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Bubbling Fluidized Bed Gasification of Biomass: A Review on the Effect of Selected Operational Parameters

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Abstract: Fluidized bed gasification is a promising technology to convert biomass to useful syngas, offering several distinct advantages. The performance of the fluidized bed gasifier (FBG) is affected by various operating parameters like fuel type, temperature, equivalence ratio, gasification agent, steam-biomass ratio, bed material, and the catalyst used. Steam gasification of biomass in a fluidized bed gasifier is an effective and efficient technique that offers a high yield of H_2 in the range of 30-60 vol%. However, the challenges associated with biomass gasification and commercial propagation of the technology are critically important issues. This paper reviews the bubbling fluidized bed gasification of biomass in several aspects, including parametric influence, biomass to H2 process mechanism, catalytic tar conversion, and the challenges and prospectus of the technology.

Keywords: Bubbling fluidized bed gasifier, biomass, syngas, catalyst, hydrogen, tar.

1. Introduction

Global energy has seen sharp demand for the last several decades due to brisk industrialization, rapid growth in population, and improved living standards. In the present scenario, fossil fuels are still the consequential player in the most energy-consuming sector, with about 81 percent of the energy share in 2018, and are the main contributor of greenhouse gas emissions like CO_2, which has caused a long-term and irreversible damage to the environment leading to global warming and climate change. Global warming, climate change, and energy security are gaining more attention worldwide, and apprehension about fossil fuel's volatile and ever-increasing price. As late as the mid-1800s, biomass supplied most of the world's energy but started to phase out as the fossil fuel era began. But with the onset of the first oil shock in the mid-1970s. This has created a renewed interest and focus on developing alternative and renewable energy sources for sustainable development. Renewable energy sources like solar, wind, and biomass could play a role of great significance in mitigating climate change. Biomass is a renewable and potentially sustainable energy source with many possible applications varying from heat generation to the production of advanced secondary energy carriers [1] and one of the most important factors for environmental protection in the 21st century [2].

Energy derived from biomass and waste is seen as one of the most dominant future renewable energy sources because continuous power generation can be guaranteed, unlike solar and wind energy. Biomass energy is the fourth-largest energy after coal, oil, and natural gas [3] and will continue to increase by 2050 [4]. The renewed interest in biomass as energy can be attributed to the development of biomass conversion technology, low cost, high conversion efficiency, and the potential threat of climate change due to greenhouse gas emissions. In addition, the use of biomass fuels provides substantial benefits as far as the environment is concerned [5, 6]. Biomass energy offers several distinct advantages such as renewability, CO_2 neutral or less CO_2 and high hydrogen content; widely available and promising alternative energy; low sulfur and nitrogen content with a low tendency to produce SO_x, NO_x, and particulate matter into the atmosphere reducing the potential problem associated with its disposal and greenhouse gas emission [7–9]. The gasification of biomass has gained much attention in recent years because the gas producer gas can be utilized in various applications depending on its qualities [10, 11].

2. Biomass Energy

Biomass generally refers to an organic matter produced by green plants through the process of photosynthesis and includes all land and water-based vegetation and organic wastes. Biomass is an important renewable source of fixed carbon (C) and can be converted into liquid, solid, and gaseous fuels and chemicals apart from providing heat and power [12]. The conversion of biomass into the next form of energy through the different technological options includes biochemical conversion and thermochemical conversion, depending on its physical nature, as shown in Figure 1. The primary fuel produced from the biomass can be liquid (ethanol, biodiesel, methanol, vegetable oil, and pyrolysis oil), gaseous (biogas (CH_4, CO_2), producer gas (CO, H_2, CH_4, CO_2, H_2), syngas (CO, H_2), substitute natural gas (CH_4)) and solid (charcoal, torrefied biomass).

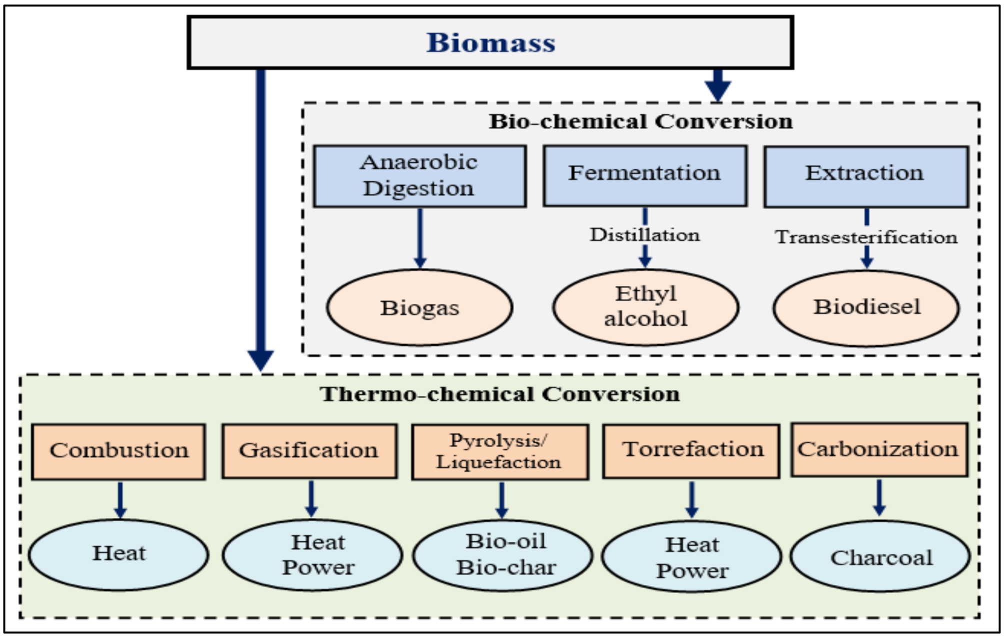

Figure 1. Conversion routes for biomass.

3. Biomass Gasification

Gasification is a thermochemical conversion of solid biomass with a limited and measured supply of gasification agents at an elevated temperature (800-1000°C), giving a gaseous mixture called producer gas or syngas. The main gasification stages include drying, pyrolysis, partial combustion, reduction [11], and several reactions, as shown in Table 1. Air gasification is commonly used for industrial applications due to its low investment cost and simple and stable operation [12]. Still, the fuel gas is highly diluted with nitrogens yielding lower heating value (LHV) gas in a range of 4-6 MJ/ Nm^3 [13]. On the other hand, if O_2 or steam is used instead of air results in syngas with a higher heating value (HHV) of 10-18 MJ/Nm^3 but making the process more complex and involving higher investment for oxygen and steam [14].

Table 1. Thermochemical reaction.

Pyrolysis	$CH_xO_y \rightarrow H_2+CO+CO_2+CH_4$+hydrocarbon + tar +char	(R1)
Oxidation	$C + O_2 \rightarrow CO_2$ −283 MJ/kmol	(R2)
Partial oxidation	$C + ½ O_2 \rightarrow CO$ −111 MJ/kmol	(R3)
Boudouard	$C + CO_2 \leftrightarrow 2CO$ + 172 MJ/kmol	(R4)
Methanation	$C + 2H_2 \leftrightarrow CH_4$ −75 MJ/kmol	(R5)
Water-gas	$C + H_2O \leftrightarrow CO + H_2$ +131 MJ/kmol	(R6)
Water-gas shift	$CO + H_2O \leftrightarrow CO_2 + H_2$ −41 MJ/kmol	(R7)
Steam reforming	$CH_4 + H_2O \leftrightarrow CO + 3H_2$ +206 MJ/kmol	(R8)
Dry reforming	$CH_4 + CO_2 \leftrightarrow 2CO + 2H_2$ +260 MJ/kmol	(R9)
Tar reforming	Tars + $H_2O \rightarrow H_2 + CO_2 + CO$ + hydrocarbons	(R10)
Hydrocarbon reforming	Hydrocarbon + $H_2O \rightarrow H_2 + CO_2 + CO$	(R11)

Gasification of lignocellulosic biomass for producing renewable fuels is a rather mature technology. It is considered an attractive conversion process as it gives better conversion efficiency for various end products using syngas for purposes such as heat and electrical power generation [15, 16]. Though the gasification technology provides the advantage of low environmental impact, high effective conversion, and reduced global CO_2 emissions [17], it is associated with the major hurdle of formation of the aromatic compounds called tar, which is a costly affair to eliminate and put serious limitations in the industrialization of gasification technology [18]. Several gasifier designs exist, which are mainly classified based on their gas-solid contact mode into three principal types: (i) fixed or moving bed, (ii) fluidized bed, and (iii) entrained-flow bed [19]. The present paper reviews the bubbling fluidized bed gasification of biomass in different aspects of operational parameters.

3.1. Fluidized bed gasifier.

Fluidized bed gasifiers (FBG) work on the principle of fluidization phenomenon in which both the fuel and inert bed material behaves like a fluid because a gasifying medium is passed at high pressure to keep it in semi suspended condition or fluidization state [20]. One of the important features of the fluidized bed system is the high heat transfer capability due to the high percentage of inert bed material [21]. A fluidized bed reactor takes advantage of the excellent mixing characteristics and high reaction rates of gas-solid phase mixing, better temperature distribution, high specific heat capacity, and a fast heat-up [22], which benefits in the efficient heat and mass transfer, providing high conversion intensity. The large thermal inertia of the bed makes FBG gasifiers relatively insensitive to the fuel quality and provides process flexibility; they can handle difficult fuel like rice straw [23]. They are an attractive alternative to solid waste treatment; they provide wide biomass fuel adaptability; they offer economic, environmental, and scale-up benefits [24, 25]; they are easy for industrial application [26]. And they promise reactors for enhanced H_2 production in the future. However, the issues like sintering, agglomeration, deposition, erosion, and corrosion are avoided in fluidized bed gasifiers by limiting operation below the ash sintering temperature [27]. The fluidized bed gasifier is sub-classified as a bubbling fluidized bed gasifier (BFB), circulation fluidized bed (CFB) gasifier, and or dual bed fluidized (DFB) gasifier, as shown in Figure 2.

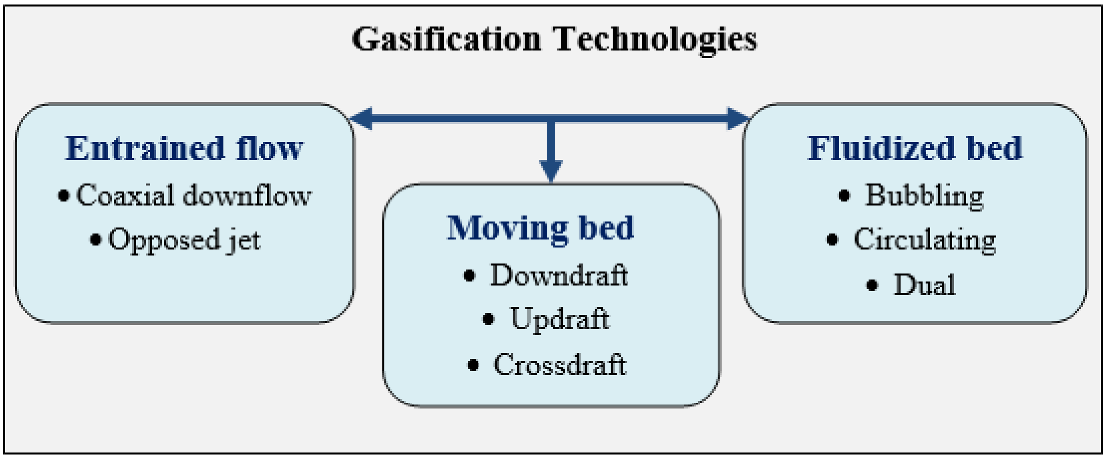

Figure 2. Classification of gasifiers.

3.1.1. Bubbling fluidized bed (BFB) gasifier.

A bubbling fluidized bed (BFB) gasifier, as shown in Figure 3, is the oldest design popular for biomass gasification [20]. It also allows *In-situ* tar reduction and other advantages such as uniform temperature distribution, low environmental impact from operation between 800-900°C, and fuel flexibility [28]. Atmospheric gasification with air in a BFB reactor is the simplest way to produce a fuel gas at a sufficient scale and keep operation cost low [14]. The performance of the BFB gasifier highly depends on bed hydrodynamics [29]. BFB gasifier can be used for chemical looping to produce high-quality syngas at lower CO_2 content [30].

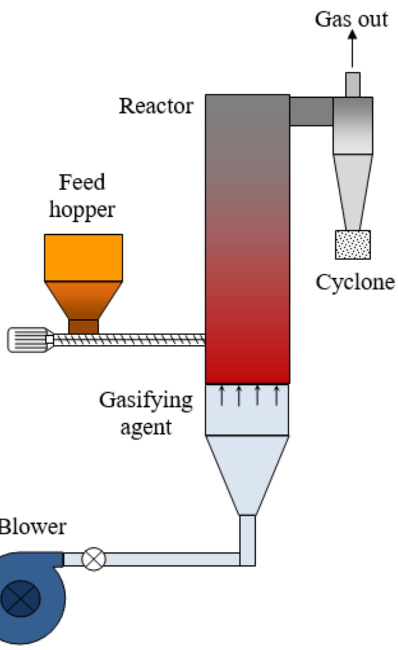

Figure 3. Bubbling fluidized bed gasifier.

3.2. Application of syngas.

The syngas produced through the gasification process can have varied applications, as shown in Figure 4. It can be burnt directly to generate heat [15, 16], or H_2-rich syngas can be utilized for power generation through internal combustion engines, solid oxide fuel cells (SOFC), and gas turbines with less pollution without CO_2 [31, 32] or for combined heat and power (CHP) using internal combustion (IC) engine or gas turbine [33, 34]. The synthesis gas ($CO+H_2$) having H_2/CO molar ratio between 1 and 2 can be converted to transportation fuels like mixed alcohol fuel, gasoline, and diesel fuel by the Fischer-Tropsch process [35, 36] with proper attention given to syngas cleaning and also for cooking [37].

