, 2008; Samaras et al., 2010), iv- recyclable materials such as ferrous and non-ferrous metals that may come out of a thermo-chemical process can be utilized (ISWA, 2006; CEWEP, 2011), v- in terms of greenhouse gas emissions, a thermo-chemical process releases less emissions than landfilling. In a study by Psomopoulos and others, it was estimated that landfilling of a waste produces 1 ton of CO<sub>2</sub> emissions more than if the same amount of waste has been combusted (Psomopoulos et al., 2009), vi- in general, due to severe emissions regulations imposed, thermo-chemical processes, gasification in particular, are characterized with better environmental performances resulting in less environmental impact compared to other energy processes (US-EPA, 2003; Rechberger and Scholler, 2006) and vii- particularly if a combined heat and power plant has been used, it is possible to environmentally exploit the renewable energy contained within the waste (Rechberger and Scholler, 2006). What discussed next is a comparison between the various thermo-chemical processes: pyrolysis, combustion and gasification. This is; then, followed by a deeper focus on gasification process, the topic of this review.

#### 4.1 Pyrolysis, Combustion and Gasification

Main characteristics of pyrolysis, combustion and gasification processes are contained in Table (3) (Arena and Mastellone, 2009; Marcin et al., 2011). Gasification process is further considered next. As included in the Table (3), in pyrolysis, solid waste (biomass) is thermally decomposed to gases (CO, CO<sub>2</sub> and CH<sub>4</sub>) and condensable volatile liquid tars (bio-oil) (Nor, et al., 2007; Wang, et al., 2008; Isack, 2012; Alok D. and Gupta .V.K., 2014). This oil can limit the use of pyrolysis process due to some difficulties that may encounter in its downstream processing and its little use (Wang, et al., 2008; Xu, Q., 2013). Products of a pyrolysis process depend on pyrolysis operation environment of temperature, pressure, heating rate and residence time (Nor, et al., 2007; Xu, Q.,

2013). According to the heating rate used, pyrolysis process can be slow or fast. In a slow pyrolysis, the heating rate is nearly 10KJ/s and it increases to be 103-104 KJ/s in a fast pyrolysis. With higher heating rates and; hence, higher temperatures yield of gases may increase while yield of liquids decrease, decreasing average molecular weights (Xu, Q., 2013). In combustion, solid waste (biomass) is thermally converted through complete oxidation in a rich oxygen environment to a flue gas at high temperature (CO<sub>2</sub>, H<sub>2</sub>O, excessive O<sub>2</sub> and N<sub>2</sub> in case air is used as an oxidant). High heat is provided by oxidation reactions of the solid waste (biomass) by oxygen (Xu, Q., 2013; Alok D. and Gupt .V.K., 2014). This heat is used to sustain the overall gasification process (Isack, 2012). In gasification; however, a fuel gas or a synthetic gas containing some combustible gases such as CO, H<sub>2</sub> and CH<sub>4</sub> and some hydrocarbons (tars) with a reasonably high heating value (HHV) is what a solid waste (biomass) is thermally converted to through partial oxidation reactions of this solid waste (biomass) in a limited amount of oxygen. CO production is an indication of a poor efficiency of a combustion process, i.e. in/no-complete combustion. Production of more CO can be as a result of local chilling of the flame at points of secondary air entries during gasification (Cohen et al, 1987). The HHV of this syn gas largely depends on fractions of these combustible gases (CO, H<sub>2</sub> and CH<sub>4</sub>) in the produced syn gas (FAO forestry paper, 1986). Heat required for overall endothermic gasification reactions can be provided by the heat generated by those exothermic partial oxidation reactions (Xu, Q., 2013). In terms of reactant gas, in pyrolysis no gas is used; in combustion (oxidation), air/oxygen is used as an oxidant in an amount larger than that required by stoichiometry of combustion; in gasification (reduction), air, pure oxygen, steam or their combinations are used as an oxidant in an amount lower than that required by stoichiometry of combustion. In fact in a gasification process, combustion reactions are efficient as the oxidant is supplied in a limited amount and adequately distributed within the gasifier creating a better

