A Comprehensive Review of Biomass Gasification Process

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Abstract

The gasification process can be considered as one of the greatest conservative techniques in the transformation of biomass because of certain crucial factors such as the consideration of space, reduction of substantial waste volume, flexibility of fuel used, as well as the recovery of energy. The general process of gasification inclines to involve the incomplete burning of the carbon-based part of fossil fuels, which forms an abundant flammable gas in the presence of hydrogen, carbon monoxide and methane or some saturated hydrocarbon gases. When we consider the process of gasification, the parameters deemed to affect its performance, including the type of catalyst used, gasifying agents, biomass ratio and temperatures, as well as the type of raw materials. The primary purpose of this paper is to address the gasification process, including the types of gasifier designs like the fluidized bed, downdrafts, and updrafts. It's also responsible for addressing the production of tar from the process of gasification. The paper explores and discusses all the primary, secondary and tertiary types of tar.

*Keywords***:** Biomass, Sawdust, Gasification, hydrogen production and Renewable Energy

1. Introduction

Gasification is a thermochemical process occurs at a high temperature usually more than 700°C to convert carbonaceous materials including fossil fuels, biomass, plastics, and coal into syngas (H_2, CH_4, CO, and CO_2). The oxygen (air) and/or steam is used as a gasifying agent and heat carrier agent. The syngas can be burnt directly to produce heat at higher temperatures. The syngas can be cleaned and employed throughout different pathways to yield useful outputs including that:

1. Production of methanol,
2. Purified syngas used in the gas engine, gas turbines, fuel cells to generate electrical energy,
3. Methane through Sabatier reaction,
4. Production of dimethyl by methanol dehydration,
5. Production of hydrogen, and
6. Manufacture of fuels like diesel and gasoline fuels [1].

The literature involves six parts: fluidized bed, an overview of biomass used in gasification, tar reduction, gasification agent and influence of gasifier operating conditions. Particular attention is paid to literature regarding in tar formation, reduction and enhancing of operational conditions during biomass gasification.

2. Fluidized Bed Gasifier

In the gasification process, the biomass is heated to a higher temperature producing chemical and physical changes resulting from volatile products and solid carbonaceous residues. The amount of volatile products depends on the heating rate, the temperature height and the type of biomass. The char gasification stage is the rate-limiting factor in the gasification of harvest residues. The composition of the produced syngas depends on the degree of equilibrium attained by various gas phase reactions [1, 2]. In the absence of a catalyst, char gasification with reactive gases such as oxygen occurs at higher temperatures. When char is gasified in the presence of the steam, the gas produced is composed mainly of CO, CO_2, H_2 and CH_4 gases. In reactor operating at lower temperatures, low heating rates and very high-pressure secondary reactions are very significant. At low pressure, high temperature and high heating rates most of the volatile products

escape from the biomass particle during the pyrolysis process. In fluidized bed gasifiers, the secondary reactions in the gas-solid and gas phase take place. The biomass gasification process is considered to be occurring in four stages: drying of the feedstock pyrolysis, gasification of the char with reactive gases such as O_2, H_2, H_2O and secondary reactions of primary gasses and tars [3]. The advantages of the fluidized bed reactors are good gas-solid contact, better temperature control, good heat transfer characteristics, and high volumetric capacity. The temperature can be controlled by both varying the feed rate or the agent rate. Low operating temperature leads to produced more slag and clinker. Fluidized bed reactors have wider adaptability to handle different types of fuel. The tar contents of the syngas gas are less than that in the syngas obtained in the updraft. The desirable features of the fluidized bed gasifiers make it more appropriate for large scale operation than downdraft gasifier [3, 5]. Gasification in fluidized beds is shown in Fig.1.

Gas

Pyrolisis

Oxidation

Reduction

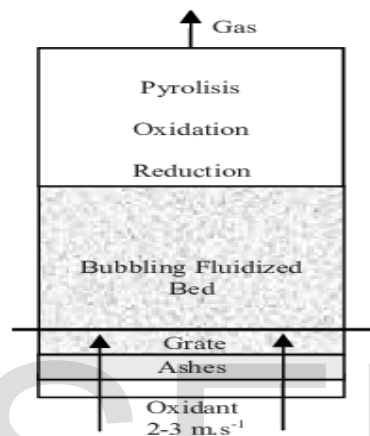Bubbling Fluidized Bed

Grate

Ashes

Oxidant
2-3 m.s⁻¹

Fig.1. Gasification in Fluidized Beds [4].

The disadvantages of the fluidized reactors are a significant pressure drop and corrosion of the reactor body. Fluidized bed reactors operate at pressures little above atmospheric, so should be designed to prevent leakage. The fluidized bed gasifier has higher tar content of the product gas [6]. Fluidized bed gasification has been widely used for coal gasification for many years. The uniformity of the temperature is obtained using a bed of fin material into which air is introduced. Fluidized bed gasifiers can be classified on the basis of their configuration and the gasifying agent velocity into bubbling fluidized bed, circulating fluidized bed and spouted fluidized bed.

2.1 Fluidization Velocity

The flow rate of oxidizing agent supplied to the fluidized-bed gasifier is a crucial parameter to maintain effective fluidization of bed materials. The fluidization is described using a superficial gas velocity which is the ratio of volumetric gas flow rate and bed cross-sectional area. If the drag force on the bed materials equals the gravitational force and this called the minimum fluidization velocity of the bed materials. At minimum fluidization condition, the bed materials lift upward and remain in suspension; bed pressure drop reaches to a maximum and remains constant with further increase in the superficial gas velocity. Fluidization characteristics depend upon the particle size and composition of the bed materials [7]. Segregation is a process which a bed material with higher particle density such as sand moves downwards in the bed while a material with lower particle density such as biomass floats upwards [8, 9]. This causes separation of biomass from sand and results in a localized accumulation of biomass particles as smaller and/or bigger sized lumps throughout the bed. These lumps further lead to channel formation, called in bed channelization that gives rise to larger void space and a shorter path to the gas flow [10]. The gas easily escapes

through in bed channels, which affect bubble formation, and thus turbulence level in the bed resulting in ineffective fluidization. Segregation occurs due to differences in densities or sizes of the bed materials such as sand and biomass [11, 12]. When a packed bed of particles is subjected to a sufficient high upward flow of fluid, the weight of the particles is supported by the drag force exerted by the fluid on the particles and the particles become freely suspended or fluidized. The behavior of fluidized suspension is similar in many aspects to pure liquid. Mass and heat transfer rates between particles and submerged objects (e.g., heat exchanger tubes) are greatly enhanced in fluidized beds to avoid or reduce carryover of particles form. Rapid particle mixing allows uniformity in bed. The fluidized bed is widely used for conducting gas-solid reactions (coal combustion) and gas-solid catalytic reactions (catalytic cracking of petroleum) [12]. The quantity of biomass in the mixture plays a crucial role in the segregation behavior of bed materials. The bed consisting of a material such as particulate matters which has adhesive or cohesive properties may enhance segregation tendency and suppress fluidization [13]. Chok et al. [14] indicated improved mixing with a decrease in the particle size ratio from 30 to 20 of palm shell and sand mixture. The segregation and channelization were predominant at higher particle size ratio, and biomass weight fraction (10% and 15%) in the mixture [15]. These methods are derived from the pressure drop method, dimensional analysis, drag force method, and terminal velocity method. At the onset fluidization, drag force by upward moving gas on the whole system of particles must be equal to the weight of particles of the bed. The range of fluidizing velocity should be within the minimum fluidization and terminal velocities of the mean bed particles. Figure 2 shows the fluidization characteristics of sand.
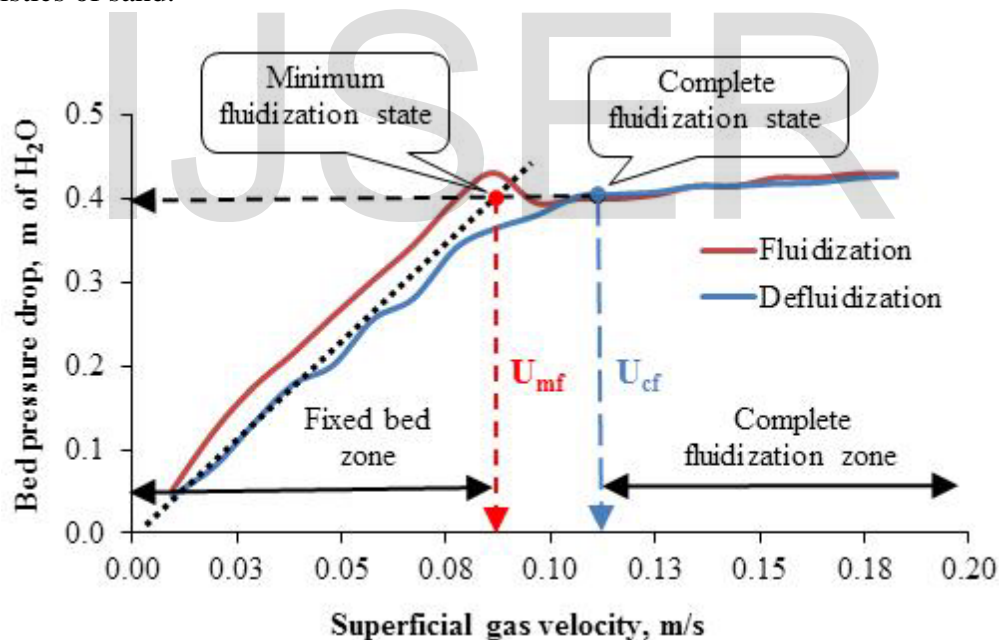

Fig.2. Fluidization characteristics of sand.

2.2 Types of Fluidized Bed Gasifier
2.2.1 Bubbling Fluidized Bed Gasifier

The bed is termed as bubbling fluidized bed when granular material is lifted in a reactor through which an upward flow of gas is passing through it at a flow rate where the pressure drop across the particles is enough to support their weight. Low fluidization velocity just above the minimum agent velocity passes through the bed in the form of bubbles. Bubbling bed gasifiers consist of a vessel with a distributor plate at the bottom through which the air is introduced. The

moving bed of fine-grained material into which the prepared biomass comes in. The setting of the bed temperature to 600-1000°C is maintained by controlling the equivalence ratio. The biomass is pyrolyzed in the hotbed to char form and gaseous compounds, the high weighted compounds being cracked by contact with the hotbed materials, giving a product gas with low tar content. The bubbling bed gasifiers can be classified according to the number of the bed, such as a single fluidized bed and multi fluidized bed [16].