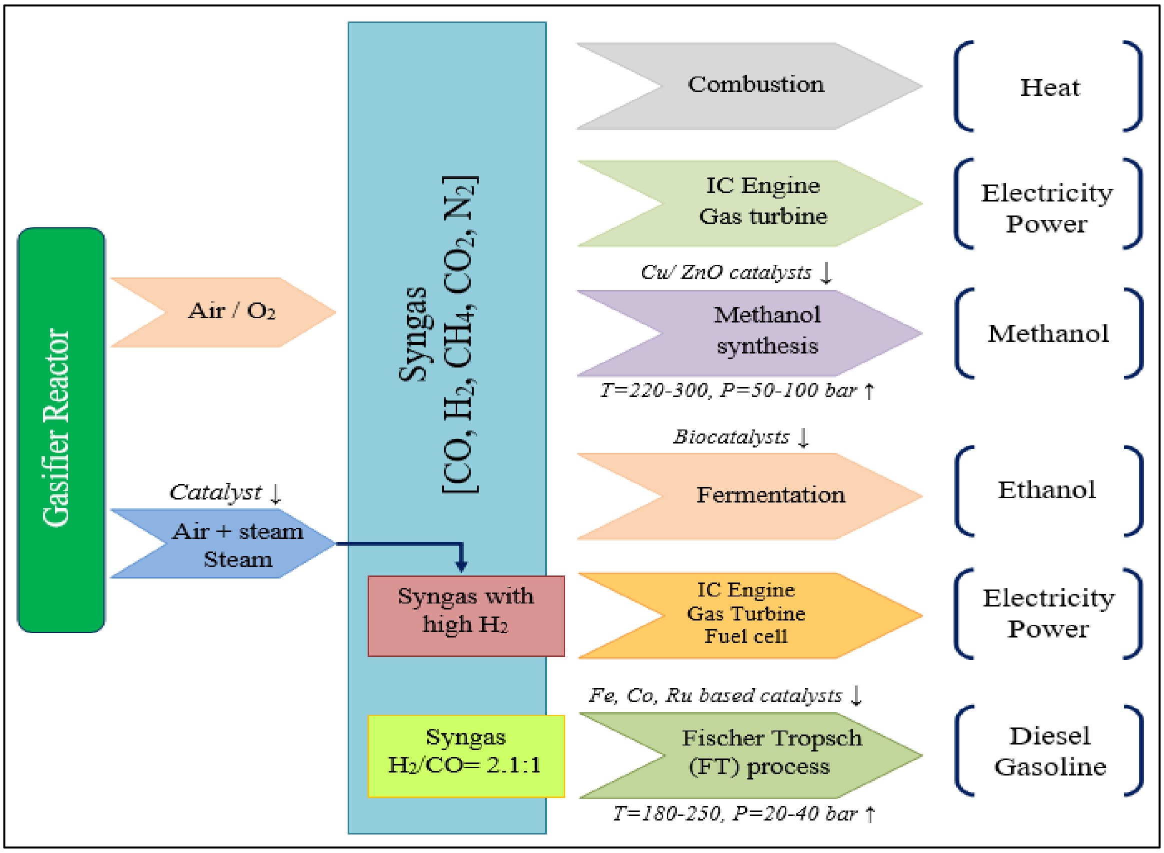

Figure 4. Conversion routes of syngas into different products.

4. Effect of Operating Parameters on Gas Distribution

Bubbling fluidized bed gasification of biomass is affected by reactor design and operating parameters like fuel moisture content, reaction temperature, etc., on syngas composition distribution, tar content, and overall performance of the gasifier system as explained below. It is important to understand the operating parameters' effect on the gasification process [38].

4.1. Effect of biomass fuel.

Biomass as a fuel and its characteristics play an important role in gasification, product gas distribution, and tar yield. Typically, biomass is characterized for determining the chemical compositions (cellulose, hemicellulose, lignin); elemental composition (C, H, N, O, S); inherent moisture, and proximate composition (volatile matter, fixed carbon, and mineral ash). For example, the proximate and elemental composition of some biomass feedstock used in

BFB gasification is shown in Table 2. These parameters are important as they influence the product gas composition and yield during biomass gasification. Therefore, the type of biomass used for gasification also influences the product gas distribution [39], which can be evident from Fig. 5 provided for different biomass.

Cellulose and lignin found in lignocellulosic biomass affect the product gas composition, as found for Japanese Oak and red pine bark, both having high cellulose and lignin [40]. The study on air steam gasification of four different biomass (white pine, citrus peels, *Posidonia oceanica*) found that lower yield of both syngas and hydrogen in the case of white pine than other feedstock, which may be due to the woody martial properties in term of lignin, cellulose, and hemicellulose [41]. The moisture content in feed material also shows the effect on product gas composition. The air-blown gasification of rice husk with 12 and 17 wt% moisture content showed that high moisture content leads to a decrease in bed temperature due to the endothermic nature of water evaporation, which in turn causes the temperature fluctuation, the problem in fluidization and massive coking [42]. The higher moisture content in biomass affects the water gas shift reaction and even the harvesting age of the tree, and the presence/absence of bark can adjust the syngas and tar profile [43].

Herguido *et al*., based on their research outcome, reported that the difference in gas yield is the result of the fast heating rate of the smaller particle in bed, which make the devitalization and char gasification steps during sawdust gasification at a faster rate than for wood chips. Therefore, at the higher reaction temperature, the amount of gas production is large according to the endothermic char reaction [39]. The heating rate of small biomass particles strongly influences the tar yield, char, and gas product devitalization [44, 45]. Esfahani *et al*. studied the hydrogen production performance for palm kernel shells at different particle sizes (0.1 mm, 2 mm, and 5 mm) and observed that in case of bigger particle size, the gas produced inside the particle is more difficult to diffuse out and the process is mainly controlled by gas diffusion [46]. The experimental study on steam gasification of the almond shell of four different particle sizes (0.3 mm,0.6 mm, 0.9 mm,1.2 mm) showed that the particle size affects the total gas yield and the yield of individual gas species. As particle size increased from 0.3 mm to 1.2 mm, H_2, CO, CO_2, and CH_4 yield decreased [47]. Larger particles produce fewer smaller particles after the gasification reaction, reducing fine particles [48]. Larger biomass particle, when gasified at a lower temperature, higher SB ratio, and higher adsorbent to biomass ratio, favors low SO2 and NO emission as found in the case of catalytic steam gasification of palm kernel shell (PKS) [49]. In contrast, a smaller particle of empty fruit bunch (EFB) produced more CO, CH_4, and less CO_2 than a larger one, while H_2 yield was almost the same [50]. Ash content in the biomass is also important for further elimination from the flue gas. Still, the ash having a low melting point shows the possibility of the formation of eutectic [39]. The main element in biomass responsible for forming eutectic is potassium and sodium in the form of K_2O and Na_2O [50] and bed agglomeration [51]. Ammonia concentration in syngas depends on nitrogen content in feedstock, operating conditions, and gasifying agents [52, 53].

Table 2. Proximate and ultimate properties of biomass used in BFB gasifier.

Feedstock	**Proximate analysis (%)**				**Ultimate analysis (%)**					**Calorific value MJ/kg**	**Reference**
	MC	**Ash**	**VM**	**FC**	**C**	**H**	**N**	**S**	**O**		
Rice straw	7.4	19.1	67.9	13.9	37.9	4.6	0.6	na	36.7	14.7[a]	[23]
Rice husk	8.3	19.3	71.4	9.1	36.1	4.8	1.9	na	37.9	13.2*	[54]
Wheat straw	4.51	12.69	72.29	10.51	40.53	5.35	0.65	0.14	36.13	13.87[b]	[55]
PKS	7.96	8.97	72.47	18.56	51.63	5.52	1.89	0.05	40.91	22.97[a]	[56]
PKS	12	8.97	30.53	48.5	51.63	5.52	1.89	0.05	40.91	24.97[a]	[46]
Eucalyptus	14	0.9	83	16.2	45.7	6.6	0.3	na	47.5	19.4[a]	[43]
Wood pellets	9.8	0.8	72.7	16.7	51.02	7.16	0.09	0.04	41.73	18.0[a]	[57]
HTS	22.11	14.16	71.40	14.45	42.29	5.74	0.42	0.07	37.32	19.58[a]	[58]
CGT	9.01	13.02	71.20	15.78	39.30	5.43	1.44	0.34	40.49	16.67[a]	[58]
EFB	7.80	4.50	79.34	8.36	43.52	5.72	1.20	0.666	48.90	15.22[a]	[59]
Sawdust	14.60	0.46	76.10	8.90	44.96	5.83	3.10	0.61	45.50	17.22[a]	[59]
Corn stalk	3.45	10.50	73.62	12.43	42.11	5.33	1.42	0.11	37.08	14.70[b]	[55]
Coconut shell	4.89	42.98	30.62	26.41	45.24	5.04	1.46	0.06	48.2	16.07[a]	[56]
Coconut shell	8.55	12.44	52.56	26.45	50.2	5.40	0.94	0.06	43.4	21.50[a]	[60]
Chicken manure	9.9	17.2	-	-	33.0	4.4	5.6	0.3	29.1	14.9[a]	[61]

[a]: higher heating value; [b]: lower heating value; *as reported; PKS: palm kernel shell; HTS: high tonnage sorghum; CGT: cotton gin trash; EFB: empty fruit bunch; PKS: palm kernel shell.

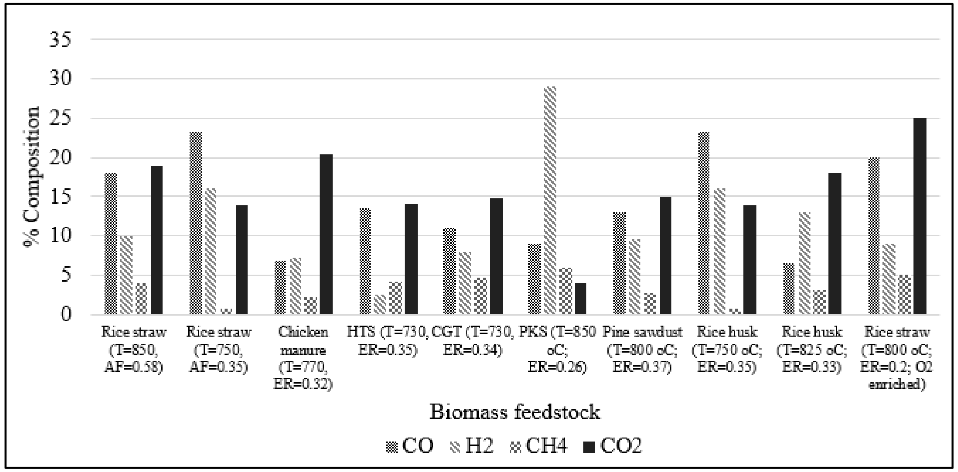

Figure 5. Product gas distribution for different feedstock.

4.2. Effect of temperature on gas composition.

Gasification temperature plays a crucial role in the final composition of the syngas. Temperature influences the fuel's reaction rate and controls some endothermic and exothermic reversible reactions and therefore affects the final gas production distribution, improves gas yield, and promotes low tar levels in the gasification progress [62, 63]. The effect of temperature using different gasification agents like air, oxygen, steam, or a mixture of these on gas composition and alteration in individual gases.

4.2.1. Air gasification.

Several studies have been reported on the air gasification of different biomass using BFB gasifiers and reported the effect of temperature on gas gasification. The experimental studies show a significant enhancement in the concentration of H_2 in syngas in the case of gasification of palm kernel shell, from 18 vol% to 39 vol% as temperature increased from 750^{o}C to 1100^{o}C [46]; coconut shell and palm kernel gasification, from 43% to 67% (mole) and 56% to 66% (mole) at temperature rise from 700 to 900^{o}C [56]; torrefied pellets of *Miscanthus + giganteus*, from 5.5% to 10.4% when the temperature in the bed was raised from 660 ^{o}C to 850 ^{o}C [64].

Nevertheless, the syngas from air gasification dilutes the syngas with nitrogen to a higher level which normally ranges about 50-55% of the total gas volume, leading to a lower gas LHV. Alternatively, gasification using oxygen or O_2-enriched air is considered to help reduce the nitrogen dilution effect and increase the reactor temperature [65] and gives medium heating value gas as oxygen-enriched air favor LHV due to less N_2 in the producer gas [66]; however oxygen gasification increase syngas heating value but requires high cost for pure oxygen [27]. The studies reported on gasification of refused derived fuel (RDF) with enriched air with oxygen (O_2) up to 44.7% [27]; and rice straw with O_2 enriched from 21% to 45% [67] showed that with increasing temperature, both H_2 and CO content increased remarkably with a significant decrease in CO_2 while CH_4 showed a limited increase. This improvement can be attributed to the thermal cracking of liquid and enhanced char reaction with the gasifying medium (air) [46]. Increased gas yield with temperature could be due to the reasons like (a) the initial pyrolysis reaction increases the production of gases at a faster rate with temperature, (b) strengthen the endothermic gasification reaction, which results in more H_2 and less CH_4 concentration, and further enhance gas yield (c) to promote the steam reforming reaction and the cracking of high hydrocarbon and tar leading to increase in the concentration of H_2, CO, and C_nH_m. According to Le Chatelier's principle, with the gasification temperature increment, an endothermic reaction such as a reforming reaction of CH_4 (R9), Boudourd reaction (R4), water gas reaction, and methanation reaction is improved, which results in the conversion of CH_4 and CO_2 to CO and H_2, along with the conversion of char and CO_2 to CO and H_2, reducing the content of CO_2 [65]. At increased temperatures, the Boudourd reaction (R4), partial carbon oxidation (R3), and water-gas reaction (R6) consume residual carbon, which improves CO content [68]. The reason for the decrease in CO_2 at elevated temperatures is that CO_2 is consumed by the Boudourd reaction (R4) [67], and the exothermic WGS reaction (R7) is shifted to the H_2O and CO side, which lowered the CO_2 yield [64].

On the other hand, Kuo *et al*. [69] state that, in air gasification, the WGS reaction is exothermic with minimal effect on temperature. In contrast, another endothermic reaction (R4, R5, R6) and tar decomposition contribute to increased H_2 and CO content with an increase in temperature. Figure 6 shows the variation in syngas composition for different biomass at different reaction temperatures, while Figure 7 presents the visible effect of temperature on gas composition.