contact with reactant gases. Pyrolysis employs temperatures between 500 and 800 °C, combustion between 850-1200 °C while gasification, depending on feed stock and gasifying agent, employs temperatures between 550-900 °C with air-gasification, 1000-1600 °C with other gasification agents (Abrar, et al., 2010; Marcin, et al., 2011; Sharmina, et al., 2013; Reem, et al., 2014; Sharmina, et al., 2014). Regarding char production, pyrolysis process produces more char than what gasification process does. In the latter process, only nearly 10% from the total products is char (Kezhen, et al., 2013). They all employ atmospheric pressure, although pyrolysis may employ higher pressure. In a study by Marcin and his co-workers (Marcin, et al., 2011) higher pressures were suggested for better gasification results. Initially, with pressurized gasification conditions volumetric gas flow rate can be reduced for which a smaller gasifier as well as compact cleaning equipment can be used (Higman and Burgt, 2003). Also, better reaction rates and higher methane yield while lower tar yield can be achieved at pressurized conditions. Having said this; however, it should also be mentioned that design and operation of a gasifier at pressurized conditions require some additional precautions (Marcin, et al., 2011). In terms of chemicals synthesis and energy generation, liquid products produced by pyrolysis process can be up-graded to a liquid fuel while gaseous products can be used as a fuel gas (Xu, Q., 2013). Heat generated out of a combustion process can be used to provide heat or generate electricity or both (co-generation of heat and electricity). Fuel gas generated from a gasification process can be used as a fuel gas or can be used to generate heat and/or electricity or to synthesize chemicals, provided that it has be adequately cooled and cleaned. It should be noted that pyrolysis, combustion and gasification all generate pollutants of particulates and compounds of chloride, nitrogen and sulfur. In addition to these pollutants tars are also generated by both pyrolysis and gasification processes; combustion products are; however, free from tars. As a result of these pollutants out of pyrolysis, combustion and gasification processes cleaning is usually required.

**Table 3:** Main Characteristics of the Three Thermo- chemical Fuel Conversion Processes, Modified from (Arena and Mastellone, 2009) and (Marcin et al., 2011)

<i>Process</i>	<i>Pyrolysis</i>	<i>Combustion</i>	<i>Gasification</i>
Main products	oil, tar (liquid/vapour), CO <sub>2</sub> ,H <sub>2</sub> O, combustible gas(es) as: CO,H <sub>2</sub> , CH <sub>4</sub> and char.	heat, flue gas and gases as: CO <sub>2</sub> , H <sub>2</sub> O, N <sub>2</sub> .	gases as: CO <sub>2</sub> , H <sub>2</sub> O and N <sub>2</sub> ) in case air was the gasifying agent), heat, tar and combustible gas(es) as: CO, H <sub>2</sub> and CH <sub>4</sub> .
Heat supply	allo-thermal.	exothermal.	allo/auto-thermal.
Carbon conversion, %	≈75.	>99.	80-95.
Oxygen stoichiometry	Nil.	>1, typically 1.3 for solid fuels.	0-1, typically 0.2-0.4.
Chemical reactivity of main product	reactive, combustible.	non-reactive.	stable, combustible.
Physical existence	solid, liquid and gas.	gas.	gas.
High heating value (HHV), MJ/kg	16-19.	Nil.	5-20.
Oxidant	none.	air.	air, pure oxygen, steam or their combinations.
Operating temperature, °C	500-800.	850-1200.	550-900 with air gasification. 1000-1600 with other gasifying agents.
Operating pressure	higher than or atmospheric.	atmospheric.	atmospheric.
Pollutants	particulates, tars and compounds of chloride, nitrogen and sulfur.	particulates and compounds of chloride, nitrogen and sulfur.	particulates, tars and compounds of chloride, nitrogen and sulfur.