2.2.2 Single Fluidized Bed Gasifiers

This system consists of one bed, into which the feedstock and the gasifying agent enters and the produced syngas and char exit. The advantage of this gasifier is lower operating and initial cost compared to multi-bed, less maintenance, and maintenance cost. The disadvantages of single bed as syngas heating value is lower than that produced by the dual bed; pyrolysis process occurs in the combustion zone at the bottom of the gasifier which leads to non-uniform temperature distribution and the separation of the inorganic materials in the feedstock is hopeless. Figures 3 and 4 show the bubbling fluidized bed and single fluidized bed gasifiers [17, 18]
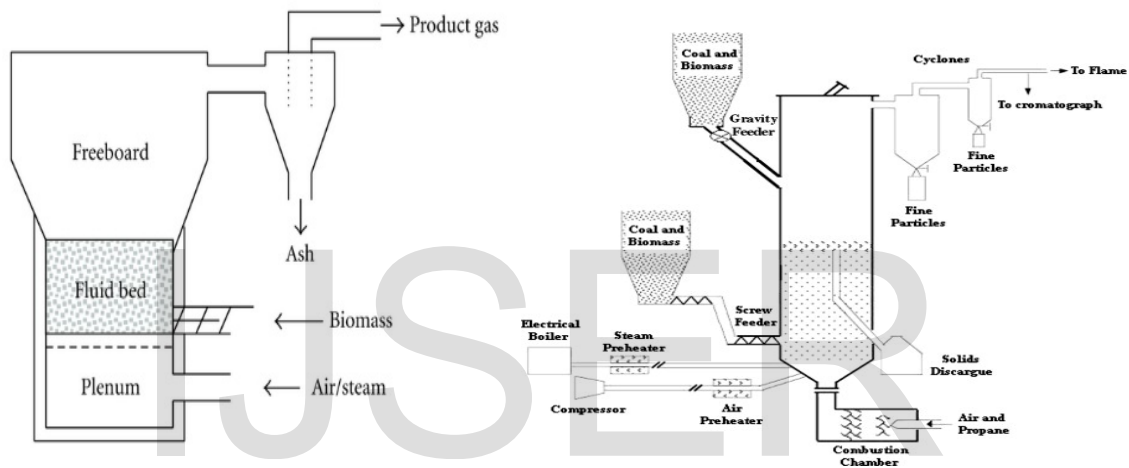

Fig.3. Bubbling fluidized bed gasifier [17].   Fig.4.Single fluidized bed gasifiers [18].

2.2.3 Dual and Multi-Fluidized Bed Gasifiers

These gasifiers consist of more than one bed commonly first bed used to burn some of the char to produce the energy for the second bed in which the pyrolysis process occurs. The syngas heating value more significant than that produced by the single bed due to the combustion of the char occurs in a separate reactor. The combustion syngas does not dilute the pyrolysis gases and separation of the inorganic material in the feed is possible. The disadvantages are higher construction cost and more maintenance requirement as compared to the single bed. Keiich Tomishige et al. [6] studied the gasification of the biomass by using the single bed and dual bed gasifier. The dual bed gasifier combined with a suitable catalyst, the tar can be converted to syngas at a lower temperature than that needed by the traditional methods with high energy efficiency. Figure 5 shows the dual fluidized bed gasifiers [19].
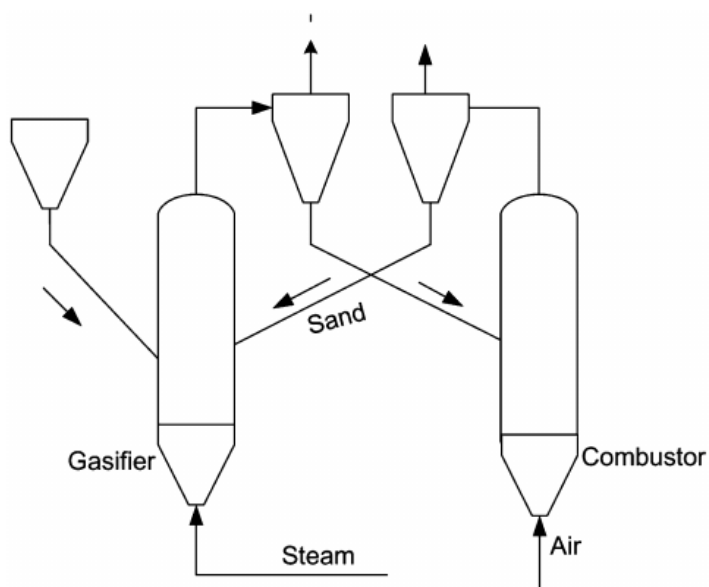
Fig. 5. Dual fluidized bed gasifiers [19].

2.2.4 Circulating Fluidized Bed Gasifiers

If the gas velocity in a bubbling bed is increased, more particles will be entrained in the syngas stream and leave the gasifier. The transport velocity of the particle is reached, and the vessel can be quickly empty of the solid except new particles. The particles leaving the vessel are returned through an outer collection system. The circulating fluidized bed has higher processing capacity compared to the conventional gasifiers, better gas-solid contact and the ability to handle coherent solids is difficult to fluidize in a bubbling bed. The circulating fluidized bed gasifiers are yet less conventional than the bubbling ones because of their height which restricts their application in terms of cost analysis [20]. Figure 6 shows the circulating fluidized bed gasifiers.
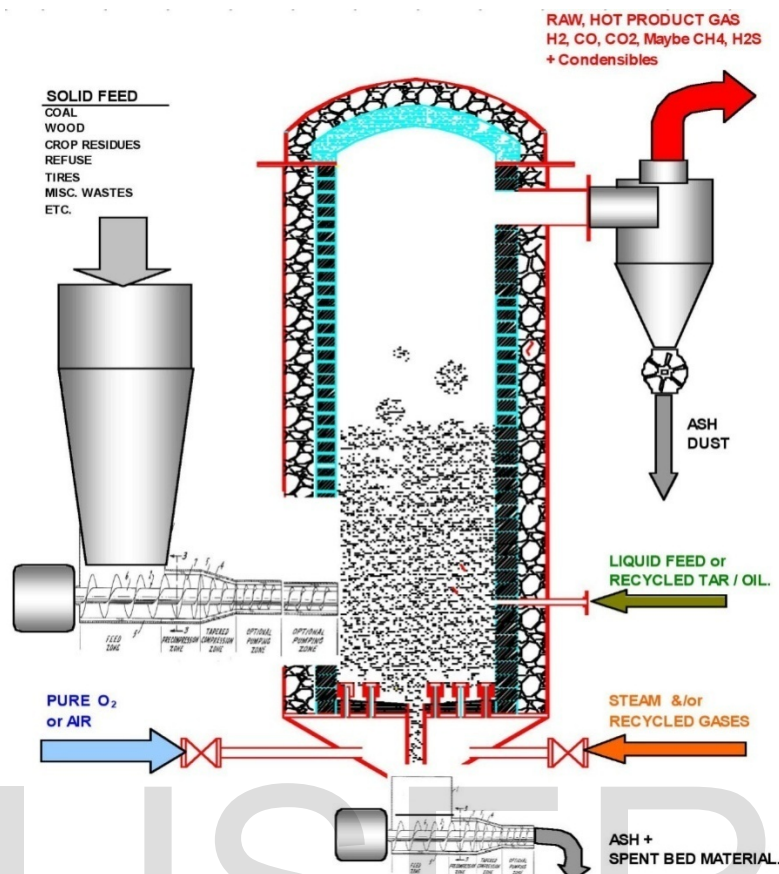
Fig.6.Circulating fluidized bed gasifiers [21].

2.2.5 Spouted Bed Gasifier

A spouted fluidized bed gasifier consists of a bed of a thick particle partially filling the reactor which is provided with a relatively large control opening at its base. Gas is injected through this aperture. The particle in the gas can be made to rise in a jet at the center of the bed and develop periodic motion on the bed as a whole. The bed motion can be assisted by the extra air at the base to produce a spouted bed. Spouted bed gasifiers have been used to gasify the coal of various ranks. Abdul Salam [22] has studied the gasification of biomass in a spouted bed, which has specific possible advantages over the fluid bed configurations. The gasification efficiency of the circular slit spouted bed was slightly high compared with that of central jet spouted at higher agent velocity. Figure 6 shows the spouted bed gasifier. Figure 7 shows the spouted bed gasifier.
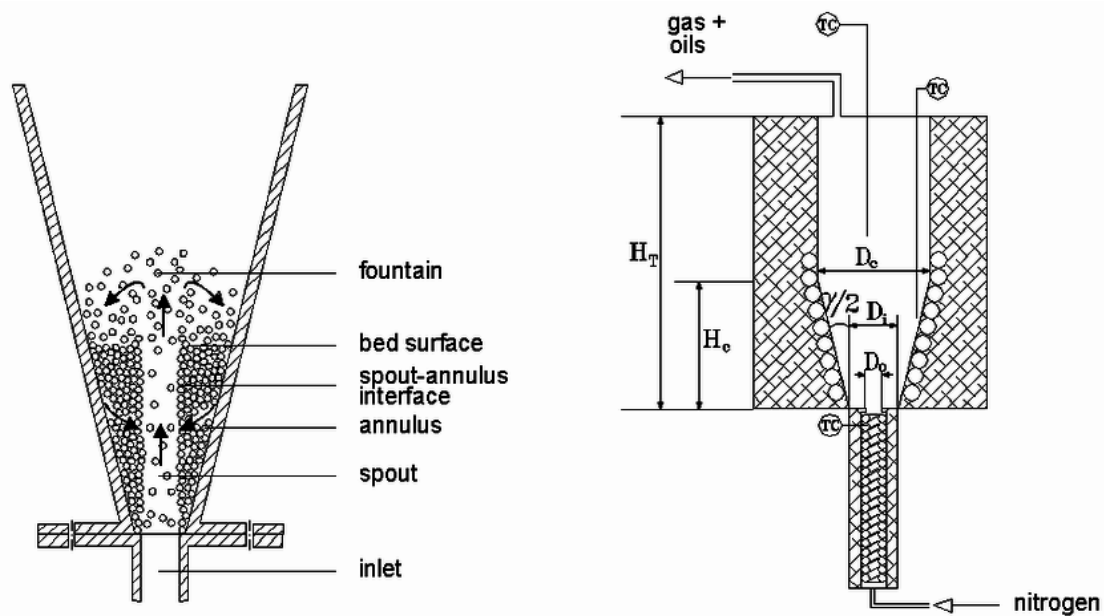
Fig.7.Spouted bed gasifier [23].

3. Overview of Biomass Used in Gasification

3.1. Crop Residues Gasification

Chen et al. [41] perform the gasification of biomass blends in a bench scale fluidized bed gasifier at atmospheric pressure. Two types of blends were prepared, which mixing of pine chips with low-grade black coal and Sabero coal. The experiments were conducted using gasification agent as mixtures of air and steam at gasification at temperatures of 840°C-910°C and fluidized gas velocities of 0.7-1.4 m/s. The lending effectively improved the performance of fluidized bed gasification of the low-grade coal and the possibility of converting the refuse coal to a low heating value syngas. The blend ratio with no less than 20% chip pellets for the low-grade coal and 40% chip pellets for the refuse coal are the most suitable. The dry product gas with low heating value increases with increasing blend ratio from 3.7 to 4.5 MJ/Nm^3 for chip pellets /low-grade coal and from 4.0 to 4.7 MJ/Nm^3 for chip pellets/refuse coal. The syngas yield increases with the increase of the blend ratio from 1.80 to 3.20 Nm^3/kg (chip pellets /low-grade coal), and from 0.75 to 1.75 Nm^3/kg (chip pellets /refuse coal), respectively.