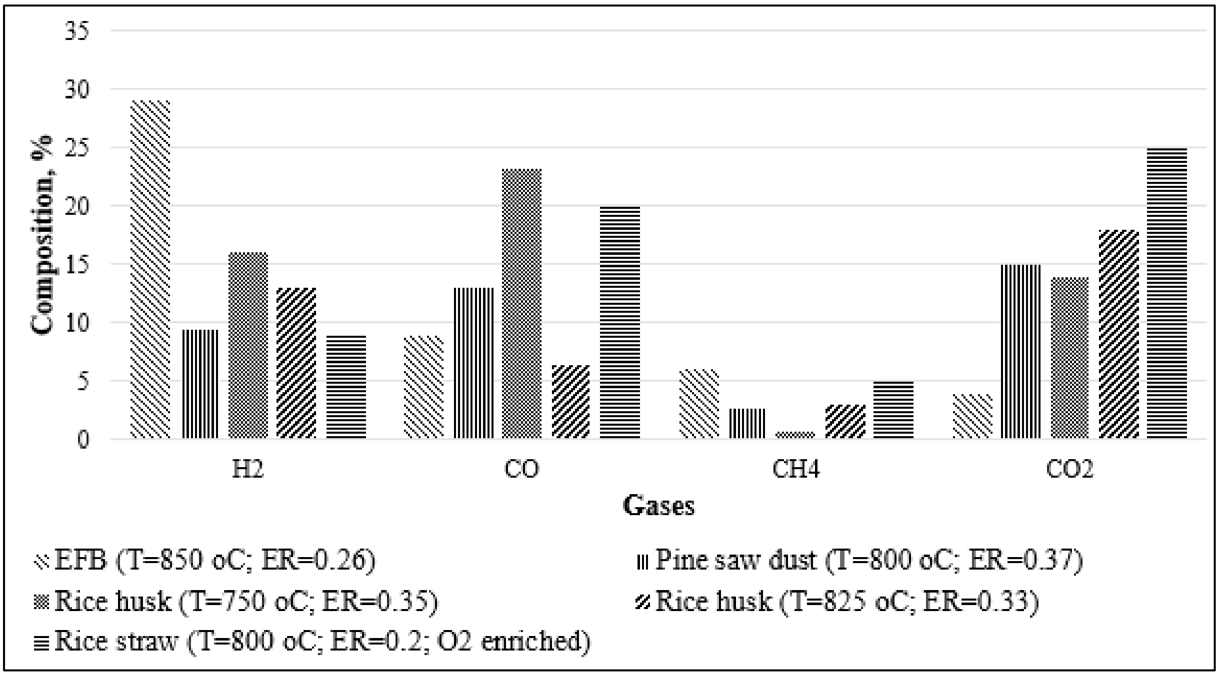

Figure 6. Syngas composition for air gasification of biomass.

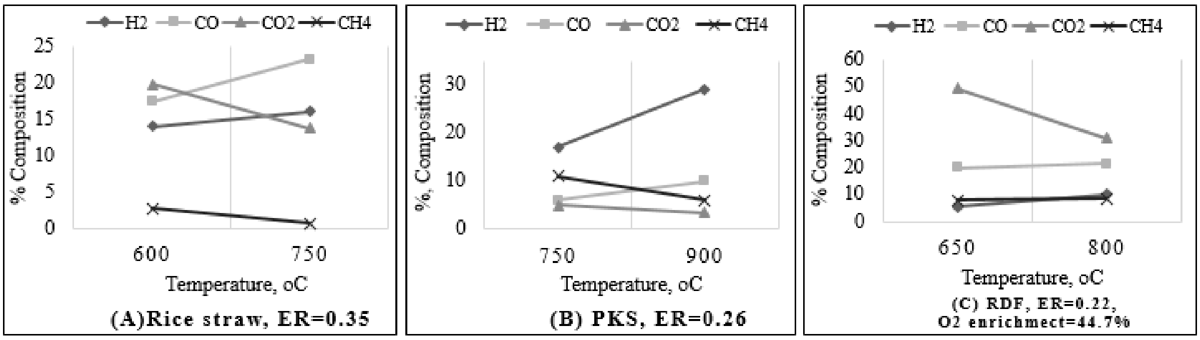

Figure 7. Variation in syngas composition for different temperatures.

4.2.2. Steam gasification.

Steam gasification of biomass has been considered an attractive process for generating hydrogen-rich syngas [70]. Air gasification produces syngas composition diluted by nitrogen, yielding a low heating value of 4-6 MJ/Nm^3 [14]. However, the use of steam has proven effective in producing good quality syngas rich in hydrogen, about 30-40%, and heating value up to 10-15 MJ/Nm^3 [71, 72], and H_2-rich syngas produced through this versatile route can be further used for varied applications. Steam performs a dual role as reaction material in the reforming reaction of hydrocarbon (R11) and the WGS reaction (R7). The temperature is crucial for overall biomass gasification. It is a major factor that affects H_2 production using steam or air steam [25] as the higher temperature is more kinetically favorable for water gas shift (WGS) reaction to produce H_2 [73]. Numerous studies have reported the effect of temperature and the enhancement of H_2 concentration in steam gasification of various biomass in BFB gasifiers at the reaction temperature between 700-900°C [74].

Yang *et al*. reported that as the temperature increased from 600°C to 800°C for steam gasification of cotton stalk chips, H_2 content increased by about 22% from 11.87% to 34.02% [3]. The trend in gas distribution with an increase in temperature, importantly for H_2, CO, and CO_2, has been reported by other researchers for different biomass like pine sawdust, pinewood chips, cereal straw, and thistles [39]; rice hull [75]; sawdust [76]; corn stalk, rice straw, wheat straw and peanut shell [55]. In combination with air, steam gasification is widely used as pure steam involves more cost. The experimental studies reported on the use of air +steam for the gasification of pine sawdust [77], wood pellets [14], and coconut shells [60]. As well study on steam + O_2 have been reported for corn stalks [78], and pine (*pinus pinaster*) chips [79] have reported a similar trend in gas composition.

The temperature must play an exceptionally important role in determining the gas composition, including reaction direction and reaction rate during steam gasification. The steam gasification follows Le Chatelier's principle, as discussed in section 4.2.1. The higher temperature is more kinetically favorable for water gas shift (WGS) reaction (R7) to produce H_2 [4], which is a dominant reaction in the temperature range of 600-800°C, enhancing cracking and reforming of volatiles relatively sufficient, due to which the increase reaction rate led to an upsurge in H_2 and CO_2 [71]. Han *et al*. reported that high temperature also promotes tar decomposition (R11), which is beneficial in producing more H_2 and favors greater conversion of char and tar into gases increasing the gas yield [76]. However, the situation for CO content is the opposite, as evident from the studies, which are attributed to the reason that the WGS reaction consumes part of CO, which results in a decrease in CO concentration in case of the rapid increase in H_2 and CH_4 [80]. Carbon dioxide is mainly formed by primary cracking of the C=O functional group, steam reforming of pyrolytic volatiles, and WGS reaction [55]. According to Acharya *et al*. [81], high temperature is not always beneficial for exothermic WGS reaction; rather, enhanced H_2 production is due to a reforming reaction which is all prompted by increased temperature. Figure 8 shows the syngas composition for the steam gasification of different biomass. In contrast, Figure 9 shows the compositional change in different gas species, especially on enhanced H_2 during steam gasification can be seen clearly.

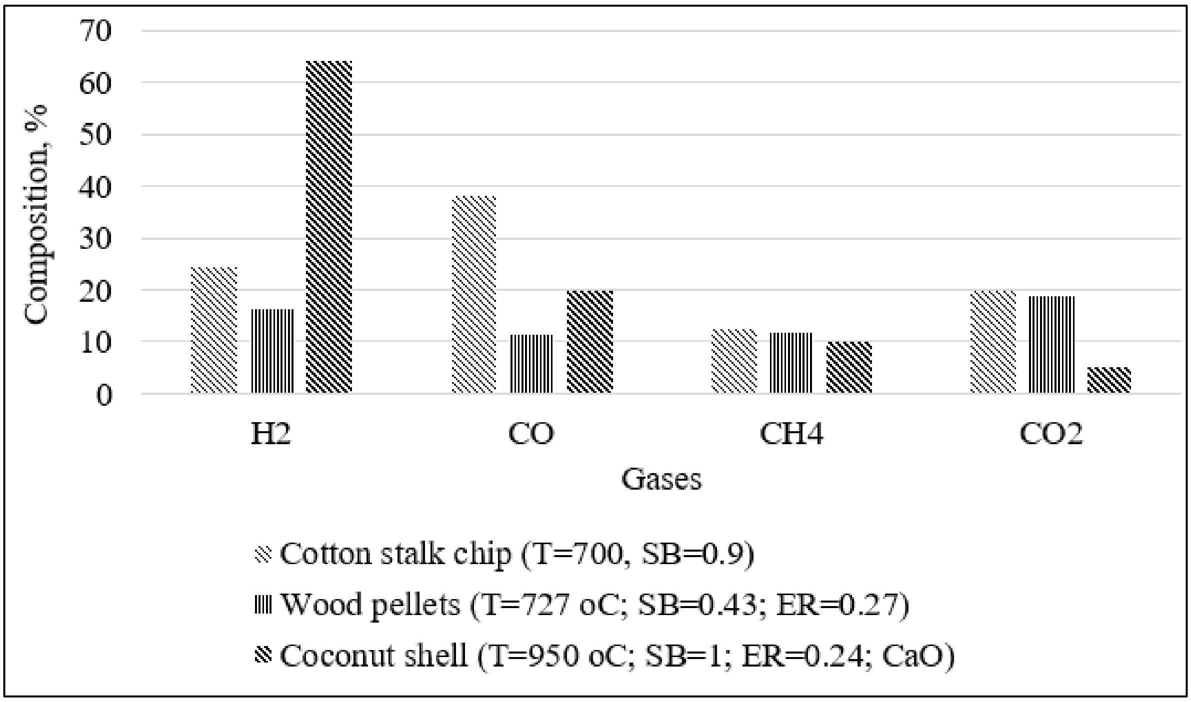

Figure 8. Syngas composition for steam gasification of biomass.

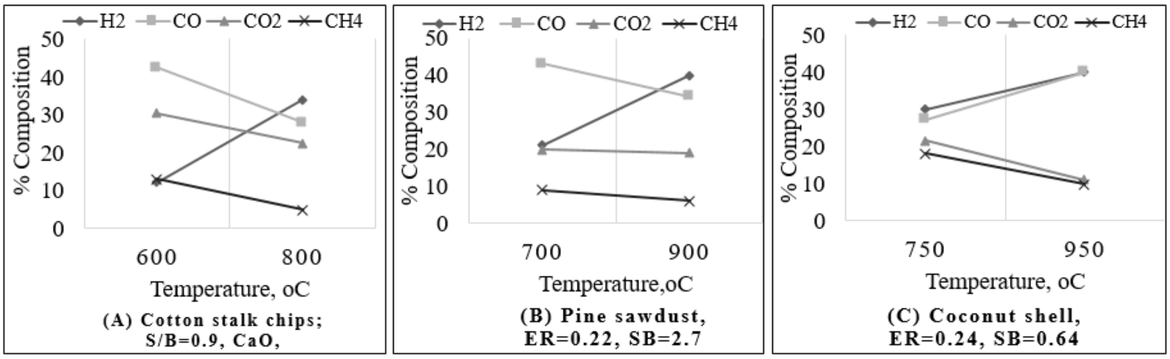

Figure 9. Variation in syngas composition for different temperatures.

4.3. Effect of equivalence ratio (ER).

Equivalence ratio (ER) is defined as the ratio of the amount of oxygen (air) needed for the stoichiometry combustion of the fuel and generally varies from 0.20 to 0.40 for biomass gasification [82]. It can be seen from several studies that ER plays a vital role in the determination of gasification performance. Normally ER represents the quantity of oxygen introduced to the reactor; it affects the gasification temperature (bed temperature) under auto-thermal operation [25, 83]; has a significant influence on the composition of the product gas and overall gasification efficiency [57]. The studies reported show that higher ER generates higher temperature, which accelerates oxidation reaction and helps to improve the product quality to a certain limit [56]. At higher ER, an increasing degree of combustion reactions releases more heat to intensify tar secondary cracking reaction, which increases produced flammable gases in the combustion reaction increasing gas yield [67]. On the other hand, lower ER makes less O_2 available for the gasification reaction to complete, thus affecting the gas composition with either value of ER [46]. It has been reported that with an increase in ER, the gas yield increase while a decrease in tar and LHV of gas is observed [82].

Narvaez *et al*. [82] reported that varying ER from 0.20 to 0.45 at T=800^oC for air gasification of pine (*pinus pinaster*), the maximum concentration of H_2 was obtained at low ER= 0.26, while as ER progressed to 0.45, the concentration of H_2, CO, CH_4, and C_2H_2 showed a decreasing trend. The results agree with the results reported for gasification of coconut shell and palm kernel shell varying ER from 0.15 to 0.45 [56]; and torrefied miscanthus at varying ER= 0.18 to 0.26 and *T*=800 ^oC [64]. Liu *et al*. [67] reported almost the same trend when O_2-enriched air at 30% was used for gasification of rice straw varying ER =0.15 to 0.24 and *T*=700 ^oC, and observed that concentration of H_2, CO, and CH_4 decreased while the increase in CO_2 content. It is noted that at the higher ER or fluidization velocity, more air is supplied, and hence more char can be combusted to form CO_2 at the expense of other combustible gases such as H_2 and CH_4 [84]. This showed that with higher ER values, oxidation of a larger fraction of carbon in feedstock takes place, along with partial oxidation of combustible gases like H_2 and CO, which results in a large increase in CO_2, with more dilution of N_2.

4.4. Effect of steam to biomass (S/B) ratio.

Steam to biomass (S/B) ratio is one of the key factors affecting the gasification results as it influences the gas composition; though it is less than temperature but notable in gas yield and gasification efficiency. The S/B ratio is defined as the amount of steam supplied to a known amount of biomass during gasification [85]. Steam is introduced into the gasification process to advance the steam reforming of tar and hydrocarbon (R11) and the WGS (R7) reaction, improving H_2 concentration and the total gas yield. The highest S/B ratio or steam to carbon (S/C) ratio is found to produce a gas composition with higher H_2 and CO_2 content and lower CO and CH_4 concentration due to dominant water gas reaction (R6) and WGS reaction (R7) [86]. Steam –biomass (S/B) ratio reflects increasing steam concentration, and partial pressure corresponds to the Le-Chateliers principle. Increasing the S/B ratio enhances the water gas (R6), WGS (R7), steam methane reaction (R8), and hydrocarbon reforming reaction (R11), which increases the H_2 and CO_2 output and decreases CO content. WGS reaction, which is exothermic and therefore thermodynamic equilibrium, shifts toward the right direction at a higher S/B ratio, enhancing H_2. Methane CH_4 content depends on methanation reaction (R5) and steam reforming reaction (R8). Steam reforming reaction strengthens when S/B increases, and methanation reaction strengthens when H2 content increases. Therefore a slight decrease in CH_4 is observed.