Simultaneously considering gasification and combustion processes, several features could be identified. Initially, in a gasification process it is aimed to produce a gas, syn gas, which can be considered to be an intermediate outcome of the process. Provided that it has been adequately treated, this syn gas can; then, be passed to a heat or power generation appliance or a combined one (cogeneration of heat and power) in which it is combusted, a unit for poly-generation of a range of chemical(s) such as: steam, sulfur, methanol, ammonia, etc. (Edward, et al., 2007) or to a unit of fuel production, e.g. hydrogen (the primary emphasis in biomass gasification (Marban, G. and T. Vald'es-Solis, 2007, Wu, H., 2013;)) or gasoline, etc. through Fischer-Tropsch reactions) (Huang, et al., 2012; Nguyen, et al., 2012; Yin, et al., 2012). In a classical combustion process; however, the merely aim is to have the concerning feedstock of solid waste (e.g. biomass) combusted although it is also possible to generate heat and steam by which heat and/or electricity can be generated via a steam turbine or via a gas turbine, respectively (Marcin et al., 2011). It is; then, obvious that gas of gasification, being a gaseous material in nature, can be transported, stored and controlled much simpler than a solid waste of any nature (Devi et al., 2003; Erich, E, 2007; Ajay, et al., 2009; Ajay, et al., 2010). It is also for this reason a small gasifier with an economical feasibility can be built but not a small combustion unit (Consonni and Vigano, 2010). In case gasification process is carried out with air as a gasifying agent, required temperature for gasification reactions may be lower than that employed in a combustion process, refer to Table (3). In fact, this might inhibit gasifier's bed agglomeration, fouling and slagging and also volatilization of alkali compounds which can be promoted by a higher temperature (Paula, et al., 2012). Also, heat loss in gasification is lower while energy production rates are better compared to those encountered and obtained from combustion, respectively (Lisy, et al., 2009). A comparison of the solid fuel combustion and gasification processes in terms of overall conversion efficiency and heat loss was made by Marcin, and his colleagues, for whom the reader is directed (Marcin, et al., 2011). Although both gasification and combustion processes *do* generate pollutants, amount and nature of these pollutants may be lower while simpler in the former process than in the latter one (Consonni and Vigano, 2010), perhaps due to the predominant reducing atmosphere imposed in gasification process (Consonni and Vigano, 2010). In combustion; however, synergic action of high temperatures and excess air required for combustion reactions results in an increased amount of emissions (Ajay, et al., 2009 ;). For further distinctive features of both gasification and combustion processes including main reactions, the reader is directed to a study made by Ronald, W. (Ronald, W., 2010).

## 4.2 Gasification

Gasification is a thermo-chemical process in which a solid waste is converted into a fuel generally known as producer or synthetic (syn) gas. The conversion process is aid by indirect combustion (thermo), in which oxidation is partial, as well as by a series of chemical reactions (chemical). The oxidant/oxidation medium, which is

synonymously termed gasification agent, is allowed to the gasification system in an amount less than that obliged by the stoichiometry of combustion reactions. Required heat can be self-supplied internally or can be provided from an external source. Internal heat (auto-thermal) required for gasification process can be facilitated through the heat generated by partly combusting the waste (fuel) undergoing gasification. An example of auto-thermal gasification is air gasification. In a gasification system operated in an auto-thermal approach, heat required for tars thermal cracking and for devolatilized solid char gasification is internally supplied as a result of those exothermic partial oxidation reactions. With this approach it is also possible to maintain isothermal operation of the gasifier. When heat is granted via an external source, gasification is known as allo-thermal, e.g. plasma torch gasification. Heat can also be supplied by using a hot-bed material or by combusting a quantity of the chars or gases separately. In either scenario, produced syn gas is different than the hot flue gas, that has no residual heating value (Higman and Burgt, 2003), usually obtained via usual direct combustion. It is a hot fuel gas rich with products that have been partly oxidized and thus far possess a calorific value. This calorific value is what, partly, grants a value to the produced syn gas to be mainly exploited for heat/power generation. Products of syn gas originate from the organic matter of the gasified waste and mainly may include carbon monoxide, hydrogen and some methane. Carbon monoxide and hydrogen in a syn gas also grant a value to syn gas as being raw materials for the production of some chemicals and fuels (Heermann et al., 2001; E4tech, 2009; Stantec, 2010; Young, 2010). In fact, syn gas obtained through gasification, compared to conventional combustion, can be used for multiple applications. Of these are: combustion in a burner for heating purposes, power generation through a steam turbine or also power generation through a gas engine, a gas turbine or a steam turbine (Hanaoka, et al., 2010). Advantages and disadvantages of each appliance of these appliances along the level of syn gas cleaning required for each appliance were discussed by Arena and Mastellone (2009) and also by Arena and others (2011) (Arena and Mastellone, 2009; Arena et al., 2011). This wide spectrum of applications of syn gas obtained via gasification may return to the diversity of its composition as a result of wide range of operating conditions of temperature, equivalence ratio (ER) and/or steam to biomass ratio (SBR), in case steam has been used as a gasifying agent, etc., possible to manipulate in a gasification process. The wide range of available reactors for gasification process can also contribute towards alteration(s) of syn gas composition. Different reactors produce a syn gas of different compositions owing to their configurations, internal details and capacities, etc. In addition to carbon monoxide, hydrogen and some methane, a syn gas may also carry some contaminants such as alkali, nitrogen and sulfur compounds, tar, particulates/dust and trace of chlorine (Heermann et al., 2001; Knoef, H., 2005).