The pyrolysis of crop residues improved the utilization of energy obtained from biomass. Xinyan et al. [25] studied the effect of temperature on the physicochemical properties of biochar and gas produced from the pyrolysis of different crop residues. The temperature at a range of 300°C-600°C has significant on the biochar and gas yield. Bio-char yield decreased while gas yield was increased significantly. Temperature increase has an effect on response variables. CO_2, CO, carbon, and energy conversion efficiencies of bio-chars decrease with increase in temperature while CH_4, H_2, C_nH_m, and higher heating values increase with temperature [25]. The solar-driven thermochemical conversion of crop residues is more efficient that auto-thermal gasification process [26]. Müllera et al. (2017) reported that solar-to-fuel energy conversion efficiency reached 18% while the feedstock heating value was upgraded by 7% using solar energy. In their experiment carried out on waste biomass feedstock consisting of unprocessed batches of soybean husk, cotton boll, black mustard husk, and straw at a temperature range of 879–1266 °C, the syngas produced has high quality with ratios of CO_2/CO = 0.28-1.40, H_2/CO =1.43-3.25 and CH_4/CO = 0.03-0.28

[26]. Yarima et al. [27] performed a thermochemical assessment on herbaceous biomass crops as fuels for energy recovery through the gasification process. The gasification process carried out under the operating condition of 770-820°C, the equivalence ratio of 0.15-0.20 and oxygen content of 21 and 27% produced gas with calorific values ranging between 3.5 and 5 MJ/Nm^3 [27].

3.2 Straw Gasification

Sadaka et al. [28] develop a fluidized bed gasifier to gasify wheat straw in an air/steam mixture as an agent. The performance of the fluidized bed gasifier (gasifier temperature, pressure drop, heating value, and syngas flow rate) was influenced by fluidization velocity, steam (agent) flow rate, and biomass/ steam ratio. The temperature of the gasification bed reached its maximum at 891°C. The agglomeration problem was overcome by injecting more air/steam mixture. The heating value of the syngas yield and the syngas flow rate reached their maximum of 10.63 MJ/Nm^3 and 2.47 Nm^3/min, respectively. The bed pressure drop occurs ranged between 37.2 to 51.6 cmH$_2$O, gives a good fluidization quality. Risens et al. [29] studied the influence of calcium addition in straw gasification. The effect of calcium addition as calcium sugar/molasses solutions to straw significantly influenced the ash chemistry and the ash sintering tendency but much less the char reactivity. Walawender et al. [30] studied the straw gasification with steam as an agent in a 0.23 m diameter fluidized bed gasifier over a temperature range of 552 to 757°C. The fraction of the biomass was converted to syngas ranged from 32% at the temperature of 552°C to 73% at the temperature of 757°C. The heating value of the syngas appeared at parabolic variation with temperature with a maximum value of 12.3 MJ/Nm^3 obtained at 672°C. The co-gasification of thermally pre-treated wheat straw with Shengli lignite for hydrogen production was reported to produce the best result at 400 °C due to the high content of alkali metals and high surface area [31]. According to Xiaoqin et al. [31], the carbon conversion and (H$_2$+CO) yield increased by 18.32% and 3.95% respectively. The performance evaluation studying was performed on the co-gasification of wheat straw and bituminous coal in entrained flow gasification system to investigate the effect of gasification temperature from 1100 to 1400°C, oxygen/carbon ratio (0.35 to 0.65), and the biomass mixing ratio (0, 0.25, 0.5, 0.75, 1). The addition of wheat straw improved the gasification performance. The gasification reactivity index and operating temperature increase with the increase of the mass ratio of the wheat straw [33]. Zhiqiang et al. (2017) recorded a decrease in the CO$_2$ and CH$_4$ content with increased temperature while H$_2$ and CO$_2$ content, and cold gas efficiency increased. The operating temperature of 1300°C and equivalence ratio of 0.45 were observed to be the optimum operating conditions for the co-gasification of bituminous coal and wheat straw [33].

Gasification reactivity is an important factor to be considered during gasification of crop residues. Ruirui and Wei [32] investigated the kinetics characteristics of straw semi-char gasification with carbon dioxide to investigate the effects of gasification factors like pyrolysis temperature, biochar particle size, and pyrolysis atmosphere. The gasification reactivity of semi-chars increases with operating temperature until it reaches its maximum value at 400°C. The best gasification reactivity was observed with the straw semi-char produced from H$_2$ pyrolysis atmosphere while that obtained from CO$_2$ atmosphere has the worst reactivity [32].

3.3 Rice Husk Gasification

Bharatha et al. [34] studied the co-gasification of Indian rice husk and Indian coal with high-ash in bubbling fluidized bed gasification reactor under atmospheric pressure and 40 kW thermal condition. ,The addition of rice husk significantly improved the response variables of synthetic gas such as cold gas efficiency, total carbon conversion, and calorific value. At the range of 50-75% power contribution of the rice husk, the carbon conversion and cold gas efficiencies

were around 89% and 78%, respectively. The calorific value of the synthetic gas is around 5.4 MJ/m^3 [34]. Yin et al. [35] tested rice husk gasification in a circulating fluidized bed for biomass gasification and power generation system to provide power for a rice mill. The system consists of a circulating fluidized bed gasifier, a gas cleaner (including an inertial separator, a cyclone, filter, a venture, and two water scrubbers). The gasifier can be operated stably within the temperature range of 700°C to 850°C. The gasification of rice husk was studied by Chen and Rei [24] at a temperature range of 600°C to 700°C. They used electrical heaters to provide the heat required to gasification in a 0.05 m internal diameter fluidized bed reactor; the bed consisted of alumina sand and agent was superheated steam. The syngas yield increased from 0.38 to 0.55 m^3/kg and the heating value varied from 12.8 to 18.5 MJ/m^3. H_2, CH_4, CO and CO_2 concentrations in the syngas produced varied from 3.6 to 13.1%, from 14.4 to 13.5%, from 52.2 to 51.1% and from 23.0 to 14.6%, respectively [36]. The higher heating value was 5.19 MJ/N m^3 while the producer gas compositions, CO, CH_4, CO_2, H_2, and N_2 were 22%, 1.7%, 8%, 13%, and 40.1%, respectively. The analysis of torrified rice husk pellet in fluidized bed gasification performed by Kanit et al. [37], the overall exergy efficiencies of the torrified rice husk pellets at 250°C and 350°C are 30% and 21%, respectively.

3.4 Cotton Gin Trash Gasification

Alka et al. [38] reported that co-gasification of coal and biomass has higher efficiency than the solitary coal gasification due to that the cellulose, hemicellulose, and lignin contained in the biomass enhance gasification rate. The extensive research in the aspect carbon reactivity pattern, reaction kinetics, heat release may help to lower the uncertainties experienced the co-gasification performance of coal and biomass blends [38, 39]. The possible means of harnessing this waste include gasification, composting, anaerobic digestion, pyrolysis, fermentation, and direct incineration. Converting this cotton waste to energy using treatments methods like gasification, pyrolysis and anaerobic digestion is more feasible. Ihsan et al. (2016) reported that pyrolysis of cotton stalks seemed to be a good option because of its potential revenue of $104 million dollars. The use of cotton gin trash in the production of ethanol another competitive option as its average production is approximately 33-47 million liters for the whole industry in Australia. The revenue estimated to be obtained from this process is about 33-47 million $, literally $1/L. The potential amount of energy to be obtained from burning cotton stalks approximates to 24.8 PJ, which equals $97 million worth of coal [39].

Some agricultural waste as biomass samples such as rapeseed, cotton refuse, sunflower shell, pinecone, and olive refuse was the first pyrolysis in air. Their chars were gasified in a gas mixture of steam and air. Pyrolysis of the biomass samples was performed at a heating rate of 20 K/min from ambient to 1273 K in a dynamic air atmosphere of 40 cm^3/min. It was concluded that gasification characteristics of biomass chars were fairly dependent on the biomass properties such as ash and fixed carbon contents and the constituents present in the ash. Singh et al. [40] performed the steam gasification of cottonwood branches in a fluidized bed gasifier and compared the produced syngas characteristics with those for pure cellulose. The syngas heating value, the energy recovery, carbon conversion and mass yield of the syngas obtained from cottonwood were found to be lower than those obtained from pure cellulose. Groves et al. [41] studied the gasification of cotton gin trash in a fluidized bed with air over the temperatures range of 649°C and 87°C in a 0.3 m internal diameter gasifier. The syngas heating value and the energy recovery increased from 3.4 to 4.3 MJ/Nm^3 and from 27 to 53%, respectively. Non-woody biomass is an agricultural waste as it is abundant and cheap. The combination of non-woody biomass with a small amount of high-grade carbon from coal or bio-char for co-gasification can help in the improvement of fuel quality.

The combined interaction effect of non-woody biomass and coal in the co-gasification process reduces the rate of tar formation and increases mineral based catalytic reactions [42].

3.5 Corn Cobs Gasification

Krongkaew et al. [43] studied the gasification behavior of raw empty corn cobs and torrified empty corn cob. The producer gas obtained from raw empty corn cobs has higher compositions of H_2 (3.63-9.37 % vol.), CO (18.20-27.79 % vol.) and CH_4 (0.17-0.33 % vol.), and lower compositions of O_2, CO_2, and N_2 than the compositions obtained from torrified empty cobs (0.97 %vol. H_2, 5.72 %vol. CO and 0.03 %vol. CH_4). Due to the higher compositions of H_2, CO, and CH_4, the higher heating value of the producer gas from raw empty corn cobs is higher than that from torrified empty corn cobs. The heating values increased by 0.835 MJ/Nm^3 and 2.84-4.25 MJ/Nm^3 for raw and torrified empty corn cobs, respectively [43]. The cold gas efficiency increased in both methods but was higher in torrified empty cobs. The gasification of corncobs over a temperature range of 500°C to 1000°C was presented by Epstein et al. [44]. Produced syngas yield increased from 0.17 to 0.60 kg/kg. The syngas contains large amounts of CO and H_2 and the heating value varied from 1.4 to 10.9 MJ/m^3. In the comparative study of pyrolysis of agricultural biomass residues including wheat straw, corn cob, rice straw and rice husk carried out by Bijoy et al. [45]. The corn cob has the highest optimum temperature and maximum bio-oil yield of 47.3wt%.

3.6 Sawdust Gasification

Ming et al. [46] studied the gasification characteristics of sawdust char at a very high temperature (~1200°C) steam atmosphere. The rate of carbon conversion increased with steam flow rate, temperature, and reaction time. At a temperature range of 800-1200 °C, the compositions of H_2 and CO increased from 53.08% to 60.01%, and 15.35% to 21.87%, respectively. CH_4 and CO_2 percentage compositions decreased. The specific surface area of the sawdust ash produced increased to 948.84 m^2/g at 800°C and 987.61m^2/g at 1000°C, respectively [46]. Wander et al. [47] stated that the technology of wood gasification could produce qualified syngas of being combusted in an internal combustion engine, as long as it is appropriately cleaned enough from tar and ashes. The gasifier has an internal gas recirculation which can burn part of the syngas produced to raise the gasification reaction temperature. The syngas yields ranged from 1.1m^3/kg at 600°C to 1.3 m^3/kg at 800°C and the heating value was more than 11.2 MJ/Nm^3 for all temperatures [48]. CO and H_2 percentage composition of the product gas, and the carbon conversion rate increased with both increases in temperature and steam flow rate. The lower heating value of the product gas decrease until it attains its minimum value at 700°C. Xiaoyan et al. [49] studied the intrinsic kinetics of birch wood chars reaction with O_2 and CO_2.