Several studies have reported the effect of the S/B ratio on gas composition. Loha *et al.* studied air-steam gasification of rice husk at an S/B ratio from 0.2 to 0.8, at T=800 ^oC and ER=0.35 and found that H_2 content increased from 7.6 to 11.8%, and CO decreased from 13.7 to 12.7% [87]. The increase of H_2 and CO_2 with decreasing CO with increasing S/B is due to the increase of homogeneous water gas shift reaction (R7) and water-gas reaction (R6) in the presence of H_2O. However, they reported that excessive steam reduces temperature, lowering the concentration of hydrogen [88]. The same trend of a significant increase in the concentration of H_2 for steam gasification of sawdust at S/B= 0.3-1.0 and T=800^{o}C [89]; and coconut shell at S/B=0.16-3.1 and T=950^{o}C [60]. The introduction of steam in biomass gasification increases the gas yield. However, excessive steam lowers the reaction temperature, which may cause a decrease in gas yield and H_2 yields, and benefits only when the amount of steam entering the gasifier is less than the amount of reaction balance requirement [77, 78]. Increasing the energy consumption of the system [90, 91] as more heat is absorbed by excess steam and, in that case, the use of external heating may reduce the influence of the higher S/B ratio [92]. Providing too small a ratio can lead to an inconsiderable value of H_2-rich gas, while too large a ratio will reduce the activity of water gas shift reaction resulting in lower gas yield and reducing gas quality [80, 81]. Therefore, the S/B should not be too large in the actual gasification process [55]. It becomes important to find an optimum point in the conversion process since a too-large S/B ratio does not favor syngas production and is not cost-effective [60].

4.5. Effect of catalyst.

The major technical problem in biomass gasification development is the organic compound (tar) in the syngas, which is formed during the gasification process [93] which creates many operational problems either in the gas engine or extensive fouling and blocking of the downstream pipeline due to condensation at a lower temperature and put a major challenge in commercialization of the technology [7]. Generally, tar is formed in the pyrolysis step due to the decomposition of lignocellulosic biomass with mainly oxygenated hydrocarbons [94]. The difference in chemical composition and nature of biomass polymers results in different tar formation characteristics of different types of biomass during gasification. Tar formation causes catalyst deactivation, operation interruption, and production of the carcinogenic element [95]. Furthermore, tar condenses under reduced temperatures, causing polymerization in such equipment as engines and turbines [96].

Many efforts have been made to remove gasification tar through physical and chemical methods, such as filtration/physical removal (non-catalytic cracking) and catalytic cracking. The catalysts are naturally occurring minerals, alkali catalyst, or noble metals like Ni-based catalyst, which promote tar cracking and reforming and enhances the concentration of H_2 and CH_4 [97]. For fluidized bed gasification, the catalyst must have high chemical activity, be effective in tar removal, have good mechanical properties, be resistant to deactivation, and be low cost [98, 99]. Catalytic steam reforming is the most attractive technique for removing tar in the presence of a catalyst. A catalyst can remove tar more effectively and simultaneously convert it into useful gases (H_2, CH_4, and CO) at a lower temperature [94]. The different types of catalysts that could be used in biomass gasification are given in Table 3.

Table 3. Different catalysts for biomass gasification.

Catalyst	Examples	Merits	Issues
Natural catalyst	Dolomite Olivine Shell	- cheap occurs abundantly - efficiently tar decompose - directly use in FBG - olivine has high mechanical strength	- Moderate reforming efficiency - dolomite has poor mechanical strength - porous and fragile at high temperature
Alkali metal catalyst	K_2CO_3 Carbonate Sodium carbonate Trona Borax	- High reforming efficiency - High H_2 yield - better catalytic cracking	- increased plugging issue - methane reforming reaction >800 °C - particle agglomeration if used with biomass - not suitable as a secondary catalyst
Nickel-based catalyst	Ni/olivine NiO/Al_2O_3 $Ni/CeO_2/Al_2O_3$ $Ni_2MgAl_4O_8$ Ni/ZrO2, Ni/TiO2, Ni/CeO2 Ni/MgO	- High reforming efficiency - High H_2 yield - tar conversion of more than 99% - best as secondary catalysts	- gradual deactivation - relatively expensive - high investment cost - long lifetime for economical operation when operated at 780 °C - coking is particularly prevalent with nickel catalysts

4.5.1. Dolomite.

Dolomite ($MgCO_3{\cdot}CaCO_3$), a magnesium ore), an attractive material for catalytic tar cracking, is extensively investigated and used. Dolomite is generally the preferred guard bed or an active primary catalyst bed for removing heavy hydrocarbon so that expensive and sensitive metal catalyst safeguard from deactivation caused by tar or other impurities and decomposes tar efficiently at the operating condition. It can provide relatively high tar conversion, decrease the risk of agglomeration, and provide the advantage of anti-sintering properties as bed material in fluidized bed gasifiers [100]. Conversely, dolomite is soft having poor mechanical strength [54], which makes it susceptible to attrition in the fluidized bed producing larger fluxes of small eroded particles which could plug pipes in the downstream process [74] and may undergo the calcination process at high temperature due to its fragility [101].

Numerous researchers worked on dolomite catalysts in FBG gasifiers as a bed material or additive. The air-steam gasification of sewage sludge in the presence of dolomite found that H_2 content increased while tar content decreased, reaching a tar removal efficiency of up to 71% [102]. Yang *et al*. reported that steam gasification of cotton stalk (T=700°C and S/B =0.9) dolomite bed gave better results for H_2 generation at 31.45% compared to olivine bed (23.72%) and quartz bed (22.79%) resulting in higher H_2/CO ratio than other bed [3] and similar observation is reported by another author for air-steam gasification [103]. Atmospheric fluidized bed gasification of birch wood at T=700-800 °C using a different kind of dolomite showed a high H_2/CO ratio [104], whereas an increase in H_2/CO ratio to 2.2 from 1.3 (air gasification without catalyst) is reported for air-steam gasification of sewage sludge [105]. Zhou *et al*. reported that crystalline dolomite (Glanshammar) has better stability in term of mechanical strength and a pore structure, allowing a much swift release of gases produced during the calcination process compared to amorphous dolomite (Sala), which have similar quantities of CaO, MgO, and SiO_2 [74].

4.5.2. Olivine.

Olivine, as dolomite, is a natural mineral having magnesium, iron, and silicon in the form of Fe_2SiO_4 or Mg_2SiO_4 [106], which has tar conversion capabilities due to the presence of magnesite (MgO) and iron oxide (Fe_2O_3) [93]. Olivine is durable for a prolonged operating period in the temperature range of 800-950°C [107]. Olivine mainly consists of silicate minerals in which magnesium and iron cations are embedded in the silicate tetrahedral [108]. According to the reports, better catalytic activity in the destruction of tar and mechanical strength at high temperatures (>800°C) [97], which makes olivine a superior choice to be used in fluidized bed gasifiers compared to dolomite and quartz sand [109]. According to some reports, olivine in its natural form or untreated state has a limited catalytic efficiency [100], which can be improved by calcination of olivine [110, 111] or loading some active metals (e.g., Fe, Ni, Co, Ce, etc.) [112]. Calcinated olivine is more active than untreated olivine due to the migration of the iron to the surface of the bed material after pre-treatment [113].

Rapagna *et al.* used an olivine bed for steam gasification of the almond shell (T=770°C, S/B ratio=1); H_2 and CO_2 increased to 52.2 vol% and 16.9 vol% respectively, compared to 43.6 vol% and 11.7 vol% for sand bed, whereas, CH_4 showed a decrease to 7.9 vol% from 11.5 [97]. Olivine was useful in generating fewer fine particles and consumed 66% less energy for bed heating than dolomite during rice husk gasification [114]. It is reported that NiO loading improves the efficiency of olivine, as observed in the steam gasification of Miscanthus x giganteus, where H2 yield increased at 50% compared to raw olivine, between 37.6 to 46.2% [115].

4.5.3. Calcium oxide (CaO).

Calcium oxide (CaO), with the main components of CaO, has attracted great research interest and gained broad attention due to its lower cost and abundance [32, 116]. The use of CaO in the gasification process is a novel one-step conversion technology developed for H_2 production in recent years. Though steam gasification increases H_2 to a higher percentage in syngas, it does not favor simultaneous CO_2 increase [117]. Much research has been reported the use of CaO to produce a high yield of H_2 with parallel capture of CO_2 [118, 119], where CO_2 produced during gasification is captured by CaO sorbents through the process of CaO carbonization [120]. Furthermore, it enhances the gasification process to increase the H_2 conversion and yield by CO_2 absorption and tar reforming process acting as a tar reduction catalyst [121].

The use of H_2 enrichment along with catalytic conversion using CaO in a BFB gasifier has been investigated by many researchers. A comparative study of calcined limestone (CaO) with sand and calcined waste concrete for steam gasification of larch and cellulose capsule showed that calcined limestone produced high gas yield with high H_2 content with high H_2/CO

ratio compared to sand and calcined concrete. The higher content of H_2 and CO_2 and lower CO content is the result of the catalytic role of CaO in converting CO to H_2 and CO_2 via a water gas shift reaction [117]. During steam gasification of palm kernel shell, the researcher observed a gradual increase in H_2 content from 62.52 vol% to 82.11 vol% as the CaO/B ratio increased from 0.5 to1.0, which can be explained as CaO facilitating more CO_2 adsorption and lowering its partial pressure in the system via WGS reaction to produces more H_2 [49]. The ratio of CaO/C shows a significant influence on H_2 concentration as it increased from 34.5% to 59.1% at CaO/C ratio =2, for steam gasification of sawdust, at H_2O/C= 1.2 and T=740°C [116]. As an absorbent, when CaO reacts with CO_2 produced during steam gasification, it decreases CO_2 and CO, simultaneously shifting the chemical reaction equilibrium of the WGS reaction (R7), resulting in the generation of more H_2 [122]. At the same time, the catalytic effect of CaO intensifies the cracking and gasification of pyrolytic volatiles to produce more H_2 [118]. A Higher CaO/C ratio increases the contact frequency between the tar species and gases, increasing CO_2 absorption [76].

4.5.4. Nickel (Ni) based catalyst.

The nickel-based catalyst has the highest attention of researchers and is widely used in industrial processes to hot gas cleaning in biomass gasification. Nickel-based catalyst is 8 to 10 times more active than dolomite [93] and are used extensively for biomass tar conversion because of their higher destruction activity, along with added activity for methane reforming and water gas shift [123] and are widely used in the industrial process for hot gas clean-up in biomass gasification [124]. But the Ni-based catalyst gradually deactivates when the throughput of tar coming with gas to the catalyst bed is high, mainly by carbon deposition on the catalyst [100]. Some research has been reported on catalyst support where nickel-based catalysts are used to improve the stability and activity of olivine, dolomite [125], alumina [126], and silica [127].

The experimental study on commercial Ni/Al_2O_3 catalyst and Ni-laded brown coal char (Ni/BCC) for steam gasification of red pine wood chip + compost shows that Ni/BCC with similar Ni loading obtained the higher gas yield of H_2, CO, CH_4, and lower tar. Ni/BCC showed the concentration of tar decreased from 2.5% to 1.4% and showed the same catalytic activity as Ni/Al_2O_3 and resistance to deactivation, unlike Ni/Al_2O_3 [86].

5. Gas Yield

The gas yield is defined as the flow rate (dry basis) produced to the mass flow dry ash-free biomass feedstock ($Nm^3/kg_{biomass}$). Gas yield and quantity per unit mass of agro-waste biomass provide important information about the capability of the waste biomass to be converted to a different product [56]. Temperature is one of the important operating parameters as total gas yield increases monotonically with temperature [128] because of enhanced endothermic steam reforming, cracking reaction of the tar, and char gasification at elevated temperatures [129]. The higher temperature facilitates more conversion of char and tar into gases enhancing gas yield [81]. Depending on the operating parameters like temperature, gasification agents, equivalence ratio (ER), catalyst, and pressure, gas yield may vary and has been reported in studies for different biomass fuels in bubbling fluidized bed gasifiers, as discussed below.

Air gasification of *Miscanthus-giganteus* showed that when temperature increased from 700 to 850 °C, gas yield increased almost by 23% from 1.7 to 2.1 $Nm^3/kg_{biomass}$ [64]. Air gasification of rice husk [130], rice straw (30% O_2 enriched air) [67], and coconut shell and palm kernel shell [56] have reported similar observations. The use of catalyst shows a positive effect on gas yield as observed in air gasification of pine dust mixed with 2-5% calcined dolomite at T=750-850°C, the gas yield varied between 2.1 to 2.5 $Nm^3/kg_{biomass}$ (dry ash-free basis) [82]. The increases in ER release more heat/temperature due to increased combustion, which promotes tar secondary cracking reactions resulting in more flammable gases involved in combustion reaction favoring high gas yield [67], as well as the promotion of initial pyrolysis rate at a high temperature which increases the gas production, or steam cracking and reforming of tars at high temperature and improved endothermic reaction of char gasification [131].

Biomass gasification using air steam improves the quality of syngas, and increasing the S/B ratio improves the overall syngas yield, and higher temperature and higher S/B led to higher gas yield [132]. The claim is supported by some experimental results like air-steam gasification of beached *Posidonia oceanica* and citrus peels at 1023 K, ER= 0.3 and S/B=0. The gas yield was almost the same for both feedstocks at 2 $Nm^3/kg_{biomass}$, whereas at S/B=1, syngas yield increased to 2.64 $Nm^3/kg_{biomass}$ [41]. The results are in good agreement with the air-steam gasification of pine sawdust [25] and coconut shells in the presence of dolomite [60]. However, the use of excess steam decreases the temperature and does more harm to the conversion of biomass to gas. The result showed a consistent decline in the total gas yield with an increase in S/B ratio with white fir [81].

6. Calorific Value, CCE%, and CGE%

Carbon conversion (CCE) expresses the transformation of the carbon contained in the fuel to gaseous species [14]. High temperatures enhance carbon conversion efficiency due to tar cracking and char gasification reaction to yield gas [133]. However, the temperature increase> 850°C does not enhance carbon conversion due to a reduction in CO_2 content despite CO production [59]. In steam gasification, with an increase in S/B, gasification efficiency, LHV, and carbon conversion rate increased largely [3, 25]. Increasing ER also affects calorific value and CGE. At the higher ER, gas yield increases with a decrease in tar but also decreases the LHV of the gas [82].

An investigation on air gasification of pine sawdust (*pinus pinaster*) showed that as ER increased from 0.25 to 0.45, the LHV decreased from 5.2-7.0 MJ/Nm^3 to 3.5-4.5 MJ/Nm^3 at ER=0.45 [82]. Air gasification of rice straw in A/F ratio = 0.579 and T= 850°C, gave a quality gas with HHV of 5.14 MJ/Nm^{-3} and CGE of 52% [23]. *Eucalyptus* gasification (T=935°C) gave about 83.6 to 91.1 % CCE with LHV of 3.08 to 3.83 MJ/Nm^{-3} [43]. As the ER and temperature increase, CCE also increases, whereas, at lower ER, CGE is supposed to be higher and decreases as ER increases [130]. At the same time, an increase in ER decreases the HHV due to reduced concentration of H_2 [64] which is also true in case of using O_2 enriched air [67].