The main emphasis in biomass gasification is the production of hydrogen. Considering current energy resources and those ones under scrutiny, hydrogen can be a successful candidate as an energy carrier for a cleaner future. Hydrogen can be generated by a number of processes such as: pyrolysis (Abrar, et al., 2010), electrolysis thermolysis, combustion and gasification (Sandi, et al., 2001), based on several feed stocks

such as: water, fossil fuels and various types of biomass, etc. (Sandi, et al., 2001). A common feature of these feed stocks is that they all contain a hydrogen source. This is required since hydrogen is not a naturally generated species; hence, it has to be generated from a hydrogen-containing stock (Luis, 2007). Among these processes and feed stocks, gasification has been reported to be the most efficient and economical choice for hydrogen generation (Abrar, et al., 2010; Wu, H., 2013) and biomass as the most beneficial fuel for hydrogen generation (Shanmughom, et al., 2014), respectively. Upon combustion, energy released by hydrogen exceeds the energy that may be released by any other fuel (Marban, G. and T. Vald'es-Solis, 2007). Since the main emphasis in biomass gasification is the production of hydrogen, those factors that may affect gasification can be related to the yield and quality of hydrogen from a gasification process, e.g. feed stock composition, biomass moisture content, type of gasifier used and gasification agent and its amount, etc. If hydrogen is sufficiently available, its utilization as an energy carrier, either as a fuel for transportation, fuel for power generation or for industrial applications, does not create those problems usually caused by combustion of fossil fuels related to global warming and its emissions (Woodrow and Clark, 2006; Shanmughom, et al., 2014).

Due to advantages of gasification technology over other thermo-chemical and non-thermo-chemical processes, gasification technology has seen increased applications in terms of waste management for the purpose of heat or power production. Variety of feed stocks available for gasification technology is tremendous. Dairy manure (Wu, H., 2013), densified sludge and wastepaper (George, et al., 1995), oil palm fronds (Samson, et al., 2014), spent poultry litter, municipal solid wastes (MSWs), green waste, wood waste and coffee beans husks (Sharmina, et al., 2013), solid waste (Sharmina, et al., 2014), corn stover and distillers grains (Ajay, et al., 2010), wood (FAO forestry paper, 1986), combined biomass and coal (Xu, Q., 2013), coal (Ihsan, 2012), sewage sludge (Dogru, et al., 2002; Calvo, et al., 2013), crop straw (grains, oil-bearing crops, cotton, hemp and sugar crops) (Zhengfeng, et al., 2014), sugarcane bagasse (Anthony, et al., 2014), agricultural residues, forestry residues, wood, animal manures, switch grass, sorghum and red cedar (Kezhen, et al., 2013), bamboo (Thanasit, et al., 2013), algae (Muhammad, et al., 2014), cashew nut shell char (Venkata, et al., 2008) and equally important refinery sludge (Reem, et al., 2014), etc. One can observe that such feed stocks are all waste of low-value but massive in amount. Furthermore, if improperly dealt with it can create a burden to the environment. In fact, via gasification such feed stocks can be turned into useful product such as heat, electricity or both heat and electricity as well as into a transportation fuel. It is not out of the ordinary such various biomasses hold different physical, chemical and/or morphological properties. To this end, different biomasses may demand different gasification processes and arrangements. By way of example, not exhaustive enumeration, several gasification investigations of several different feed stocks have been carried out. Young and Pian (2003), examined the possibility of incorporating an advanced gasifier to