3.7 Cellulose Material Gasification

The physicochemical properties and the gasification reactivity of co-pyrolysis char were investigated by Zhiqiang et al. [50]. The presence of cellulose helps to enhance the uniformity and order of micro-scale structure in both anthracite and bituminous char, but the improvement in pore structure was observed to be more pronounced in anthracite. Huanga et al. [51] studied the effect of torrefaction on high-temperature steam gasification of cellulose, using non-stoichiometric equilibrium model. A molar ratio of steam/cellulose less than 1.0 was recommended for both raw and torrefied celluloses as the H_2, and CO_2 ratio increased with steam/cellulose molar ratio. The molar number of H_2 was found to increase from 1.992 to 2.016 as the torrefaction temperature increased from 250 to 300 °C. Haimiao et al. [52] investigated the catalytic gasification characteristics of biomass components (cellulose, hemicellulose, and lignin), pine and straw in a small-scale entrained-flow gasifier using Na_2CO_3 and dolomite as catalysts. Both Na_2CO_3 and dolomite improved hemicellulose gasification by increasing the gasification efficiency, carbon

conversion and calorific value of gas. The tar yield was significantly reduced. The dolomite improved the gasification of straw, cellulose, lignin, and pine, while Na_2CO_3 inhibited the gasification process [52]. The components of biomass determine the type of catalyst to be used in gasification.

Walwender et al. [35] performed alpha cellulose gasification in a bench scale fluidized bed gasifier with steam as an agent within a temperature range of 600°C to 800°C. The significant components of the produced syngas were H_2, CO_2, CO and CH_4, and the volumetric syngas yields were 0.5-1.4m^3/kg, the average gas heating value was 11.8MJ/Nm^3. The energy recovery and carbon conversion were within the range of 32-90% range. Hoveland et al. [3] studied the steam gasification of alpha cellulose at higher temperatures and confirmed that proposed the existence of two temperature regimes for cellulose gasification, one below 567°C dominated by volatile cracking and the other above 567°C dominated by the water gas shift reaction.

3.8 Manure Gasification

Daniel et al. [53] analyzed the concentration of impurities in the product gas and gasification performance for the steam gasification of manure, wood pellets, and sewage sludge. The compositions of the producer gas did not diverge much, but there was a significant variation in the composition of product gas impurities (such as NH_3, C_1, tar, and H_2S) due to different sulfur, nitrogen and chlorine content of the fuels. Daniel et al. [53] deduced that the addition of limestone helps to reduce the amount of impurities in the product gas. Hussein et al. [54] reported that gas yield was higher at higher temperatures due to tar cracking, while CO_2 and steam as gasification agents produced the highest syngas. Air gasification produced the highest carbon conversion. The tar cracking enhances carbon conversion as cracking helps to break hydrocarbon bonds. Tanczuk et al. [55] carried out an experimental analysis on fixed bed gasification process of the mixtures of biomass and chicken manure. Two different cases of mixture of wood pellets and raw, pre-dried chicken manure, and blends of wood pellets and pelletized chicken manure showed that co-gasification of chicken manure and biomass is promising as the lower heating values obtained in the generated combustible syngas for both raw, pre-dried chicken manure and pelletized chicken manure are 2.0 MJ/m^3 and 2.7 MJ/m^3, respectively.

Sweeten et al. [56] reported that feedlot manure has approximately half the heating value of coal, twice the volatile matter of coal, four times the N content of coal on a heat basis. The ash content is roughly 9-10 times that of low ash (5%) coal due to soil pollution during collection. The addition of 5% biomass residues had a little apparent effect on heating value. The percentage of alkaline oxides is reduced in the ash, the increased total ash percentage results in an increase of total alkaline oxides per unit mass of fuel. Raman et al. [57] tested the gasification of feedlot manure with different fluidization velocities. The fluidization velocities did not have a significant influence on produced syngas yield, heating value or composition. Walawender and Fan [58] studied the feedlot manure gasification using air as agent found that the produced syngas yield, the energy recovery and the higher heating value increased by 131%, 244% and 77% when the temperature increased from 627 to 827°C. Halligan et al. [59] gasified feedlot manure in a 0.05 m internal diameter fluidized bed gasifier. The agent was a mixture of air and steam, and the bed consisted of the feed material only. Over the temperature range from 693°C to 796°C, the syngas yield flow rate increased from 0.6 to 1.3 m^3/kg, and the gas heating value increased from 8.7 to 9.8 MJ/Nm^3. The energy recovery and carbon conversion increased from 23 to 49% and from 20 to 50%, respectively.

4. Tar Reduction

Tar is one of the most complex compounds produced from biomass gasification, and its formation is strongly dependent on the operating conditions such as gasification temperature, the gasifying agent used and equivalence ratio. The tar reduction is necessary before the final use of the product syngas to avoid various problems related to tar condensation and formation of tar dust. Tar is defined as the organics produced under thermal or partial oxidation regimes of any organic material and generally assumed to be hugely aromatic [60]. Unanimity on the definition of tar was agreed by the European Committee for Standardization (CEN), and tar is defined as all organic compounds existing in the gasification product gases with molecular weight more than benzene [61, 62]. During the biomass gasification process, tar is generally formed in a series of complex reactions and its formation is strongly dependent on the process conditions. The tar formation layout proposed by Elliott and summarized by Milne [63], which shows the transition of tar as a function of process temperature from primary products to phenolic compounds to aromatic hydrocarbons. Evans and Milne [60] reported that the tar could be classified into four product classes which are identified as a result of gas-phase thermal cracking reactions:

1. Primary products which are characterized by cellulose-derived, hemicellulose-derived and lignin-derived products;
2. Secondary products are characterized by phenolics and olefins;
3. Alkyl tertiary products which are mainly methyl derivatives of aromatic compounds; and
4. Condensed tertiary products which are PAH series without a substituent.

The composition, quantity, and properties of tar in product syngas vary depending upon the biomass feedstock, gasification agent, gasifier type and gasification conditions. The type of gasifier is one of the essential parameters that influence the tar content. The downdraft fixed bed was the favored effective method in suppressing the formation of tar during biomass gasification. Boerrigter et al. [64] reported that the naphthalene concentration in product syngas should be less than 2 ppm to avoid condensation during the compression stroke before catalytic conversion for Fischer-Tropsch (FT) Diesel synthesis. Bui et al. [65] mentioned that the preferable tar and dust loads in syngas for engines must be lower than 10 mg/Nm^3.

Zia et al. [66] reported that its efficiency is 84.4±1.2% when compressed to 0.8 MPa and 83±1.1% when compressed to 0.2MPa at ambient temperature for compression mechanism in tar reduction as an efficient means of reducing tar yield in biomass gasification. Pallozzia et al. [67] studied the efficiency of combining gas conditioning and cleaning for reduction of tars in biomass gasification. The combined effect is more efficient with the efficiency level of 97% and product gas dew point temperature of 17°C compared to the 56°C dew point temperature. Pavleta et al. [68] reported that the addition of K_2CO_3 increased the activity of ash coated olivine that was used as a catalyst towards tar reduction. Devi et al. [69] reported that tar removal technologies could be divided into two types: primary methods and secondary methods. The primary method includes the proper selection of the operating conditions, the use of a suitable bed additive or a catalyst during gasification and a suitable gasifier design. Secondary methods consist of chemical (catalytic cracking) or physical (mechanical separation) treatment [70]. Corella et al. [71] found no significant difference in their influence concerning tar reduction. Sutton et al. [72] revealed that a reasonable blend of various essential and optional medications is probably going to enhance gasifier execution and created syngas with least tar focus [71]. Milne et al. [63] and Neeft et al. [73] reported that primary methods are gaining a lot of attention as they may eliminate or profoundly reduce the need for downstream cleanup.

4.1. Effect of Temperature on Tar Reduction

The temperature is one of the most critical factors affecting the overall biomass gasification process. Temperature can influence the amount of tar formed as well as the composition of tar. Kinoshita et al. [74] reported that the total number of detectable tar species produced from sawdust gasification decreased as well increasing of temperature. Lower temperatures favored the formation of more aromatic tar species with diversified substituent groups, while higher temperatures favored the formation of fewer aromatic tar species without substituent groups. Li et al. [75] reported that the amount of tar gain from biomass gasification strong decreased from 15 to 0.54 gram/Nm^3 as the average temperature increased from 700°C to 820°C. Van Paasen and Kiel [76] observed that tar concentration decreased with within temperature range from 750°C to 950°C at the same time the tar compositions shifted from alkyl substituted poly-aromatic hydrocarbons (PAHs) to non-substituted PAHs. The gasification temperature affects the formation and composition of tar. Kurkela et al. [77] and Simell and Leppälahti [78] studied the effects of operating conditions on the formation of tar produced from different feedstocks ranging from hard coals to wood gasification in a pressurized fluidized bed gasifier. The total tar concentration in the pressurized fluidized bed product syngas appears to depend mainly on the feedstock and on the gasification temperature. Michael and Holger [79] investigate the steam reforming of tar at pressures of 5 bar and temperature range of 600 -700°C. The model tar component of naphthalene was converted to CO and H_2 using steam out of the synthesized gasification gas. Although the nickel catalyst deactivates, a stable and reproducible conversion of naphthalene was reached within several hours or days some cases, even though the nickel catalyst gets deactivated.

4.2. Effects of Equivalence Ratio and Steam to Fuel Ratio on Tar Formation

The increase in equivalence ratio has a useful effect on reducing tar yield. Young-Kon et al. [80] studied the influence of equivalence ratio, the weight ratio of activated carbon to feed, and feed rate on the product gas composition and removal of tar. The equivalence ratio of 0.5 has a strong influence on tar, NH_3, and H_2S contents of the producer gas by reducing them to 27 mg/Nm^3, 443, and 470 ppm, respectively. Muflih et al. [81] reported that the tar obtained from the pyrolysis stage is converted into syngas by adjusting the ER (O_2 flow rate) in the combustion zone. Jennifer et al. [82] simulated the air-steam gasification process of woody biomass using Aspen Plus and developed a comprehensive model that best predict the behavior of the biomass gasification process. The model predicts product gas composition with reasonable accuracies in varying operating conditions like steam-to-biomass and equivalence ratio. Figure 8 showed the effect of gasification temperature on tar concentration and dew-point.