The introduction of steam increases gasification efficiency, LHV, and carbon conversion rate. It was found that with an increasing S/B ratio from 0.3 to 1.1 at T=700°C, gasification efficiency increased from 15.46% to 42.53%, and the carbon conversion rate increased from 20.52% to 53.21%. A slight decline in LHV was observed from 12.98 MJ/Nm^3 to 12.16 MJ/Nm^3 as S/B increased from 0.3 to 1.1 [3]. The carbon conversion increases with increasing S/B ratio.

Table 4. Performance of gasifier with different biomass, gasification agents and catalyst.

Gasification agent	Biomass	T,°C	Catalyst	ER	S/B	H_2	CO	CO_2	CH_4	CV MJ/Nm^3	CCE, %	CGE, %	Reference
						vol%							
Air	Rice husk	800	-	0.35	-	16.08	23.24	13.83	0.73	5.28	85.43	54.62	[130]
	EFB	770	-	0.21	-	5.55	16.62	4.31	19.24	4.53	71	40	[59]
	HTS	730	-	0.35	-	5.24	13.56	14.06	4.11	4.09	82.28	42.64	[58]
	Pine saw dust	800	Dolomite	0.37	-	9.5	13.0	15	2.7	4.6	-	-	[82]
*Air+O_2	RDF	800	Dolomite	0.22	-	13	30	27	7.0	8.62	79.52	54.85	[27]
Steam+Air	Wood pellets	752	-	0.23	0.18	14.6	13.8	16.9	5.2	5.2	89	40	[14]
	Wood residue	823	Ni/Al_2O_3	0.17	0.71	24.71*	20.22	42.24	9.57	-	72.12	45.12	[135]
Steam + catalyst	Almond shell	770	Dolomite	-	1	55.5	24.0	14.1	6.4	10.94	-	-	[97]
	Almond shell	770	Olivine	-	1	52.2	23.0	16.9	7.9	11.37	-	-	[97]
	PKS	675	CaO, Ni	-	2	84.62	4.27	1.15	9.95	13.34	20.61	27.21	[49]
	Wheat straw	650	CaO	-	1	61.23	15.55	9.13	12.11	13.37**	-	-	[55]
	Corn stalk	650	CaO	-	1	58.69	16.34	9.58	13.28	12.79**	-	-	[55]

EFB: empty fruit bunch; HTS: high tonnage sorghum; PKS: palm kernel shell; *adopted from graph; **calculated values.

Still, the excessive quantity of low-temperature steam lowers the reaction temperature, which causes the gas quality to degrade and hence decreases the LHV and CCE [134]. The syngas composition, CCE, CGE for different biomass at different operating parameters is shown in Table 4.

7. Tar

The major drawback of syngas production through biomass gasification is the generation of contaminants like tar, particulates, hydrogen sulfide, hydrogen chloride, and other undesired compounds [136]. The various factors that affect the amount and composition of the tar during the gasification are reaction temperature, equivalence ratio, feedstock composition, moisture content of the feedstock, residence time, and gasifier pressure [137]. The tar yield may vary between 0.5-150 g/Nm^3 [138], and its amount in product gas accounts for about 5% to 15% of total energy, which is difficult to use efficiently and leads to lower gasification efficiency [67].

7.1. Tar cracking methods.

The raw syngas from the gasification process contains impurities, as discussed, regardless of the type of gasifier, and need to be cleaned for tar and particulates before the end application. Generally, two methods are applied for tar destruction thermal tar cracking and catalytic tar cracking. The thermal cracking method uses high temperatures to heat the raw gas derived from gasification or pyrolysis so that tar molecules in the gas can be cracked into lighter gases [139]. To achieve high tar cracking efficiency, the temperature requirement is required in the range of 1000^oC to 1300^oC with sufficient residence time [140, 141]. Catalyst tar cracking converts the tar into useful gases. It adjusts the composition of the product gas, where the catalyst performs the dual role of purification and compositional adjustment of the product gas. Tar cracking is achieved by passing the hot syngas over a solid catalyst in a fluidized bed or fixed bed under temperature and pressure conditions [98]. From an economic point of view, the catalytic process is a promising alternative that gives a high degree of purity at low temperatures and simultaneously increases the fuel value. The temperature range from 350-700^oC is desirable for the efficient cracking process of tar [142]. Catalytic cracking is the most feasible method since the removal of tar and the reduction of methane content, and the conversion of a hydrocarbon to syngas increases the biomass gasification process's efficiency and economic viability [60, 98]. Catalytic tar conversion can be done by adopting two methods: Mixing catalyst with biomass feedstock to achieve catalytic gasification, also called in-situ, which converts tar inside the reactor. The second approach uses a separate reactor (secondary reactor) located downstream of the gasifier and converts tar outside the gasifier. Although the latter has high effectiveness in removing tar, it is either costly or complex for that small and medium-scale systems. Table 6 shows the tar content for some biomass used in BFB gasifiers with different gasification agents and bed materials.

Table 6. Tar yield from different biomass used in BFB gasifier.

Biomass	MC, (%wb)	T, °C	ER	SB ratio, S/C ratio	Bed material	Tar content g/Nm^3$_{daf}$	Reference
Rice husk	8.3	720	0.3	-	Silica sand	7.26	[143]
	8.3	855	0.3	-	Silica sand	0.33	
Chicken manure	11	700	0.34	-	Quartz sand	11.2	[61]
	11	770	0.34	-	Quartz sand	1.92	
Wood pellets	6.3	804	0.35	0.22	Ofite	-	[14]
	6.3	789	0.33	0.45	Ofite	-	
Coconut shell	8.55	850	-	2	Dolomite	7.63	[60]
Wood pellets	9.8	850	0.25	1	Silica sand	38.79	[144]
	9.8	850	0.25	1	Limestone	4.39	
Straw pellets	10.3	850	0.25	1	Silica sand	35.32	
	10.3	850	0.25	1	Limestone	9.85	
Wood pellets	8.1	939	0.48	-	Silca sand	2.5	[145]
	8.1	939	0.39	-	Silica sand	3.8	
Cotton stalk chips	13.3	800	-	0.9	Olivine	19.72	[3]
	13.3	700	-	0.9	Dolomite	31.34	
	13.3	700	-	0.9	Olivine	39.20	
	13.3	700	-	0.9	Quartz	52.14	
	13.3	700	-	0.3	Olivine	136.95	
	13.3	700	-	1.1	Olivine	38.1	
Pine sawdust	23.5	800	0.32	-	Silica sand	-	[82]
	21.0	800	0.37	-	Silica sand	-	
	23	800	0.47	-	Silica sand	-	
Almond shell	7.9	770	-	1	Sand	43	[97]
	7.9	770	-	1	Dolomite	0.6	
	7.9	770	-	1	Olivine	2.4	

MC: moisture content; T: gasification temperature; SB ratio: steam to biomass ratio; S/C; steam to carbon ratio; daf: dry ash-free basis

8. Bed Material

Different materials with catalytic and non-catalytic effects can be used as bed material in fluidized bed gasifiers, as mentioned in Table 7, depending on the final requirement of the syngas quality. Silica sand is a commonly used bed material due to its inert nature and better heat transfer. Industrial sand with porous bed material mixed with silica gel, zeolite, and activated alumina generates higher H_2 concentration and gas yield and higher quality of gas than ordinary bed material due to larger surface area and more conducive to heat transfer than general sand material [78]. Quartz sand, a common bed material, is wear-resisting, easy to obtain, and suitable for heat conduction media but lacks catalytic effect [3]. Naturally occurring dolomite and olivine are widely used bed materials as they are available at low cost and abundantly [146] as both show good performance for tar destruction and increase in production of permeant gases [97]. Calcined dolomite exhibits good catalytic activity but has poor mechanical strength, which gives a large production of fines due to fragmentation [147], while olivine gives negligible fines under the operating conditions of a fluidized bed gasifier [97]. Magnesite (MgO 45% + CO_2 50%) has proven to have tar conversion capabilities due to its Mg and Fe [1], and MgO as a bed material could help in preventing bed agglomeration, too [23]. Calvo *et al*. used alumina-silicate sand (210 µm) and magnesium oxide (40-100 µm) in rice straw gasification. However, it faced the issue of agglomeration for alumina-silicate beds [23].

Table 7. Bed materials used in bubbling fluidized bed gasifier.

Bed material	Composition	Particle size	Density kg/m^3	Reference
Glass bead	SiO_2,CaO, Fe2O3	0.2−0.8 mm	1470	[46]
Olivine sand	SiO_2, MgO, FeO + Fe_2O_3	0.5-1.5 mm	1550	[148]
Alumina-silicate	Al_2O_3.SiO_2	210 µm	2300*	[23]
Magnesium oxide	MgO	40-100 µm	3580*	[23]
Olivine	MgO, SiO_2, Fe_2O_3	0.410 mm	2500	[97]
Alumna bauxite	Al_2O_3. SiO_2 *	20-40 mesh	1422*	[149]
Ofite	Ca, Mg, Fe, Ti, $Al_2(SiAl)_2O$	290 µm	2650	[14]
Quick lime	CaO, MgO	0.15–0.25 mm	3340*	[49]
Calcined dolomite	$MgCO_3$ $CaCO_3$	0.450 mm	1534	[97]

*web/internet adopted values.

The static bed height ratio, i.e., height to diameter (H/D) ratio, also affects the gas yield as an increase in static H/D ratio from 1.26 to 2.52, primary gas yield increased by 7%, lowered char yield, and improved CCE [43]. At the fixed fluidizing velocity, increasing the bed height ratio would prolong the product's time in the high-temperature dense bed, which can favor the secondary cracking of the tar and heavy hydrocarbon and char reaction, increasing the gas yield [150]. However, there might be an optimum bed height for a particular ER at which gas yield reaches a maximum, but too high a bed height has a negative effect due to forming a large bubble [56].

9. Agglomeration in BFB Gasifier

The high temperature in fluidized bed gasifiers is associated with the agglomeration of bed material, which poses a major challenge in fluidization involved in biomass fluidized bed gasification. The lignocellulosic biomass gasification has a greater tendency towards bed material agglomeration as most biomass fuels contain alkali metals that could cause agglomeration in FBG, which may result in an unscheduled system shutdown [69]. The tendency of agglomeration is mainly dependent on temperature, bed material, ash content, and composition. Therefore, BFB gasifier should use fuels with high ash melting temperature or operates at a temperature lower than ash melting temperature to prevent bed agglomeration and further de-fluidization [15]. However, it is notable that gasification temperature above 950^{o}C has little impact on gasification [151]. Therefore most of the fluidized bed gasifiers are operated in the temperature window of 800-900^{o}C for biomass feeds [17]. Air gasification of grass pellets in a bubbling fluidized bed reactor has shown an agglomeration above 800^{o}C due to high ash content [152]. The gasification above the slagging temperature, silica and potassium oxide in ash fuses on the surface of rice husk char particles forming a glass-like barrier that prevents the further reaction of the carbon [153]. Therefore, low gasification temperatures at 600^{o}C to 650^{o}C prevent sintering and agglomeration of ash [84, 154]. However, temperature reduction would not be a suitable option for preventing bed agglomeration as it decreases the energy performance of the BFB gasifier [155].

Alkali-induced agglomeration and de-fluidization of the bed may cause severe operational problems and can be detrimental to the overall process [156]. Potassium is considered one of the major element casing agglomerations during thermal conversion [157]. Lignocellulosic biomass feedstock containing potassium, sodium, and alkali earth metals, along with chlorine and sulfur to a lesser extent, creates low-meting ash with the silica bed [20, 158] forming sticky and glassy melt, which causes sintering and agglomeration of bed material which further reduces the fluidization tendency or even cease it and thus create a serious problem [159]. De-fluidization causes poor mixing of bed material and creates an inhomogeneous and increased bed temperature profile which can be detected by remarkable pressure drop and temperature segregation over the bed [51]. The increase in temperature during bed agglomeration or de-fluidization may increase H_2 and CO production, contributing to LHV under other operating parameters such as ER and the amount of bed material [160]. Increasing bed material does not influence the chemical reaction but affects particle agglomeration tendency during de-fluidization [69].

There are studies that have reported an issue of agglomeration in BFB gasifiers. Gasification of palm empty fruit bunch (EFB) and sawdust in a pilot-scale air-blown BFB gasifier at T=1050 ^{o}C observed the major issue of agglomeration, probably due to the presence of K_2O in EFB (44%) in comparison to sawdust (4.5%). Therefore gasification was performed at 770 ± 20^{o}C [59]. Rice straw gasification at 850 ^{o}C observed the agglomeration using an alumina silicate bed which was prevented by the addition of MgO (67% w/w) [23] as MgO reaction with ash shifts melting temperature to a higher level [158]. Zhou *et al.* carried out an agglomeration study using four different types of bed material (glanshammar & sala dolomite, magnesite, and silica sand). They found that dolomite has a good ability to decrease the risk of agglomeration in pressurized FBG gasifier [161]. Gang *et al*. also reported clinker formation during the gasification of *Miscanthus x giganteus* using magnesite as a bed [162]. Palm empty fruit bunch (EFB), a susceptible feedstock to agglomeration due to its high content of alkali material potassium (K), was gasified with rubberwood sawdust (RWS) (RWS: EFB = 75:25) with no agglomeration [163].

10. Industrial Application of BFB

The dispersed nature of biomass over a wide area and its energy content makes it costly for collection and transportation. Therefore decentralized utilization using middle-class biomass gasification and power generation technology may be feasible for developing countries. The BFB technology seems to be economically more suitable for medium size applications (15-40 MW), while the CFB technology is most economical on a larger scale (40-100 MW) [164]. The performance of some pilot-scale and commercial plants operating on bubbling fluidized bed technology using biomass as feed material is discussed here.