enhance the operation of a dairy farm for the purpose of power production based on biomass conversion (Young and Pian, 2003). Priyadarsan and his co-workers studied the gasification of feedlot manure and poultry litter biomass in a fixed bed gasifier (Priyadarsan et al., 2004). Adiabatic fixed bed gasification of dairy biomass waste using steam and air as a gasification agent was also carried out by Gordillo and Annamalai (2010) (Gordillo and Annamalai, 2010). Wu, H. (2013) has studied the gasification of dairy manure and feedlot manure biomasses. It should be emphasized that properties of each feed stock of these may vary which in turn may lead to the production of different products including chars subsequent to a gasification process (Kezhen, et al., 2013). Advantages of gasification technology include: i- adaptability of most gasifiers to most wastes in terms of size, shape and physical characteristics. Corn stover, municipal solid waste, sawdust, soybeans and wood, etc. are all common feed stocks for biomass gasification of which their particles sizes as well as their other physical characteristics are not necessarily uniform. ii- shorter conversion time of the processed feedstock into a fuel than anaerobic digestion, iii- energy efficiency obtained via gasification process is much higher than those obtained via pyrolysis or combustion processes (Faaij et al., 1997; Stiegel and Maxwell, 2001; Ajay, et al., 2009; Rentizelas et al., 2009; Xu, Q., 2013). A reason of high efficiency in gasification process is that combustion step is performed through several stages not in one single stage as the case with combustion process (Ihsan, 2012). Also, use of such advanced technologies such as fuel cells and turbines to process the syn gas obtained from a gasification process can also increase the energy efficiency (Sipilä, K., 1993), iv- in addition to the great variety of feed stocks available for gasification, syn gas of gasification can also be employed for a number of important practical applications including: heat and/or power generation or both (combined heat and power, CHP) and synthesis of some chemicals. Synthesis of chemicals based on gasification's syn gas is based on the content of syn gas of gases such as CO and H<sub>2</sub> (C1 chemistry). Such chemicals include: ammonia, urea, resins, methanol, acetic acid, formaldehyde, oxo-alcohols, etc. (Higman and Burgt, 2003), v- furthermore, according to end-line application(s), composition of gasification syn gas can also be controlled through changing operating condition(s), gasification agent, etc. (Xu, Q., 2013), vi- destruction of pathogens and pharmaceutically active compounds due to high temperatures employed and vii- low to zero fugitive gas emissions, that's environmentally friendly (Rajvanshi, 1986; Cantrell et al., 2007; Whitty and Zhang, 2008; Ajay, et al., 2009; Wang, 2013; Wu, H., 2013). One reason of low emissions in gasification process is that combustion step is performed through several stages not in one single stage as the case with combustion process (Ihsan, 2012). Although, out of gasification process there is an amount of CO<sub>2</sub> emissions may be emitted to the atmosphere, theoretically; however, this amount is equal to the amount of CO<sub>2</sub> that was required for biomass growth prior to the gasification process. To this end, throughout carbon cycle on the earth, it can be inferred that there will be no additional CO<sub>2</sub> emissions to the atmosphere (Jingjing, et al., 2001, Panigrahi et al., 2003, L. et al., 2007, Ajay, et al., 2010; Sharmina, et al., 2013). Also, emissions of NO<sub>x</sub> and SO<sub>x</sub> out of a gasification (a reduced-oxygen environment) process are much lower than those released from burning of a fossil fuel

through a combustion process (Boyel, 2004; Jorge, et al., 2008). Once a biomass, that's a solid phase, has undergone a gasification process, it is; virtually has been converted and; of-course, so its constituents (nitrogen and sulfur containing compounds, etc.) into the gas phase in full with the exception of some solid residues, perhaps. Such a phase conversion renders separation of whatever undesired constituent(s), that's in the gaseous phase, an easier task (Rezaian and Cheremisnoff, 2005). Consequently, formation of their corresponding NO<sub>x</sub> and SO<sub>x</sub> during the combustion step through gasification can be avoided or at least minimized; hence, reducing the amount of those dangerous emissions in the environment (Ajay, et al., 2010).

## 5. Conclusions

Dependence on traditional, limited and environmental-harmful fossil fuels to generate electricity should be diminished. Biomass could be an alternative to such fossil fuels to generate electricity, although via different routes, e.g. incineration, pyrolysis, combustion. In terms of hydrogen production, biomass is a good candidate for gasification process in comparison to incineration, pyrolysis, combustion processes. Biomass exploitation for the purpose of power generation; nevertheless, has not been enough as it should. Gasification-based syn gas can be used for several applications such as: combustion in a burner for heating purposes, power generation through a steam turbine or also power generation through a gas engine, a gas turbine or a steam turbine. Versatility of products obtained via gasification process is also another advantage of gasification process over combustion process.

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