Narvaez et al. [83] studied operating conditions on the product syngas produced from sawdust pellets gasification with air in an atmospheric bubbling fluidized bed gasifier. The tar content produced from sawdust pellets gasification at 800°C decreased with increasing ER, the tar content was found at about 2-7 gram/Nm^3 obtained at an ER value of 0.45. Also, the H/C ratio is also almost important, and the tar content decreases with increasing H/C ratios. Figure 9 showed the effect of free-board temperature on the total amount of tar in the pressurized fluidized bed gasification with different feed-stocks. Levy et al. [84] reported that the lower heating value of the product gas decreased with an ER increase due to intensification oxidization reactions of product syngas. Steam to fuel ratio (SFR) influences tar formation due to more tar steam reforming reactions. Herguido et al. [85] observed that the amount of tar decrease in sharply trending from 8% wt. to minimal content with an increasing SFR range from 0.5 to 2.5. Aznar et al. [86] reported that variation of the ratio for ((steam/oxygen) / biomass mass) from 0.7 to 1.2 more than 85% reduction in the total tar was recorded. Figure 10 showed tar concentration at different equivalence ratio values at 800°C.
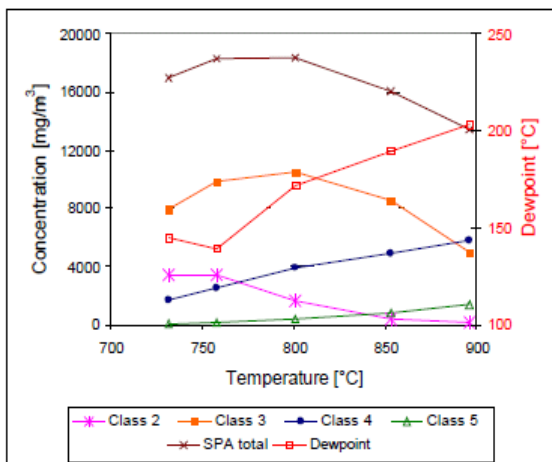
Fig. 8. Effect of gasification temperature on tar concentration and dew-point [76].
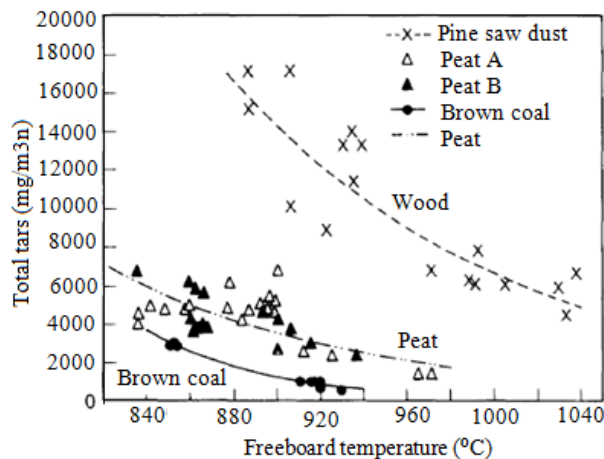

Fig.9. Effect of free-board temperature on the total amount of tar in the pressurized fluidized bed gasification with different feed-stocks [77].
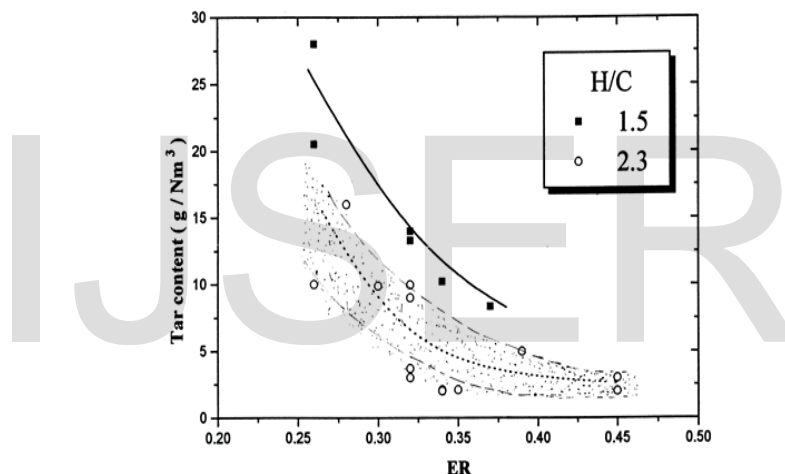

Fig.10.Tar concentration at different equivalence ratio values at 800°C [87].

5. Effect of Agent Type on Gasification

Biomass gasification using fluidized bed has been performed in various gasifying agents such as air, steam, pure oxygen, carbon dioxide and hydrogen [75]. In the following subsections, a detailed discussion of agent types and their applications are presented.

5.1 Air Gasification

Gasification process using air as a gasifying agent is the most straight forward and widely used method. Excess char formed by the pyrolysis process within the gasifier is burned with a limited supply of air. The syngas has a lower value of the heating value due to the dilution effect of nitrogen from the air. The heating value of the produced syngas is in the range of 3.5-7.8 MJ/Nm^3, which makes it suitable for boiler and engine applications.

The reactor temperature is dependent on the air flow rate and/or biomass feed rate. Groves et al. [41] tested the fluidized bed air partial oxidation of the cotton gin trash within temperatures range of 922 K and 1144 K in a 0.3 m internal diameter. The syngas yield heating value increased from 3.4 to 4.3 MJ/m^3. Lian and Findley [88] showed that the tar and char yields decreased as temperature increased by 6%. Walawender and Fan [3] stated that the syngas produced, heating

value and energy recovery increased by 131%, 77%, and 244%, respectively; when the temperature increased from 900 K to 1100 K.

Yijun et al. [89] showed that gas heating value, carbon conversion rate, gasification efficiency and syngas yield of 5.15 MJ/Nm^3, 71.50%, 50.80%, and 1.29 Nm^3/kg, respectively at secondary air rate of 0.20 and bottom air rate 0.50. Guanyi et al. [90] reported that high temperature favors air gasification of biogas-derived digestate. High ER of about 0.3 increases gas yield and reduces tar concentration to an optimal and minimum value of about 2.15 Nm^3/kg and 1.61 g/Nm^3, respectively. Medium value ER of 0.28 improves gas quality and cold gas efficiency to optimal LHV of 4.78 MJ/Nm^3 and of 67.01%. Lingqin et al. [91] recorded that increasing the concentration of oxygen is a reliable means to produce higher quality gas and higher gasification efficiency. The study of biomass gasification with oxygen-enriched air in fluidized bed gasifier shows that increasing oxygen concentration from 21% to 45% increases the heating value of the producer gas and the gasification efficiency from 4.0 MJ/kg to 5.24 MJ/kg and 29.6% to 33.59%, respectively. Injection of oxygen (secondary injection) leads to tar reduction from 15.78 g/Nm^3 to 10.24 g/Nm^3. Optimal secondary oxygen ratio is approximately 33.00% but increasing it to 46.86% leads to reduction in monocyclic aromatics from 28.17% to 19.65% while PAHs increases from 34.97% to 44.05%, leading to the increase aromatization of tar [91]. Ergudenler [75] tested the effect of ER on the syngas quality and its flow rate in the air as an agent of wheat straw through a fluidized bed gasifier. At ER of 0.25, the mole fraction of the combustible syngas achieved their maximum. Cao et al. [92] studied the sawdust gasification in a fluidized bed using air. They combined two individual zones of pyrolysis, gasification, and combustion of biomass fuel in one gasifier. The primary air stream and the biomass fuel were interfering to the gasifier from the bottom and the top, respectively. Secondary air was injected into the upper zone of the reactor to maintain a high temperature. Under optimum operating conditions, syngas produced at a rate of 3.0 Nm^3/kg and heating value at about 5.0 MJ/Nm^3. The concentration of carbon monoxide, hydrogen, and methane in the fuel gas produced were 9.25%, 9.27%, and 4.21%, respectively.

5.2 Steam Gasification

The steam-gasification process requires an external heat source is used as a gasifying agent, unlike air gasification. Using a mixture of steam/air as a gasifying agent is not superior technology. The oxygen present in the air helps to provide the required energy due to the exothermic nature of biomass fuel burning. The high temperature assists the devolatilization process of biomass to produce various gases. Steam reacts with carbon monoxide to produce hydrogen and carbon dioxide in water-gas-shift reaction. Steam gasification produces a higher energy content producer syngas. Boateng et al. [93] studied the effects of reactor temperature and SFR on product syngas composition and heating value. The syngas yield contains a high concentration of hydrogen and heating value ranged from 11.1 MJ/Nm^3 at 700°C to 12.1 MJ/Nm^3 at 800°C. Energy recovery varied from 35%-59% within the same temperature range. Walwender et al. [3] studied corn grain-dust gasification in a 0.05 m internal diameter fluidized bed gasifier by steam as agent and a mixture of sand/limestone as the bed material. The produced syngas increased from 0.13 m^3/kg at 867 K to 0.73 m^3/kg at 1033 K. The syngas heating value increased from 9.4 MJ/Nm^3 to 11.5 MJ/Nm^3 in the examined temperature range. The main components of the syngas were H_2, CO_2, CO, and CH_4 and the syngas flow rate yield was 0.5-1.4 m^3/kg, heating value was 11.8 MJ/m^3 and the carbon conversion within range of 32-90%.

Slapak et al. [94] reported that steam gasification is one of the possibilities for recycling waste in a fluidized bed reactor. The produced syngas has a heating value of about 8.6 MJ/Nm^3. Mermoud et al. [95] perform experimental gasification of charcoal using steam of beech charcoal

spheres of different diameters (10-30 mm) at different temperatures (830°C-1030°C). A difference in gasification rate as high 6.5 to 1 was observed between temperatures at 1030°C and 830°C. Experiments carried out with mixtures of H_2O/N_2 at 10%, 20%, and 40% mole of steam proven that oxidant partial pressure influences gasification. A gasification rate of 1.9 was gained for H_2O partial pressure varying from 0.4 to 0.1 bar. Corella et al. [85] observed on steam gasification of four different biomasses (wood chips, thistle, sawdust, and straw) in a 0.15 m internal diameter fluidized bed gasifier. They determined the syngas produced, char and tar yield at temperatures ranged of 650°C-780°C for each type of biomasses. Straw and sawdust showed higher syngas and lower tar yields compared to wood chips and thistle. Wei et al. [96] tested the legume straw and sawdust pellets as biomass in downdraft gasifier by varying the operating conditions during experiments, the tested factors affecting the hydrogen concentrations are detected. The product gas was reported to contain 58.26% concentration of hydrogen and obtaining 0.03 kg of hydrogen from 1kg of biomass is achievable [97]. For the oxy-steam and air-steam gasification of hydrolytic residues from bio-refinery, Nadia et al. [98] reported that oxy-steam gasification is more efficient with syngas heating value of 10.9 MJ/m^3 and plant thermal power output of 67 kW. Using air/steam as the gasifying agent, bio-oil gasification in an entrained flow gasifier was performed by Ji-Lu et al. [99] to investigate the effect of temperature and steam to bio-oil ratio on the product gas quality and performance of the gasification process. The steam to bio-oil ratio has an optimal effect at a value of approximately 2.5. The maximum concentration of hydrogen in the product gas was reported to be 30% and 2.0 H_2/CO ratios.

5.3 Oxygen Gasification

The measure of nitrogen provided to the gasification procedure is confined, the syngas will not contain nitrogen hence the regular vitality content (around 12-21 MJ/Nm^3). The syngas can be conveyed in pipeline arrange frameworks at bring down cost, in this way for process warm or potentially as amalgamation gas energizes. Oxygen plant or closer wellsprings of oxygen are required and raises the underlying cost required for the plant establishment. Gunung et al. [100] explored the use of mixed air and oxygen to perform coal gasification as a replacement for expensive pure oxygen-blown gasification systems. The composition of the syngas was more significantly affected by the Boudouard reaction with increased gasification temperature. Carbon conversion and CGE also increased as a result. When gasification was performed with an increasing ER, carbon conversion also increased. By varying and fixing ER and feed flow rate under various conditions, it was discovered that ER influenced gasification efficiency [100]. Lingqin et al. [101] investigate the properties of enriched biomass gasification identified the relevant parameters in a two-stage fluidized bed. Rice straw was used, and the parameters were affecting the operation of the fluidized bed was analyzed. The higher temperature is conducive favored the performance of the gasification while an increasing ER was shown to go against adding gas heat value. The study focused on the role of oxygen addition to steam gasification of chicken manure at various concentrations as well as the evolutionary behavior of the gases evolved with time was done by Hussein et al. [102]. The addition of oxygen to steam gasification decreased the reaction time by half and was found to be a more economically favorable to significantly shorten the waste manure residence time which enabled lesser process energy required to generate steam required for gasification.