A novel demonstration project (11.5 MWth) located at Skive, Denmark, is a bubbling fluidized bed gasifier that uses wood biomass to produce syngas in reciprocating engines in a combined heat and power (CHP) application. The plant started in late 2007 and could produce 40 GW of electricity annually. The gasification plant is designed to run on wood pellets/chips with moisture content typically below 10% and operates at a temperature of about 850^oC and pressure over 2 bar. The plant uses air as gasifying media and dolomite as bed material. The syngas generated has a typical composition of gases CO (22%), H_2 (20%), and CH_4 (5%) by volume and heating value of about 5 MJ/Nm^3 [165]. Another study was conducted by Wu *et al.* to analyze the operational characteristic of air-blown 1.2 MW rice husk gasification and power generation plant, which used 200kW and 400 kW gas engines for power generation. The key observations reported were an increase in syngas heating value from 5.45 MJ/Nm^3 to 6.4 MJ/Nm^3 as the temperature increased from 700-800^oC and the influence of gasifier operation due to the water content in rice husk. As the water content of the rice husk increased up to 15%, it increased ER and gas yield, while above 15% caused an abnormal temperature fluctuation. The wastewater issue needed to be handled with some suitable equipment for gas cleaning [42]. Huynh and Kong reported a study on a pilot-scale plant based on BFB gasification using O_2-enriched air at 21 vol%, 45 vol%, and 80 vol% (dry basis) to study the effect of the gasifying agent on ammonia concentration. The biomass feedstock used was pine, maple oak, and discarded seed corn to gasify at 800 ^oC. It was observed that with 40% O_2 enrichment, H_2 content increased about 70%, 47%, and 32% for pine, maple-oak, and seed corn, respectively, proving that O_2 and steam are effective for feedstock. Ammonia and NO_x concentration in syngas increased as O_2 enrichment increased [166]. The RENUGAS® gasifier with 12t/day feed capacity consists of a bubbling fluidized bed gasifier, a feeding system, a cyclone, gas purification and upgrading section with tar cracker and hot gas clean up the unit, a flare unknits, and a sampling system. The gasifier unit consists of inert deep bed solid alumina that operates at temperature up to 980^oC, the pressure at 34 bar, and uses steam and air/O_2 as a gasifying agent [167].

Pio *et al*. demonstrated a pilot-scale 80 kWth bubbling fluidized bed gasifier and analyzed the influence of process parameters using residual forest biomass (RFB) as biomass feed. The system was operated at T=700-850 ^oC and ER=0.17-0.36, which produced gas with the composition of CO (14-21%); H_2 (2-12.7%); CH_4 (1.3-2.4%); and CO_2 (14.2-17.5%) with LHV between 4.4 to 6.9 $MJ/Nm^{3.}$ The cold gas efficiency (CGE) of the system ranged from 41.1 to 62.6% [168]. A pilot-scale bubbling fluidized bed gasifier capacity of 100 kg/h having a thermal output at about 400 kW was tested to evaluate the technical feasibility of the solid recovered product gasification. The gasifier used olivine as bed material and operated at a temperature between 816^oC-850^oC and ER = 0.26-0.39 using preheated air at 509^oC-540^oC. The syngas composition varied for three different tests H_2 (10.7-13.3%); CO (7.3-9.5%); CO_2 (19.8-20.7%), and CH_4 (3.3-6.6%), contributing the LHV of syngas between 4-4.9 MJ/Nm^3. The CGE and CCE were varied between 58% to 67% and 85% to 98%, respectively. The impurities like tar (27 to 59 g/Nm^3), HCl (33.2-99 mg/Nm^3), H_2S (4.6-57 mg/Nm^3), NH_3 (91-3.1 mg/Nm^3) show that solid recovered fuel can be a technically suitable feedstock for gasification [169]. A pilot scale dual bubbling fluidized bed gasifier used an olivine bed, resulting in high hydrogen content at 35% and a tar yield of 12 g/Nm^3 using hazelnut shells as feed [170].

The techno-economic analysis conducted by Porcu *et al.* [148] validates the feasibility of a BFB gasifier for commercial application for small-scale (2MWe) power generation based on a preliminary study of a 500 kWth pilot-scale air-blown bubbling fluidized bed gasifier plant installed at Sotacarbo Research Centre (Italy) and commissioned in December 2017. The analysis showed that air-blown BFB gasification could be profitable with low-cost agricultural waste with a net present value of up to 6 M if biomass is provided for free. However, for high-quality biomass wood, the technology is not competitive [148].

The research outcomes and analysis show that biomass's pilot-scale and industrial-scale BFB gasification display promising applications and economic feasibility. However, more attention must be provided to biomass availability at lower cost, the water content in biomass, and downstream handling of wastewater, as these factors put critical limitations on the propagation of the technology.

11. Prospectus and Challenges

Gasification offers a competitive thermal conversion route for diverse, highly distributed, and low energy density lignocellulosic biomass to syngas for thermal application, power generation, combined heat and power (CHP), and synthesis of liquid fuels and H_2. However, the technology faces some specific challenges: Biomass with low bulk density, high O_2 content, and high inorganic compounds (K, Ca, Na, Si, P, and Cl) are critical challenges to the thermochemical conversion process; Biomass is a good alternative to produce renewable H_2; however, thermodynamic equilibrium still limits H_2 yield from conventional biomass steam gasification. The concentration of H_2 in the producer gas is generally limited to < 50 vol% along with other carbonaceous gases (e.g., CO, CO_2, and CH_4), and tar still exist in the syngas; The operational issues like sintering, agglomeration, deposition, erosion, and corrosion related to the ash put major obstacles to the economic and viable application of biomass gasification technologies; Fluidized bed gasifiers face operation and design challenges, especially scaling up the different interconnected systems of fuel and air reactors because of their complexity under pressurized conditions required for H_2 production; Tar generation during the gasification process is a major challenge as still syngas high purity could not be achieved. Catalytic Steam gasification using a noble metal catalyst having high catalytic activity, coke resistance, and long-term activity involves high cost; Development of novel catalysts and supporting materials to improve the syngas cleaning and downstream utilization process's selectivity, activity, productivity, and economy.

12. Conclusions

Fluidized bed gasification of several biomasses can be performed, resulting in low to medium calorific value syngas that can be used to generate the next forms of energy like heat, electricity, and liquid fuel synthesis. Different gasification parameters affect the overall operating performance of FBG in which reactor temperature and equivalence ratio profoundly influence the product gas composition and gas yield, whereas H_2 and CO are mostly affected gas components. Steam gasification of biomass proves to be a convenient route to renewable hydrogen production, which can be enhanced further through catalytic activity. Despite the few operational issues like agglomeration in FBG gasification, low energy density, and the highly distributed nature of lignocellulosic biomass, thermochemical conversion through a fluidized bed gasifier is a promising renewable and alternate energy technology.

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Conflicts of Interest

The authors declare no conflict of interest.

References

1. Siedlecki, M.; de Jong, W.; Verkooijen, A.H.M. Fluidized Bed Gasification as a Mature and Reliable Technology for the Production of Bio-Syngas and Applied in the Production of Liquid Transportation Fuels-a Review. *Energies* **2011**, *4*, 389-434, https://doi.org/10.3390/en4030389.
2. Demirbas, A. Hydrogen-Rich Gases from Biomass via Pyrolysis and Air-Steam Gasification. *Energy Sources Part A: Recover Util Environ Eff* **2009**, *31*, 1782-1836, https://doi.org/10.1080/15567030802459693.
3. Yang, H.M.; Liu, J.G.; Zhang, H.; Han, X.X.; Jiang, X.M. Experimental Research for Biomass Steam Gasification in a Fluidized Bed. *Energy Sources, Part A: Recover Util and Environ Eff* **2019**, *41*, 1993–2006, https://doi.org/10.1080/15567036.2018.1549128.
4. Haberl, H.; Erb, K.H.; Krausmann, F.; Bondeau, A.; Lauk, C.; Müller, C.; Plutzar, C.; Steinberger, J.K. Global Bioenergy Potentials from Agricultural Land in 2050: Sensitivity to Climate Change, Diets and Yields. *Biomass and Bioenergy* **2011**, *35*, 4753-4769, https://doi.org/10.1016/j.biombioe.2011.04.035.
5. Demirbas, A. Combustion Characteristics of Different Biomass Fuels. *Progress in Energy and Combustion Science* **2004**, *30*, 219-230, https://doi.org/10.1016/j.pecs.2003.10.004.
6. Panwar, N.L.; Rathore, N.S.; Kurchania, A.K. Experimental Investigation of Open Core Downdraft Biomass Gasifier for Food Processing Industry. *Mitig Adapt Strateg Glob Chang* **2009**, *14*, 547-556, https://doi.org/10.1007/s11027-009-9173-x.
7. Asadullah, M.; Miyazawa, T.; Ito, S.I.; Kunimori, K.; Tomishige, K. Demonstration of Real Biomass Gasification Drastically Promoted by Effective Catalyst. *Appl Catal A: General* **2003**, *246*, 103-116, https://doi.org/10.1016/S0926-860X(03)00047-4.
8. Kern, S.; Pfeifer, C.; Hofbauer, H. Gasification of Wood in a Dual Fluidized Bed Gasifier: Influence of Fuel Feeding on Process Performance. *Chem Eng Sci* **2013**, *90*, 284-298, https://doi.org/10.1016/j.ces.2012.12.044.
9. Narnaware, S.L.; Panwar, N.L. Catalysts and Their Role in Biomass Gasification and Tar Abetment: A Review. *Biomass Conversion and Biorefinery* **2021**, https://doi.org/10.1007/s13399-021-01981-1.
10. Puig-Gamero, M.; Pio, D.T.; Tarelho, L.A.C.; Sánchez, P.; Sanchez-Silva, L. Simulation of Biomass Gasification in Bubbling Fluidized Bed Reactor Using Aspen Plus®. *Energy Convers Manag* **2021**, *235*, 113981, https://doi.org/10.1016/J.ENCONMAN.2021.113981.
11. Safitri, K.A.; Pramono, M.; Dafiqurrohman, H.; Surjosatyo, A. Exergy Analysis of Self-Bed Feedstock in Rice Husk Bubbling Fluidized Bed Gasifier. *J Phys Conf Ser* **2021**, *1858*, 012032, https://doi.org/10.1088/1742-6596/1858/1/012032.
12. Klass, D.L. (Ed.). *Biomass for Renewable Energy, Fuels, and Chemicals* **1998**, Academic Press, https://doi.org/10.1016/B978-0-12-410950-6.X5000-4.
13. Wang, L.; Weller, C.L.; Jones, D.D.; Hanna, M.A. Contemporary Issues in Thermal Gasification of Biomass and Its Application to Electricity and Fuel Production. *Biomass and Bioenergy* **2008**, *32*, 573-581, https://doi.org/10.1016/j.biombioe.2007.12.007.

14. Campoy, M.; Gómez-Barea, A.; Villanueva, A.L.; Ollero, P. Air-Steam Gasification of Biomass in a Fluidized Bed under Simulated Autothermal and Adiabatic Conditions. *Ind Eng Chem Res* **2008**, *47*, 5957-5965, https://doi.org/10.1021/ie800220t.
15. Samiran, N.A.; Jaafar, M.N.M.; Ng, J.H.; Lam, S.S.; Chong, C.T. Progress in Biomass Gasification Technique - With Focus on Malaysian Palm Biomass for Syngas Production. *Renewable and Sustainable Energy Reviews* **2016**, *62*, 1047-1062, https://doi.org/10.1016/j.rser.2016.04.049.
16. Molino, A.; Larocca, V.; Chianese, S.; Musmarra, D. Biofuels Production by Biomass Gasification: A Review. *Energies* **2018**, *11*, 811, https://doi.org/10.3390/en11040811.
17. Li, X.T.; Grace, J.R.; Lim, C.J.; Watkinson, A.P.; Chen, H.P.; Kim, J.R. Biomass Gasification in a Circulating Fluidized Bed. *Biomass and Bioenergy* **2004**, *26*, 171-193, https://doi.org/10.1016/S0961-9534(03)00084-9.
18. Heyne, S.; Thunman, H.; Harvey, S. Exergy-Based Comparison of Indirect and Direct Biomass Gasification Technologies within the Framework of Bio-SNG Production. *Biomass Conversion and Biorefinery* **2013**, *3*, 337-352, https://doi.org/10.1007/s13399-013-0079-1.
19. Basu, P, (Ed.). *Biomass Gasification, Pyrolysis and Torrefaction: Practical Design and Theory* **2013**, Academic Press, https://doi.org/10.1016/C2011-0-07564-6.
20. Basu, P, (Ed.). *Combustion and Gasification in Fluidized Beds* **2006**, CRC Press, Boca Raton, https://doi.org/10.1201/9781420005158.
21. Ergudenler, A.; Ghaly, A.E. Agglomeration of Silica Sand in a Fluidized Bed Gasifier Operating on Wheat Straw. *Biomass and Bioenergy* **1993**, *4*, 135-147, https://doi.org/10.1016/0961-9534(93)90034-2.
22. Warnecke, R. Gasification of Biomass: Comparison of Fixed Bed and Fluidized Bed Gasifier. *Biomass and Bioenergy* **2000**, *18*, 489-497, https://doi.org/10.1016/S0961-9534(00)00009-X.
23. Calvo, L.F.; Gil, M.V.; Otero, M.; Morán, A.; García, A.I. Gasification of Rice Straw in a Fluidized-Bed Gasifier for Syngas Application in Close-Coupled Boiler-Gasifier Systems. *Bioresour Technol* **2012**, *109*, 206-214, https://doi.org/10.1016/j.biortech.2012.01.027.
24. Schuster, G.; Löffler, G.; Weigl, K.; Hofbauer, H. Biomass Steam Gasification - An Extensive Parametric Modeling Study. *Bioresour Technol* **2001**, *77*, 71-79, https://doi.org/10.1016/S0960-8524(00)00115-2.
25. Lv, P.M.; Xiong, Z.H.; Chang, J.; Wu, C.Z.; Chen, Y.; Zhu, J.X. An Experimental Study on Biomass Air-Steam Gasification in a Fluidized Bed. *Bioresour Technol* **2004**, *95*, 95-101, https://doi.org/10.1016/j.biortech.2004.02.003.
26. Ewan, B.C.R.; Allen, R.W.K. A Figure of Merit Assessment of the Routes to Hydrogen. *Int J Hydrogen Energy* **2005**, *30*, 809-819, https://doi.org/10.1016/j.ijhydene.2005.02.003.
27. Niu, M.; Huang, Y.; Jin, B.; Sun, Y.; Wang, X. Enriched-Air Gasification of Refuse-Derived Fuel in a Fluidized Bed: Effect of Gasifying Conditions and Bed Materials. *Chem Eng Technol* **2014**, *37*, 1787-1796, https://doi.org/10.1002/ceat.201400167.
28. Vodička, M.; Michaliková, K.; Hrdlička, J.; Hofbauer, C.; Winter, F.; Skopec, P.; Jeníková, J. External Bed Materials for the Oxy-Fuel Combustion of Biomass in a Bubbling Fluidized Bed. *J Clean Prod* **2021**, *321*, 128882, https://doi.org/10.1016/J.JCLEPRO.2021.128882.
29. Kong, D.; Luo, K.; Wang, S.; Yu, J.; Fan, J. Particle Behaviours of Biomass Gasification in a Bubbling Fluidized Bed. *Chem Eng J* **2022**, *428*, 131847, https://doi.org/10.1016/J.CEJ.2021.131847.
30. Nguyen, N.M.; Alobaid, F.; Epple, B. Chemical Looping Gasification of Torrefied Woodchips in a Bubbling Fluidized Bed Test Rig Using Iron-Based Oxygen Carriers. *Renew Energy* **2021**, *172*, 34–45, https://doi.org/10.1016/J.RENENE.2021.03.006.
31. Tanksale, A.; Beltramini, J.N.; Lu, G.Q.M. A Review of Catalytic Hydrogen Production Processes from Biomass. *Renewable and Sustainable Energy Reviews* **2010**, *14*, 166-182, https://doi.org/10.1016/j.rser.2009.08.010.
32. Chen, S.; Wang, D.; Xue, Z.; Sun, X.; Xiang, W. Calcium Looping Gasification for High-Concentration Hydrogen Production with CO_2 Capture in a Novel Compact Fluidized Bed: Simulation and Operation Requirements. *Int J Hydrogen Energy* **2011**, *36*, 4887-4899, https://doi.org/10.1016/j.ijhydene.2010.12.130.
33. Hasler, P.; Nussbaumer, T. Gas Cleaning for IC Engine Applications from Fixed Bed Biomass Gasification. *Biomass and Bioenergy* **1999**, *16*, 385-395, https://doi.org/10.1016/S0961-9534(99)00018-5.
34. Cao, Y.; Wang, Y.; Riley, J.T.; Pan, W.P. A Novel Biomass Air Gasification Process for Producing Tar-Free Higher Heating Value Fuel Gas. *Fuel Process Technol* **2006**, *87*, 343-353, https://doi.org/10.1016/j.fuproc.2005.10.003.
35. Boerrigter, H.; Den Uil, H.; Calis, H.-P. Green Diesel from Biomass via Fischer-Tropsch Synthesis: New Insights in Gas Cleaning and Process Design. *Pyrolysis Gasif Biomass Waste, Expert Meet* **2002**.