Bailie [103] records the relationship between the heating value of a product gas and oxygen yield in the agent. At oxygen concentration of 20% and 100%, the heating values of the syngas yield were 6 and 11.2 MJ/Nm^3, respectively. At the concentration of oxygen in the agent improved from 20% to 100%, the methane, hydrogen, and carbon monoxide mole fraction increased from 4

to 6%, from 13 to 19% and from 25 to 55%, respectively. Tillman [104] studied municipal solid waste gasification using oxygen as an agent. The biomass fuel (shredded and magnetically sorted) was fed into the top of the gasifier, and the oxygen was fed at the bottom. Char was gasified by the assist of oxygen at the bottom of the gasifier to produce enough energy at temperatures in the range of 1593°C-1704°C and to yield a molten slag from all noncombustible materials. The maximum concentrations of the produced syngas for CO, H_2, CO_2, and CH_4 detected were 44%, 31%, 13%, and 4%, respectively. The maximum lower heating value was 10.6 MJ/Nm^3. Watkinson et al. [105] gasified coal to study the effect of an oxygen/steam mixture on carbon conversion and syngas low heating value during the gasification in a spouted bed. By increasing the ratio of oxygen/biomass ratio from 0.5 to 1.1kg/kg, the low heating value of the syngas yield increased sharply from 5 MJ/kg to 16 MJ/kg. Biogas dry reforming is a catalytic process that operates at 500°C-800°C to produce gas that simultaneously consumes two main greenhouse gases, CH_4 and CO_2, therefore supporting environmental preservation efforts [106]. The ratio of the produced H_2/CO is unity in stoichiometric reaction, which is suitable for further use in hydro-formulation and carboxylation process to synthesize liquid fuels [107]. Therefore, dry reforming has become a better option for renewable biogas energy, although, several problems might prevent its further industrial application. The primary attention is energy consumption [108]. Because dry biogas reforming is a highly endothermic reaction, for the dynamic thermal significance, a higher temperature is necessary to gain higher conversions. Another attention is the active catalyst suppression, mainly caused by the carbon sedimentation and active metal sintering [109], mainly when using base catalysts, which will also increase the operating cost of biogas reforming process. Finally, biogas is consisting of a number of gas species, and the effects of components besides CH_4 and CO_2, such as O_2 have not been enough study on biogas reforming. Studies have observed that two primary reactions can be caused to carbon formation which including CH_4 decomposition and CO disproportionation [110]. On another hand, a reaction that often occurs during dry biogas reforming is reverse water gas shift reaction which consumes more H_2 and produces more CO. Therefore the decreasing in the H_2/CO ratio occurs [111]. In the presence of oxygen, partial CH_4 oxidation and total CH_4 oxidation, carbon oxidation, CO oxidation, and H_2 oxidation may occur, where carbon gasification can help to remove carbon sedimentation.

The process of combining of dry and partial oxidative reforming of methane, also known as auto-thermal reforming of methane, have been recorded to be effective in recover energy consumption of dry reforming and adjusting the H_2/CO ratio in syngas yield. The use of pure oxygen and steam required a large amount of input energy and expensive initial investments [112]. Butterman and Castaldi studied the production of more active chars formed by the heat treatment of woody biomass as fuel with CO_2, compared to those formed using steam [90]. Seiler et al. suggested that it's possible to modify the economics of the biomass to liquid process through the sale of N_2 which formed as a by-product from the production of oxygen enriched air [112]. The gasification process with oxygen enriched air and CO_2 is considered as one of the most favorable. In this case, it's needed to enhance the boundary reaction using biomass chars produced under an N_2/CO_2/O_2 atmosphere with CO_2. If a CO-rich gas is yields during the gasification process, so, the feed gas with desirable H_2/CO ratio appropriate for the Fischer-Tropsch synthesis reaction can be results without new H_2 by promoting the water gas shift reaction in the downstream process at a lower temperature compared to that in the gasification step. In practice, CO_2 gasification of biomass char produced under an N_2/CO_2/O_2 atmosphere has not been sufficiently studied [113].

5.4. Carbon Dioxide Gasification

Gasification is a thermo-chemical process, in which a solid or liquid fuel is converted at higher temperatures and in the presence of gasification agent (air, H_2O, O_2 or CO_2) to a mixture of combustible gases (H_2, CO, CH_4 and others minor gases), accompanying gases (CO_2, N_2) and undesired components (tars, dust and others). Several attempts have been made for the production of carbon monoxide from biomass with CO_2 as a gasifying agent as follows.

Using a thermo-gravimetric analyzer, the carbon dioxide gasification characteristics of three biomass char samples and bituminous coal char were studied by Lihle et al. [114]. It was found that Char SB exhibited higher reactivity than chars SW and HW while the coal char gasification reactivity was observed to be lower than those of the three biomass chars. The addition of 10% biomass had no significant impact on the coal char gasification reactivity while that of 20 and 30% biomass additions resulted in increased coal char gasification rate. During co-gasification, chars HW and SW caused increased coal char gasification reactivity at lower conversions, while char SB resulted in increased gasification rates throughout the entire conversion range. The amount of biomass in the blends impacted the kinetic parameters, and ER decreased with increasing biomass fractions [114]. Yongming et al. [115] performed a parametric study aimed at investigating the effect of essential cycle variables on the performance of a power plant consisting of a direct-fired carbon dioxide power cycle coupled to coal gasification process. The aim was to determine potential chances for efficiency improvement. The performance of the plant is improved by adding a detailed turbine cooling model, and critical parameters are studied to understand their effect on the cycle performance. The deductions made from the experimental result shows that with high carbon capture, the efficiency is significantly higher, and the pump inlet temperature and pressure all have a significant effect on the efficiency. Subsequent modification to the base case was found to increase the efficiency to 38.87% [115]. Another study was based on the gasification of pine and oak bio-chars, and coal and blended feed-stocks in carbon dioxide in MDTR and TGA reactors at varying temperatures of 833, 900, and 975 °C respectively. Beaglea et al. [116] found that the reaction rate increased as temperature increased while the gasification time was reduced at the same time. Additive analysis of biochar/coal blend gasification showed inhibitory effects with synergy indices less than unity for all tested cases. The results support the use of biochar from pyrolysis as gasification feed-stocks with coal or alone, and suggest complex fuel interactions during gasification.

Zhang et al. [117] studied the effect of the pyrolysis mediums composition in the biomass fluidized bed gasification process at 550°C. their pyrolysis mediums were CO_2, air, CO, H_2, and CH_4. The authors report that the liquid yield, gas composition, and syngas heating value depend on the gasification agent composition. The gasification with CO_2 at atmospheric pressure was producing less char than in the other agent. In the case of CO_2 as an agent, the CO_2 in gas yield decreased compared to the CO_2 yield obtained in air. Furthermore, the CO_2 led to the highest yield of acetic acid compared to the other atmospheres. Zhang et al. illustrate these observations by two possible mechanisms; the CO_2 reacts with the active volatiles or with the char. newly, in their study on macro-algae pyrolysis/gasification, Kwon et al. [118] observed that, uses of CO_2 in the pyrolysis process at 550°C in a cylindrical gasifier minimized of the generation of pyrolysis oil. They detected that, a decrease in the pyrolytic oil by the ratio of 24.3% and promoted pyrolysis syngas production. This observation means that hydrocarbons yields from the pyrolysis process can be decomposed in the presence of CO_2. The same authors performed another study about the pyrolysis of styrene butadiene rubber [119] they reported that the CO_2 increases C_4 hydrocarbons cracking in addition to impeding the gas phase addition reaction by which is formed benzene. There

pyrolysis experiments performed at 650 °C in a free and in CO_2/ air mixture. The authors showed that the amount of condensable hydrocarbons decreased by a ratio of 30 to 50% when adding CO_2 to a modification of the syngas. The authors studied the effect of CO_2 on a volatile matter during the thermal dissolution of cellulose [119] at low and high heating rates of 500°C/min. The authors reported that there is a substantial increase in H_2 and CO production in the presence of CO_2. The authors performed experimental tests on cellulose gasification in a cylindrical gasifier. The concentrations of H_2, CO, and CH_4 in the presence of CO_2 increased by ratios of 4%, 10%, and 7%, respectively. As the boundary reaction is only favorable at temperatures values higher than 700°C, this increase of gaseous compounds is related to the fact that CO_2 likely accelerate the thermal cracking of volatile compounds release biomass fuel. The condensable hydrocarbons collected during the experiments were decreased by approximately 67% based on the mass balance. The author evidenced that the main influence of CO_2 during biomass thermal degradation is perceived in the gas phase was this latter found to participate in the hydrocarbons cracking leading to more permanent gases. The same results were found using real biomass from corn stove. The authors did not observe noticeable differences in the thermo-gravimetric analysis of the different biomasses degradation under CO_2 and N_2 respectively. Kwon, et al. [119] performed macro-algae gasification tests with steam and variable concentrations of CO_2 in a tubular reactor with temperatures ranging from 600°C to 1000°C. The authors observed that the CO concentration increased by a factor of 2 even at 600°C and 700°C with a CO_2 concentration of 30% compared to a reference state of a CO_2-free atmosphere. The yield of C_2 hydrocarbons also increased, and the amount of tar was reduced by 51.2% which can be directly correlated with the gas yield augmentation. In their paper on CO_2 as a carbon neutral fuel source via enhanced biomass gasification, the authors studied the gasification of several kinds of wood, grasses, and agricultural residues with steam and CO_2 via thermo-gravimetric analysis and gas chromatography. The CO_2 concentrations were varied between 0% and 100% with steam as a co-reactant. The authors observed that, when only injecting 5% of CO_2 with steam, CO concentration increased by a ratio of 10% and H_2 decreased by the ratio of 3.3% at 900°C. Increasing of CO_2 from 5% to 50% resulted in continued CO increases and H_2 decrease by a ratio of 3% at 900 °C. High CO_2 fraction in gasifying agent generally resulted in low H_2 yield and high CO yield. Generally, the CO_2 can potentially react in the gas phase with hydrocarbons, such as methane, through dry reforming reaction. The CO_2 can also react with hydrogen atoms according to the reverse water gas shift reaction (RWGS). As well, in biomass gasifier; CO_2 can react with the carbon in the char form after the pyrolysis step through the heterogeneous boundary reaction. The main results of these reactions are enhanced CO production. The authors' conclusion, the introduction of CO_2 generally decrease the energy yield of the producer syngas, but on the other hand, decrease the preheating energy of gasifying agent resulting in a greater thermal efficiency under testing conditions ranges. The highest thermal efficiency of the process without O_2 was 52% under N_2 (40%), CO_2 (60 %) at 850°C. For the process using O_2, where the part of gasifying agent preheating energy supplied by the partial biomass combustion the higher thermal efficiency was 60% under the CO_2 (60%), O_2 (8.3 %) and N_2 (31.7%) atmosphere at 950°C. Beside good thermal efficiency, the authors discussed if the use of CO_2 in biomass gasifies as an agent can provide an N_2-free syngas which is more suitable for the synthesis of liquid fuels and chemicals. M. Pohorel et al. [113] found that the use of CO_2 as an agent in the process of catalytic biomass gasification had an important effect on the conversion of biomass fuel into gaseous and on decreasing the tar yields. The authors performed their study on beech wood pellets in a fluidized bed gasifier. The bed material was

dolomitic limestone preheated to 500°C with the gasification agent. The gasification reactions were performed at 850°C, respectively in H_2O/O_2, air/O_2, and CO_2/O_2/air mixtures. The higher cold gas efficiency was observed when gasifying biomass with a CO_2 containing air.

6. Factors Affecting Gasification Performance

Many variables appear effect on the gasification performance, syngas composition and tar yields, including bed pressure, bed temperature, fluidization velocity, bed height, gasifying medium, ER, feed material moisture content, biomass particle size, SFR and presence of catalysts. In the following, a brief discussion about more factors influencing of the gasification process.

Elita et al. [120] reported that integrating non-woody biomass with a small amount of high-grade carbon gotten from coal or bio-char into pellets of fuel for co-gasification can potentially improve fuel quality, and also reduce tar formation. It can also enhance the occurrence of mineral-based catalytic reactions. According to Elita et al. [120], the factors that influence these effects are complex and needs further investigations. In another study, it was found that steam-carbon gasification reaction can be improved by adding a suitable catalyst with H_2O as gasification agent in a DC-SOFCs system. In addition, the fuel percentage in product and gas performance DC-SOFCs increased with increasing operating temperature [121]. Haixia et al. [122] reported the catalytic effect of sodium in coal ash. According to the report, good gasification performance of Zhundong coal was observed as the concentration of CH_4 is approximately 1% and slightly changes with increasing temperature.

6.1. Effect of Gasification Temperature

The gasifier bed temperature affects all of the chemical reactions that occur in the gasification process. In an experiment conducted by Narvaez et al. [83], an increase in gasifier bed temperature from 700°C to 850°C, at a constant ER of 0.30, the composition of the syngas produced was changed as; H_2 concentration increased from 5% to 10%, CO increased from 12% to 18%, CO_2 decreased from 16% to 14%. Methane and C_2H_2 decreased minimally. The results from a similar experiment conducted by Radmanesh et al. [123] validated the conclusions drawn from Narvaez et al. [83] in that when the temperature of the gasifier bed is increased, and the ER is held constant, the concentrations of H_2 and CO in the syngas increased. From Petersen and Werther's[124] study on a circulating fluidized bed gasifier using sewage sludge as the fuel, a significant change in syngas composition was observed with an increase in bed temperature from 530°C to 730°C at an ER of 0.30. The H_2 to CO ratio doubled over this temperature range. In a sewage sludge gasification experiment from de Andrés et al. [125], it was shown that higher bed temperatures favor hydrogen production and that the concentration of CH_4 increases somewhat with increasing bed temperatures. Higher temperatures produce more intense volatilizations and cracking reactions instead of producing more intense reforming reactions. Thus at higher temperatures, there is an increase in H_2 and light hydrocarbons in the syngas [125]. This configuration is shown for temperature ranges of 750°C-850°C at constant ERs of 0.20, 0.30, and 0.40. The tar concentration also reductions as temperature rises. These changes in composition affect the overall heating value and quality of the gas. An increase in bed temperature, up to a point, increases the heating value and decreases the tar content which makes for a better quality syngas. Note that increased bed temperature could have positive effects on the syngas quality (lower tar content) but could also be detrimental to the amount of energy produced (lower heating value). Experimental literature has shown that increases in temperature in sewage sludge gasifier-bed improve the heating value of the gas until the temperature reaches 1470°F for a bubbling fluidized bed gasifier and 1340°F for a circulating fluidized bed gasifier [124, 117].

The FLETGAS method used in the laboratory experiment conducted by Gómez-Barea, et al. [126] consisted of a (1) devolatilizer, a (2) reformer, and (3) a moving bed. The devolatilizer is where most of the volatile syngas are free from the biomass fuel, and was performed at temperatures in the range of 700°C-750°C which are high sufficient to release the volatile syngas from the sewage sludge however not high sufficient to cause any tar cracking so a significant amount of tar was released from the fuel in the devolatilizer. The tar and syngas were directed to another stage downstream of the volatilization zone called the reformer. Oxygen-enriched air (40%O_2) and high-temperature steam were blown into the reformer to reduce the amount of tar significantly by increasing the temperature till 1200°C which incompletely combusted the tars. The solids (ash and char) produced in the fluidized bed were then transferred to the third stage, the moving bed. The reformer gases flowed into and transferred heat to the moving bed. The bed acted as a catalytic filter in helping tar cracking reactions while steam introduced into the bed promoted endothermic char gasification reactions. Lastly, the ashes exited at the bottommost of the moving bed containing very little carbon and the syngas exited immediately the bottom of the moving bed containing negligible amounts of tar due to the two reduction steps encountered in the process. The final stage of the system, the moving bed, cooled the ash and produced gas which increased the chemical energy of the syngas and thus the overall gasification efficiency.

6.2. Effect of Equivalence Ratio

The equivalence ratio (ER) is definite as; the ratio between the air flow rate introduced into the gasifier and stoichiometric air flow rate that required for complete combustion/pyrolysis of the biomass fuel. It has also been specified in the literature that it is one of the most significant operating conditions in the biomass gasification process [83,124].

Where O_2 Supplied is the oxygen mass flow rate introduced into the gasifier (kg/hr.). Theoretical O_2 required is the theoretical amount of oxygen needed for complete combustion/pyrolysis of biomass (kg/hr.). ER greatly affects the syngas composition. As the ER increases, the concentrations of combustible gases (H_2, CO, CH_4, and tars) reduction during the volumetric concentrations of CO_2 and H_2O growth. Increases in ER provide more O_2 to the gasifier then goes to oxidize CO, H_2, CH_4, and tars. The methanation and oxidation reactions use O_2 to oxidize CH_4 to CO and H_2; hydrogen is oxidized to H_2O. This trend can be seen in the literature over temperature ranges of 700-850°C for both biomass and sewage sludge fuel [83, 124]. Recommendations in the literature for an optimum ER vary based on feedstock and kind of gasifier. In Petersen and Werther's [124] experiment using sewage sludge as biomass fuel and a circulating bed gasifier reactor, the optimal ER was found to be 0.30. Narvaez et al. [83] recommend values among 0.18 and 0.45 for the ER in their tests using biomass as a fuel and a bubbling fluidized bed gasifier. A lower ER is not practical because too much tar is produced and a higher ER produces syngas with a low heating value. In Manyà, et al. [127] tests with a dried sewage sludge fed fluidized bed gasifier, an optimal ER was found at 0.35; the optimum qualification was determined by the highest concentration of H_2 in the syngas. Also, a high degree of combustion occurs at a higher value of ER; which supplies more amount of air into the gasifier and promote char burning to produce more CO_2 instead of combustible gases as H_2, CO, and CH_4. Also, the ER increase results in a decrease in the low heating value (LHV) of the syngas because it hinders in the CH_4 generation other light hydrocarbons which have relatively large LHV. In additional to, at higher ER, extra nitrogen provided by air dilutes the producer syngas which in turn results in its low energy content [127]. Studies have shown that too lesser in ER is also aggressive for biomass gasification as it lowers the reaction temperature [83]. Hence, an optimum value for ER in biomass gasification exists in the range of 0.2-0.4 which varies according to various operating parameters.

Selection of the suitable ER is somehow depended on the producer gas subsequent application. When the raw producer gas is going to be burnt in downstream furnaces, tar is not a serious issue. Also, the gas should have a high heating value, and therefore the gasifier can be operated at the minimum ER of about 0.2. In the case of temperatures lower than of 850°C, tar yield is high, and ER should be increased to about 0.3-0.4 to compensate such negative effects. Lv et al. [84] studied the effect of ER on gas yield and LHV. They varied the ER from 0.19 to 0.27 and realized that the variation of ER could be divided into two stages of 0.19-0.23 and 0.23-0.27. In the first stage, the gas yield increased from 2.13 to 2.37 m^3/kg, and the gas LHV increased from 8.82 to 8.84MJ/Nm^3. It was observed that in the second stage, the LHV and gas yield decreased due to the improvement of the oxidation reactions which also decreased the concentration of CO, CH_4, and C_nH_m and increased the CO_2 concentration. So, the value of 0.23 was selected as the optimum ER. In another set of experiments conducted by Narvaez et al. [83], ER was varied in the range of 0.25-0.45 to find the optimum ER. It was observed that increasing the ER reduced the amount of H_2, CO, CH_4, and C_2H_2. Maximum H_2 concentration of 10% was obtained at the ER of 0.26. They also realized that while the ER was increased the tar content of the producer gas was gradually decreased, and at ER of 0.45, minimum tar concentration of 27g/m^3 was achieved. They obtained LHV of 5.2-7MJ/m^3 and 3.5-4.5MJ/m^3 at ERs of 0.25 and 0.45, respectively. It was also concluded that the gas yield was in a direct relationship with ER. Similar trends were obtained by Li et al. [94] who investigated the co-gasification of biomass and coal while the ER was in the range of 0.31-0.47. They also explained that as ER increased, more oxygen was introduced into the gasifier which enhanced the combustion and increased the bed temperature from 948 to 1026°C. Skoulou et al. [128] also studied the effect of ER variation (0.2-0.4) as one of the most important operation parameters on the quality of the producer gas. They reported the favored concentration of CO at low ER of 0.2 and its hindered production at ER of 0.4 because of complete oxidation of carbon to CO_2. Also, H_2 production peaked at the ER of 0.2. The lower heating value of the producer gas was obtained at high ER which was due to the promotion of the oxidation reaction and dilution of the producer gas with N_2.