36. Unruh, D.; Pabst, K.; Schaub, G. Fischer-Tropsch Synfuels from Biomass: Maximizing Carbon Efficiency and Hydrocarbon Yield. *Energy and Fuels* **2010**, *24*, 2634-2641, https://doi.org/10.1021/ef9009185.
37. Atienza, A.H.; Aceituna, A.; Samar, X.E. Small Scale Bubbling Fluidized Bed Gasifier for Syngas Extraction from Napier Grass. *IOP Conf Ser Earth Environ Sci* **2021**, *765*, 012068, https://doi.org/10.1088/1755-1315/765/1/012068.
38. Gupta, S.; Choudhary, S.; Kumar, S.; De, S. Large Eddy Simulation of Biomass Gasification in a Bubbling Fluidized Bed Based on the Multiphase Particle-in-Cell Method. *Renew Energy* **2021**, *163*, 1455–1466, https://doi.org/10.1016/J.RENENE.2020.07.127.
39. Herguido, J.; Corella, J.; González-Saiz, J. Steam Gasification of Lignocellulosic Residues in a Fluidized Bed at a Small Pilot Scale. Effect of the Type of Feedstock. *Ind Eng Chem Res* **1992**, *31*, 1274-1282, https://doi.org/10.1021/ie00005a006.
40. Hanaoka, T.; Inoue, S.; Uno, S.; Ogi, T.; Minowa, T. Effect of Woody Biomass Components on Air-Steam Gasification. *Biomass and Bioenergy* **2005**, *28*, 69-76, https://doi.org/10.1016/j.biombioe.2004.03.008.
41. Maisano, S.; Urbani, F.; Cipitì, F.; Freni, F.; Chiodo, V. Syngas Production by BFB Gasification: Experimental Comparison of Different Biomasses. *Int J Hydrogen Energy* **2019**, *44*, 4414-4422, https://doi.org/10.1016/j.ijhydene.2018.11.148.
42. Wu, C.Z.; Yin, X.L.; Ma, L.L.; Zhou, Z.Q; Chen, H.P. Operational Characteristics of a 1.2-MW Biomass Gasification and Power Generation Plant. *Biotechnol Adv* **2009**, *27*, 588-592, https://doi.org/10.1016/j.biotechadv.2009.04.020.
43. Cross, P.; Kulkarni, A.; Nam, H.; Adhikari, S.; Fasina, O. Bubbling Fluidized Bed Gasification of Short Rotation Eucalyptus: Effect of Harvesting Age and Bark. *Biomass and Bioenergy* **2018**, *110*, 98-104, https://doi.org/10.1016/j.biombioe.2018.01.014.
44. Cetin, E.; Moghtaderi, B.; Gupta, R.; Wall, T.F. Influence of Pyrolysis Conditions on the Structure and Gasification Reactivity of Biomass Chars. *Fuel* **2004**, *83*, 2139-2150, https://doi.org/10.1016/j.fuel.2004.05.008.
45. Fushimi, C.; Araki, K.; Yamaguchi, Y.; Tsutsumi, A. Effect of Heating Rate on Steam Gasification of Biomass. 1. Reactivity of Char. *Ind Eng Chem Res* **2003**, *42*, 3922-3928, https://doi.org/10.1021/ie030056c.
46. Esfahani, R.M.; Wan Ab Karim Ghani, W.A.; Mohd Salleh, M.A.; Ali, S. Hydrogen-Rich Gas Production from Palm Kernel Shell by Applying Air Gasification in Fluidized Bed Reactor. *Energy and Fuels* **2012**, *26*, 1185-1191, https://doi.org/10.1021/ef2010892.
47. Rapagnà, S.; Latif, A. Steam Gasification of Almond Shells in a Fluidised Bed Reactor: The Influence of Temperature and Particle Size on Product Yield and Distribution. *Biomass and Bioenergy* **1997**, *12*, 281–288, https://doi.org/10.1016/S0961-9534(96)00079-7.
48. Leung, D.Y.C.; Wang, C.L. Fluidized-Bed Gasification of Waste Tire Powders. *Fuel Process Technol* **2003**, *84*, 175-196, https://doi.org/10.1016/S0378-3820(03)00054-7.
49. Khan, Z.; Yusup, S.; Ahmad, M.M.; Chin, B.L.F. Hydrogen Production from Palm Kernel Shell via Integrated Catalytic Adsorption (ICA) Steam Gasification. *Energy Convers Manag* **2014**, *87*, 1224-1230, https://doi.org/10.1016/j.enconman.2014.03.024.
50. Mohammed, M.A.A.; Salmiaton, A.; Wan Azlina, W.A.K.G.; Mohammad Amran, M.S.; Fakhru'L-Razi, A.; Taufiq-Yap, Y.H. Hydrogen Rich Gas from Oil Palm Biomass as a Potential Source of Renewable Energy in Malaysia. *Renewable and Sustainable Energy Reviews* **2011**, *15*, 1258-1270, https://doi.org/10.1016/j.rser.2010.10.003.
51. Olofsson, G.; Ye, Z.; Bjerle, I.; Andersson, A. Bed Agglomeration Problems in Fluidized-Bed Biomass Combustion. *Ind Eng Chem Res* **2002**, *41*, 2888-2894, https://doi.org/10.1021/ie010274a.
52. Norton, G.A.; Brown, R.C. Wet Chemical Method for Determining Levels of Ammonia in Syngas from a Biomass Gasifier. *Energy and Fuels* **2005**, *19*, 618-624, https://doi.org/10.1021/ef040065d.
53. Zhou, J.; Masutani, S.M.; Ishimura, D.M.; Turn, S.Q.; Kinoshita, C.M. Release of Fuel-Bound Nitrogen during Biomass Gasification. *Ind Eng Chem Res* **2000**, *39*, 626-634, https://doi.org/10.1021/ie980318o.
54. Makwana, J.P.; Joshi, A.K.; Athawale, G.; Singh, D.; Mohanty, P. Air Gasification of Rice Husk in Bubbling Fluidized Bed Reactor with Bed Heating by Conventional Charcoal. *Bioresour Technol* **2015**, *178*, 45-52, https://doi.org/10.1016/j.biortech.2014.09.111.
55. Li, B.; Yang, H.; Wei, L.; Shao, J.; Wang, X.; Chen, H. Hydrogen Production from Agricultural Biomass Wastes Gasification in a Fluidized Bed with Calcium Oxide Enhancing. *Int J Hydrogen Energy* **2017**, *42*, 4832-4839, https://doi.org/10.1016/j.ijhydene.2017.01.138.
56. Wan Ab Karim Ghani, W.A.; Moghadam, R.A.; Mohd Salleh, M.A.; Alias, A.B. Air Gasification of

Agricultural Waste in a Fluidized Bed Gasifier: Hydrogen Production Performance. *Energies* **2009**, *2*, 258-268, https://doi.org/10.3390/en20200258.
57. Kim, Y.D.; Yang, C.W.; Kim, B.J.; Kim, K.S.; Lee, J.W.; Moon, J.H.; Yang, W.; Yu, T.U.; Lee, U.D. Air-Blown Gasification of Woody Biomass in a Bubbling Fluidized Bed Gasifier. *Appl Energy* **2013**, *112*, 414-420, https://doi.org/10.1016/j.apenergy.2013.03.072.
58. Maglinao, A.L.; Capareda, S.C.; Nam, H. Fluidized Bed Gasification of High Tonnage Sorghum, Cotton Gin Trash and Beef Cattle Manure: Evaluation of Synthesis Gas Production. *Energy Convers Manag* **2015**, *105*, 578–587, https://doi.org/10.1016/j.enconman.2015.08.005.
59. Lahijani, P.; Zainal, Z.A. Gasification of Palm Empty Fruit Bunch in a Bubbling Fluidized Bed: A Performance and Agglomeration Study. *Bioresour Technol* **2011**, *102*, 2068-2076, https://doi.org/10.1016/j.biortech.2010.09.101.
60. Alipour Moghadam, R.; Yusup, S.; Azlina, W.; Nehzati, S.; Tavasoli, A. Investigation on Syngas Production via Biomass Conversion through the Integration of Pyrolysis and Air-Steam Gasification Processes. *Energy Convers Manag* **2014**, *87*, 670-675, https://doi.org/10.1016/j.enconman.2014.07.065.
61. Di Gregorio, F.; Santoro, D.; Arena, U. The Effect of Ash Composition on Gasification of Poultry Wastes in a Fluidized Bed Reactor. *Waste Manag Res* **2014**, *32*, https://doi.org/10.1177/0734242X14525821.
62. Chen, G.; Andries, J.; Spliethoff, H. Catalytic Pyrolysis of Biomass for Hydrogen Rich Fuel Gas Production. *Energy Convers Manag* **2003**, *44*, 2289-2296, https://doi.org/10.1016/S0196-8904(02)00254-6.
63. Han, S.W.; Lee, J.J.; Tokmurzin, D. *et al*. Gasification Characteristics of Waste Plastics (SRF) in a Bubbling Fluidized Bed: Effects of Temperature and Equivalence Ratio. *Energy* **2022**, *238*, 121944, https://doi.org/10.1016/J.ENERGY.2021.121944.
64. Xue, G.; Kwapinska, M.; Horvat, A.; Kwapinski, W.; Rabou, L.P.L.M.; Dooley, S.; Czajka, K.M.; Leahy, J.J. Gasification of Torrefied Miscanthus×giganteus in an Air-Blown Bubbling Fluidized Bed Gasifier. *Bioresour Technol* **2014**, *159*, 397-403, https://doi.org/10.1016/j.biortech.2014.02.094.
65. Cheng, G.; He, P-wen.; Xiao, B.; Hu, Z-quan.; Liu, S-ming.; Zhang, Le-guan.; Cai, L. Gasification of Biomass Micron Fuel with Oxygen-Enriched Air: Thermogravimetric Analysis and Gasification in a Cyclone Furnace. *Energy* **2012**, *43*, 2229-233, https://doi.org/10.1016/j.energy.2012.04.022.
66. Meng, F.; Ma, Q.; Wang, H.; Liu, Y.; Wang, D. Effect of Gasifying Agents on Sawdust Gasification in a Novel Pilot Scale Bubbling Fluidized Bed System. *Fuel* **2019**, *249*, 112-118, https://doi.org/10.1016/j.fuel.2019.03.107.
67. Liu, L.; Huang, Y.; Cao, J.; Liu, C.; Dong, L.; Xu, L.; Zha, J. Experimental Study of Biomass Gasification with Oxygen-Enriched Air in Fluidized Bed Gasifier. *Sci Total Environ* **2018**, *626*, 423-433, https://doi.org/10.1016/j.scitotenv.2018.01.016.
68. Ma, Z.; Wang, J.; Zhou, H.; Zhang, Y.; Yang, Y.; Liu, X.; Ye, J.; Chen, D.; Wang, S. Relationship of Thermal Degradation Behavior and Chemical Structure of Lignin Isolated from Palm Kernel Shell under Different Process Severities. *Fuel Process Technol* **2018**, *181*, 142–156, https://doi.org/10.1016/J.FUPROC.2018.09.020.
69. Kuo, J.H.; Lin, C.L.; Wey, M.Y. Effect of Agglomeration/Defluidization on Hydrogen Generation during Fluidized Bed Air Gasification of Modified Biomass. *Int J Hydrogen Energy* **2012**, *37*, 1409-1417, https://doi.org/10.1016/j.ijhydene.2011.10.001.
70. Tsekos, C.; del Grosso, M.; de Jong, W. Gasification of Woody Biomass in a Novel Indirectly Heated Bubbling Fluidized Bed Steam Reformer. *Fuel Process Technol* **2021**, *224*, 107003, https://doi.org/10.1016/J.FUPROC.2021.107003.
71. Franco, C.; Pinto, F.; Gulyurtlu, I.; Cabrita, I. The Study of Reactions Influencing the Biomass Steam Gasification Process. *Fuel* **2003**, *82*, 835-842, https://doi.org/10.1016/S0016-2361(02)00313-7.
72. Yang, J.; He, Q.S.; Yang, L. A Review on Hydrothermal Co-Liquefaction of Biomass. *Applied Energy* **2019**, *250*, 926-945, https://doi.org/10.1016/j.apenergy.2019.05.033.
73. Li, B.; Wei, L.; Yang, H.; Wang, X.; Chen, H. The Enhancing Mechanism of Calcium Oxide on Water Gas Shift Reaction for Hydrogen Production. *Energy* **2014**, *68*, 248-254, https://doi.org/10.1016/j.energy.2014.02.088.
74. Zhou, C.; Rosén, C.; Engvall, K. Selection of Dolomite Bed Material for Pressurized Biomass Gasification in BFB. *Fuel Process Technol* **2017**, *159*, 460-473, https://doi.org/10.1016/j.fuproc.2017.01.008.
75. Boateng, A.A.; Walawender, W.P.; Fan, L.T.; Chee, C.S. Fluidized-Bed Steam Gasification of Rice Hull. *Bioresour Technol* **1992**, *40*, 235-239, https://doi.org/10.1016/0960-8524(92)90148-Q.
76. Han, L.; Wang, Q.; Luo, Z.; Rong, N.; Deng, G. H_2 Rich Gas Production via Pressurized Fluidized Bed