6.3. Effect of Steam to Fuel Ratio

Steam to fuel ratio (SFR) is defined as the flow rate of the steam fed into the gasifier divided by the biomass flow rate is one of the important process parameters involved in steam gasification [75]. A test considers biomass air-steam gasification was driven by Lv et al. [84]. They investigated the effect of SFR on the quality of the producer gas in the range of 0-4.4. It was observed that the introduction of steam to the system improved the gas yield, LHV and carbon conversion efficiency. They reported the SFR range of 1.35-4 as the optimum SFR in which the CO, CH_4 and C_2H_2 content of the producer syngas decreased, whereas the CO_2 and H_2 concentration gradually increased. It was explained that in this SFR range, more steam reforming reactions of CO, CH_4, and C_2H_2 occurred in the presence of steam which resulted in high concentrations of H_2 and CO_2. Over the optimum range, a decreasing trend was observed in the syngas yield, LHV and carbon conversion efficiency due to the low reaction temperature affected by low-temperature steam. Thermochemical biomass gasification was performed on a bench-scale fluidized-bed gasifier with steam and air as fluidizing and oxidizing agents and the effects of the gasification operating conditions on the syngas composition, carbon conversion efficiency, and energy conversion efficiency was investigated by Ajay et al. [129]. The result should be that the value of the energy equivalence ratio was influenced by the gasification operating conditions which included furnace temperature, steam to biomass ratio and equivalence ratio. The result showed that the methane and hydrogen content of the syngas, as well as carbon conversion efficiency, was influenced by ER

and furnace temperature. Also, the methane content, carbon conversion efficiency, and energy efficiency increased and then decreased after reaching maximal with increasing SBR [129]. A work directed towards the investigation of effects of activated carbon, the ash of activated carbon, steam to fuel ratio and the combination of additives on syngas quality was done by Young-Kon et al. [130]. Dried sewage used for producing the syngas in a two-stage gasifier using steam/oxygen as the gasifying agent in the SFR ranges of 0.52-0.90. Activated carbon was found to reduce NH_3 in the syngas, while the ash components helped in tar cracking. Increasing the SFR caused the H_2 and NH_3 in the syngas to increase while the extra addition of CaO and activated carbon to the base additive (activated carbon) led to increased H_2 production and active tar cracking. Thus it was concluded that producing an H_2-rich and tar-free syngas in a two-stage gasifier using steam/oxygen is possible [130]. Ji-Lu et al. [131] carried out a study based on the production of gas through bio-oil gasification and the effect of steam to bio-oil ratio and gasifier temperature on the quality of the product gas as well as the gasification process performance. The result of the experiment showed that the impact of the steam to bio-oil on the gas quality and gasification performance had an optimum point while the influence of the gasifying temperature showed a sole monotone function. Compared to chopped or baled biomass, it is believed that large scale production of the product gas would be fairly suitable because the high density of bio-oil will lead to lower transportation and storage costs [131]. Various applications were suggested for the product gas including power generation in gas turbines, fuel gas for cooking, as well as application in CO hydrogenation processes, such as Co-catalyzed Fischer-TropschSynthesis (FTS).

Qin et al. [132] examined the effect of SFR on tar formation and the resultant tar properties. In their experiments, SFR was varied in the range of 0.49-2.66 at 900°C. The results showed that, as the SFR was increased, the tar yield slowly decreased from 3.87 to 1.71%. It was also concluded that high SFR values lower the aromacity of the tar contents. Another set of experiments was conducted by Gil et al. [133] who studied the effect of steam/oxygen gasification on product concentrations. Their results showed steam to oxygen ratio, and steam/oxygen to biomass ratios was varied in the range of 2-3 mol/mol and 0.6-1.6 kg/kg, respectively. The achieved results shown that the H_2 content of the syngas was in the range of 14-30% and decreased as the steam/oxygen to biomass ratio was increased, or the steam/oxygen ratio was steadily decreased. As the O_2 introduced into the system was increased, more H_2 was combusted in the gasifier and less was found in the discharge stream. A similar trend was observed for CO while changing the distinct ratios, and its concentration in the producer syngas was found in the range of 30-50%. The tar content of the syngas obviously reduced to less than 10 gram /m3 as the steam/oxygen to biomass ratio was increased to 1.0-1.1kg/kg. The char produce also decreased to 10% while the gasifying agent to biomass ratio was increased to the values higher than 1.0. As mentioned previous, steam gasification can provide a gas stream with a high content of H_2, but the concentration of the unattractive products, for example, CO_2 is also increased. To improve the efficiency of the steam gasification process, considerable efforts have been dedicated to the production of producer gas with a high yield of H2 with instantaneous capture of CO_2. Steam gasification can give a gas stream a high substance of H_2, yet the centralization of the appalling things, for example, CO_2 is furthermore extended. In this way, to improve the adequacy of the steam gasification process, noteworthy undertakings have been focused on the making of creator gas with an exceptional yield of H_2 with the quick catch of CO_2.
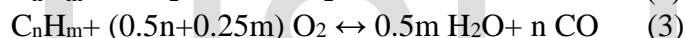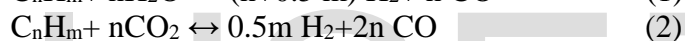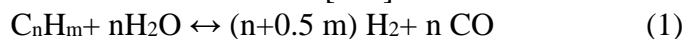
6.4. Effect of Biomass Size

It has been known that small particle size biomass significantly increases the overall energy efficiency of the gasification process, but it also increases the gasification plant cost. It has been

estimated that for a 5-10 MW gasification plant, about 10% of the output energy is required for the biomass particle size reduction [134]. On the contrary side, a development in mass atom evaluate decreases the pretreatment costs, yet the devolatilization time increases, and in like manner for a described throughput the gasifier measure increases [134]. Hence, a balance should be considered while investigating the effect of biomass particle size on the gasification efficiency. Lv et al. [39] studied the effect of biomass size on the quality of the producer syngas in four ranges as of 0.6-0.9, 0.45-0.6, 0.3-0.45 and 0.2-0.3mm. They detected that small particle size biomass created more amounts of CH_4, CO and C_2H_4 and less CO_2 in comparison to large particles. Consequently, the producer syngas yield, LHV, and carbon conversion were enhanced as the biomass particle size decreased. It was clarified that small biomass particles contribute to large surface area and high heating rate which in turn produce more light gases and less char and condensate. Thus, the flow rate and composition of the producer syngas improved while using the small particle biomass.

6.5. Effect of Bed Materials (Catalyst)

Bed materials are of great significance in fluidized bed gasifiers. They turn as a heat transfer medium, but their key role involves in tar cracking which avoids complex downstream tar removal process [135]. The presence of the catalyst in the bed material during biomass gasification promotes several chemical reactions which influence the composition and heating value of the producer gas. It also reduces the tar yield and prevents solid agglomeration tendency of the bed [136]. The catalytic reforming reactions through which tar is converted into valuable gaseous compounds are summarized as follows [136]:

$$C_nH_m + nH_2O \leftrightarrow (n+0.5\ m)\ H_2 + n\ CO \quad\quad (1)$$
$$C_nH_m + nCO_2 \leftrightarrow 0.5m\ H_2 + 2n\ CO \quad\quad (2)$$
$$C_nH_m + (0.5n+0.25m)\ O_2 \leftrightarrow 0.5m\ H_2O + n\ CO \quad (3)$$
$$C_nH_m \leftrightarrow 0.5m\ H_2 + n\ C \quad\quad (4)$$

Usually, three main groups of catalysts are implemented to eliminate tar from the producer syngas [135]: (1) natural catalysts such as dolomite and olivine; (2) alkali-based catalysts such as (Li, Na, K, Rb, Cs and Fr) and (3) metal-based catalyst such as nickel catalysts. Dolomite is the most usually used catalyst which effectively removes heavy hydrocarbons from the syngas stream [111,135,137]. It also decreases accumulation in fluidized bed while using biomass with high alkali content. But, the undesired property of dolomite is its rapid calcination in the gasifier which subsequently results in a syngas with high particulate. Alkali-based catalysts (Li, Na, K, Rb, Cs, and Fr) are capable of increasing the gasification rate and decreasing the tar content of the producer syngas. However, effort in recovery, high cost, and accumulation at high temperatures are some of the difficulties of the alkali-based catalysts [137]. Metal-based catalysts are also considered effective in eliminating tar and increase the superiority of the producer syngas. The main difficulties associated with this type of catalysts are carbon deposition and nickel particle growth, which cause catalyst deactivation [135]. Study based on the use of a clay material, sepiolite, as bed material for biomass gasification in a lab-scale bubbling fluidized bed using silica sand as a reference bed material was carried out by Daniel et al. [138]. By comparing the gas of the two-bed materials, it was discovered that the use of sepiolite do not improve the gas composition, generating more CO_2 and less CO than the gas produced by silica sand while the H_2 content does not show a clear trend between the two-bed materials. Their tar composition was also found to differ appearing single ring alkylated and oxygenated compounds in sepiolite, and disappearing tars with a molecular weight higher than anthracene. It is believed that the physical nature of sepiolite was responsible for the high reduction of tars in the product gas. During CFB gasification performed by Xiaobin et al. [139], the use of an effective bed material has always been crucial to remit

slagging/agglomeration for high-sodium lignite. This work explored the feasibility of the use of three minerals- quartz sand, corundum and boiler ash- obtained from mining in Zhundong district as potential bed materials for this process. In the gasification experiment, their slagging and de-fluidization properties were investigated, and the results showed that the probability for de-fluidization increased with increased particle size while sodium underwent a different transformation as a result of the action of the bed materials. It was also discovered that it was not possible to improve the ash fusibility of TCMLc by addition to silicon dioxide. Since attrition alters the size distribution of bed particles and their surface morphology, fluidization conditions, and product quality, it is essential to identify the effects of design and operational parameters. Shivali et al. [140] investigated the effects of various design and operational parameters (superficial air velocity, bed inventory, and spacer height) on the attrition of bed material and its size distribution with increasing operation time in a recirculating fluidized bed (RCFB). It was discovered that besides the operating time, attrition was influenced by every one of the parameters mentioned above.

Asadullah et al. [135] studied the performance of the heterogeneous catalyst of $Rh/CeO_2/SiO_2$ in fluidized bed gasification to that of dolomite, steam reforming catalyst and inert bed materials whereas the ER was set at 0.31 and the bed temperature within the range of 823K-973K. It was detected that the tar content of the producer was completely negligible while using $Rh/CeO_2/SiO_2$ as the bed material. However, the tar concentration at about 113 and 139gram/m^3 was achieved with dolomite and inert bed materials, respectively. It was also concluded that in the case of $Rh/CeO_2/SiO_2$ catalysts the efficiency of cold gas was about 71% more than others cases. Also, little char and coke were observed in the experiments with the $Rh/CeO_2/SiO_2$ as catalysts. Skoulou et al. [128] used quartz sand and olivine as bed materials in a bubbling fluidized bed gasifier at ER of 0.2-0.4 and bed temperature as 750°C-850°C. They reported that, while quartz sand is an economy and abundant material, it produced severe de-fluidization due to its tendency to tar formation at temperatures below 800°C. They replaced quartz sand with olivine and observed that, at low gasification temperature of 750°C and ER of 0.2, components of tar were pyrolysis and released H_2 and CO, under the catalytic effect of iron-based olivine. Li et al. [94] examined the influence of bed material on tar elimination efficiency in a circulating fluidized bed. They used silica sand and a commercial Ni-alumina catalyst as bed material. At the bed temperature of 800°C, the quantity of tar reduced from 0.4 gram/m^3 to 0.15 mg/m^3, as silica sand was substituted with Ni-alumina catalyst.

Conclusion

It is evident that the current studies are channeled towards the production of hydrogen-rich gas from gasification of biomass. From the latest advancements in research and technology, gasification of biomass is a potential source for sustainable energy development in developing countries. In this comprehensive review, many observations were made from various studies, and the following conclusions were deduced;

1. The biomass was observed to be a source of sustainable energy for agricultural dependent economic countries.
2. Thermo-chemical conversion or gasification of biomass is a viable route to alternative energy generation in a decentralized manner.
3. Product gas quality, tar yield and gasification performance are dependent on reaction zone temperature, fuel prosperities, equivalence ratio, steam to fuel ratio and gasification agent.

4. Using primary tar reduction methods is very attractive since working conditions have a significant influence on tar yield and formation. Therefore, to investigate the fate of tar during biomass gasification, tar measurement and analysis is primarily required.

5. There is a significant variation among kinetic parameters derived from combustion and gasification of different biomass chars depending on biomass fuel types and fuel properties.

Conflicts of Interest

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

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