Gasification of Sawdust with in Situ CO_2 Capture. *Appl Energy* **2013**, *109*, 36-43, https://doi.org/10.1016/j.apenergy.2013.03.035.
77. Lv, P.; Chang, J.; Xiong, Z.; Huang, H.; Wu, C.; Chen, Y.; Zhu, J. Biomass Air-Steam Gasification in a Fluidized Bed to Produce Hydrogen-Rich Gas. *Energy and Fuels* **2003**, *17*, 677-682, https://doi.org/10.1021/ef020181l.
78. Sun, Y.; Li, R.; Yang, T.; Kai, X.; He, Y. Gasification of Biomass to Hydrogen-Rich Gas in Fluidized Beds Using Porous Medium as Bed Material. *Int J Hydrogen Energy* **2013**, *38*, 14208-14213, https://doi.org/10.1016/j.ijhydene.2013.08.096.
79. Aznar, M.P.; Caballero, M.A.; Gil, J.; Martín, J.A.; Corella, J. Commercial Steam Reforming Catalysts to Improve Biomass Gasification with Steam-Oxygen Mixtures. 2. Catalytic Tar Removal. *Ind Eng Chem Res* **1998**, *37*, 2668-2680, https://doi.org/10.1021/ie9706727.
80. Shen, L.; Gao, Y.; Xiao, J. Simulation of Hydrogen Production from Biomass Gasification in Interconnected Fluidized Beds. *Biomass and Bioenergy* **2008**, *32*, 120-127, https://doi.org/10.1016/j.biombioe.2007.08.002.
81. Acharya, B.; Dutta, A.; Basu, P. An Investigation into Steam Gasification of Biomass for Hydrogen Enriched Gas Production in Presence of CaO. *Int J Hydrogen Energy* **2010**, *35*, 1582-1589, https://doi.org/10.1016/j.ijhydene.2009.11.109.
82. Narváez, I.; Orío, A.; Aznar, M.P.; Corella, J. Biomass Gasification with Air in an Atmospheric Bubbling Fluidized Bed. Effect of Six Operational Variables on the Quality of the Produced Raw Gas. *Ind Eng Chem Res* **1996**, *35*, 2110-2120, https://doi.org/10.1021/ie9507540.
83. Parrillo, F.; Ardolino, F.; Calì, G.; Marotto, D.; Pettinau, A.; Arena, U. Fluidized Bed Gasification of Eucalyptus Chips: Axial Profiles of Syngas Composition in a Pilot Scale Reactor. *Energy* **2021**, *219*, 119604, https://doi.org/10.1016/J.ENERGY.2020.119604.
84. Mansaray, K.G.; Ghaly, A.E.; Al-Taweel, A.M.; Hamdullahpur, F.; Ugursal, V.I. Air Gasification of Rice Husk in a Dual Distributor Type Fluidized Bed Gasifier. *Biomass and Bioenergy* **1999**, *17*, 315-332, https://doi.org/10.1016/S0961-9534(99)00046-X.
85. Chang, J.; Fu, Y.; Luo, Z. Experimental Study for Dimethyl Ether Production from Biomass Gasification and Simulation on Dimethyl Ether Production. *Biomass and Bioenergy* **2012**, *39*, 67-72, https://doi.org/10.1016/j.biombioe.2011.01.044.
86. Xiao, X.; Meng, X.; Le, D.D.; Takarada, T. Two-Stage Steam Gasification of Waste Biomass in Fluidized Bed at Low Temperature: Parametric Investigations and Performance Optimization. *Bioresour Technol* **2011**, *102*, 1975-1981, https://doi.org/10.1016/j.biortech.2010.09.016.
87. Loha, C.; Chattopadhyay, H.; Chatterjee, P.K. Energy Generation from Fluidized Bed Gasification of Rice Husk. *J Renew Sustain Energy* **2013**, *5*, 043111, https://doi.org/10.1063/1.4816496.
88. Salami, N.; Skála, Z. Use of the Steam as Gasifying Agent in Fluidized Bed Gasifier. *Chem Biochem Eng Q* **2015**, *29*, 13-18.
89. Fu, Q.; Huang, Y.; Niu, M.; Yang, G.; Shao, Z. Experimental and Predicted Approaches for Biomass Gasification with Enriched Air-Steam in a Fluidised Bed. *Waste Manag Res* **2014**, *32*, 988-996, https://doi.org/10.1177/0734242X14552555.
90. Florin, N.H.; Harris, A.T. Hydrogen Production from Biomass Coupled with Carbon Dioxide Capture: The Implications of Thermodynamic Equilibrium. *Int J Hydrogen Energy* **2007**, *32*, 4119-4134, https://doi.org/10.1016/j.ijhydene.2007.06.016.
91. Florin, N.H.; Harris, A.T. Enhanced Hydrogen Production from Biomass with in Situ Carbon Dioxide Capture Using Calcium Oxide Sorbents. *Chemical Engineering Science* **2008**, *63*, 287-316, https://doi.org/10.1016/j.ces.2007.09.011.
92. Luo, S.; Xiao, B.; Hu, Z.; Liu, S.; Guo, X.; He, M. Hydrogen-Rich Gas from Catalytic Steam Gasification of Biomass in a Fixed Bed Reactor: Influence of Temperature and Steam on Gasification Performance. *Int J Hydrogen Energy* **2009**, *34*, 2191-2194, https://doi.org/10.1016/j.ijhydene.2008.12.075.
93. Abu El-Rub, Z.; Bramer, E.A.; Brem, G. Review of Catalysts for Tar Elimination in Biomass Gasification Processes. *Industrial and Engineering Chemistry Research* **2004**, *43*, 6911-6919, https://doi.org/10.1021/ie0498403.
94. Guan, G.; Kaewpanha, M.; Hao, X.; Abudula, A. Catalytic Steam Reforming of Biomass Tar: Prospects and Challenges. *Renewable and Sustainable Energy Reviews* **2016**, *58*, 450-461, https://doi.org/10.1016/j.rser.2015.12.316.
95. Huang, B.S.; Chen, H.Y.; Chuang, K.H.; Yang, R.X.; Wey, M.Y. Hydrogen Production by Biomass Gasification in a Fluidized-Bed Reactor Promoted by an Fe/CaO Catalyst. *Int J Hydrogen Energy* **2012**, *37*,

6511-6518, https://doi.org/10.1016/j.ijhydene.2012.01.071.
96. Pereira, E.G.; Da Silva, J.N.; De Oliveira, J.L.; MacHado, C.S. Sustainable Energy: A Review of Gasification Technologies. *Renewable and Sustainable Energy Reviews* **2012**, *16*, 4753-4762, https://doi.org/10.1016/j.rser.2012.04.023.
97. Rapagnà, S.; Jand, N.; Kiennemann, A.; Foscolo, P. U. Steam-Gasification of Biomass in a Fluidised-Bed of Olivine Particles. *Biomass and Bioenergy* **2000**, *19*, 187-197, https://doi.org/10.1016/S0961-9534(00)00031-3.
98. Sutton, D.; Kelleher, B.; Ross, J.R.H. Review of Literature on Catalysts for Biomass Gasification. *Fuel Processing Technology* **2001**, *73*, 155-173, https://doi.org/10.1016/S0378-3820(01)00208-9.
99. Miccio, F.; Piriou, B.; Ruoppolo, G.; Chirone, R. Biomass Gasification in a Catalytic Fluidized Reactor with Beds of Different Materials. *Chem Eng J* **2009**, *154*, 369-374, https://doi.org/10.1016/j.cej.2009.04.002.
100. Devi, L.; Ptasinski, K.J.; Janssen, F.J.J.G. A Review of the Primary Measures for Tar Elimination in Biomass Gasification Processes. *Biomass and Bioenergy* **2003**, *24*, 125–140, https://doi.org/10.1016/S0961-9534(02)00102-2.
101. Boynton, R.S. (Ed.) *Chemistry and Technology of Lime and Limestone*. Wiley, **1980**.
102. Roche, E.; De Andrés, J.M.; Narros, A.; Rodríguez, M.E. Air and Air-Steam Gasification of Sewage Sludge. The Influence of Dolomite and Throughput in Tar Production and Composition. *Fuel* **2014**, *115*, 54-61, https://doi.org/10.1016/j.fuel.2013.07.003.
103. Tian, Y.; Zhou, X.; Lin, S.; Ji, X.; Bai, J.; Xu, M. Syngas Production from Air-Steam Gasification of Biomass with Natural Catalysts. *Sci Total Environ* **2018**, *645*, 518-523, https://doi.org/10.1016/j.scitotenv.2018.07.071.
104. Baratieri, M.; Pieratti, E.; Nordgreen, T.; Grigiante, M. Biomass Gasification with Dolomite as Catalyst in a Small Fluidized Bed Experimental and Modelling Analysis. *Waste and Biomass Valorization* **2010**, *1*, 283-291, https://doi.org/10.1007/s12649-010-9034-6.
105. De Andrés, J.M.; Narros, A.; Rodríguez, M.E. Behaviour of Dolomite, Olivine and Alumina as Primary Catalysts in Air-Steam Gasification of Sewage Sludge. *Fuel* **2011**, *90*, 521-527, https://doi.org/10.1016/j.fuel.2010.09.043.
106. Xu, C.; Donald, J.; Byambajav, E.; Ohtsuka, Y. Recent Advances in Catalysts for Hot-Gas Removal of Tar and NH_3 from Biomass Gasification. *Fuel* **2010**, *89*, 1784-1795, https://doi.org/10.1016/j.fuel.2010.02.014.
107. Skoulou, V.; Koufodimos, G.; Samaras, Z.; Zabaniotou, A. Low Temperature Gasification of Olive Kernels in a 5-KW Fluidized Bed Reactor for H_2-Rich Producer Gas. *Int J Hydrogen Energy* **2008**, *33*, 6515-6524, https://doi.org/10.1016/j.ijhydene.2008.07.074.
108. Michel, R.; Rapagnà, S.; Burg, P.; di Celso, M.G.; Courson, C.; Zimny, T.; Gruber, R. Steam Gasification of Miscanthus X Giganteus with Olivine as Catalyst Production of Syngas and Analysis of Tars (IR, NMR and GC/MS). *Biomass and Bioenergy* **2011**, *35*, 2650-2658, https://doi.org/10.1016/j.biombioe.2011.02.054.
109. Virginie, M.; Courson, C.; Niznansky, D.; Chaoui, N.; Kiennemann, A. Characterization and Reactivity in Toluene Reforming of a Fe/Olivine Catalyst Designed for Gas Cleanup in Biomass Gasification. *Appl Catal B: Environ* **2010**, *101*, 90-100, https://doi.org/10.1016/j.apcatb.2010.09.011.
110. Koppatz, S.; Pfeifer, C.; Hofbauer, H. Comparison of the Performance Behaviour of Silica Sand and Olivine in a Dual Fluidised Bed Reactor System for Steam Gasification of Biomass at Pilot Plant Scale. *Chem Eng J* **2011**, *175*, 468-483, https://doi.org/10.1016/j.cej.2011.09.071.
111. Kirnbauer, F.; Wilk, V.; Kitzler, H.; Kern, S.; Hofbauer, H. The Positive Effects of Bed Material Coating on Tar Reduction in a Dual Fluidized Bed Gasifier. *Fuel* **2012**, *95*, 553-562, https://doi.org/10.1016/j.fuel.2011.10.066.
112. Meng, J.; Wang, X.; Zhao, Z.; Zheng, A.; Huang, Z.; Wei, G.; Lv, K.; Li, H. Highly Abrasion Resistant Thermally Fused Olivine as In-Situ Catalysts for Tar Reduction in a Circulating Fluidized Bed Biomass Gasifier. *Bioresour Technol* **2018**, *268*, 212-220, https://doi.org/10.1016/j.biortech.2018.07.135.
113. Christodoulou, C.; Tsekos, C.; Tsalidis, G.; Fantini, M.; Panopoulos, K.D.; De Jong, W.; Kakaras, E. Attempts on Cardoon Gasification in Two Different Circulating Fluidized Beds. *Case Stud Therm Eng* **2014**, *4*, 42-52, https://doi.org/10.1016/j.csite.2014.06.004.
114. Thakkar, M.; Makwana, J.P.; Mohanty, P.; Shah, M.; Singh, V. In Bed Catalytic Tar Reduction in the Autothermal Fluidized Bed Gasification of Rice Husk: Extraction of Silica, Energy and Cost Analysis. *Ind Crops Prod* **2016**, *87*, 324-332, https://doi.org/10.1016/j.indcrop.2016.04.031.
115. Michel, R.; Rapagnà, S.; Di Marcello, M.; Burg, P.; Matt, M.; Courson, C.; Gruber, R. Catalytic Steam Gasification of Miscanthus X Giganteus in Fluidised Bed Reactor on Olivine Based Catalysts. *Fuel Process*

Technol **2011**, *92*, 1169-1177, https://doi.org/10.1016/j.fuproc.2010.12.005.
116. Han, L.; Wang, Q.; Yang, Y.; Yu, C.; Fang, M.; Luo, Z. Hydrogen Production via CaO Sorption Enhanced Anaerobic Gasification of Sawdust in a Bubbling Fluidized Bed. *Int J Hydrogen Energy* **2011**, *36*, 4820-4829, https://doi.org/10.1016/j.ijhydene.2010.12.086.
117. Weerachanchai, P.; Horio, M.; Tangsathitkulchai, C. Effects of Gasifying Conditions and Bed Materials on Fluidized Bed Steam Gasification of Wood Biomass. *Bioresour Technol* **2009**, *100*, 1419-1427, https://doi.org/10.1016/j.biortech.2008.08.002.
118. Chen, H.; Li, B.; Yang, H.; Yang, G.; Zhang, S. Experimental Investigation of Biomass Gasification in a Fluidized Bed Reactor. *Energy and Fuels* **2008**, *22*, 3493-3498, https://doi.org/10.1021/ef800180e.
119. Xie, Y.; Xiao, J.; Shen, L.; Wang, J.; Zhu, J.; Hao, J. Effects of Ca-Based Catalysts on Biomass Gasification with Steam in a Circulating Spout-Fluid Bed Reactor. *Energy and Fuels* **2010**, *24*, 3256-3261, https://doi.org/10.1021/ef100081w.
120. Hu, G.; Xu, S.; Li, S.; Xiao, C.; Liu, S. Steam Gasification of Apricot Stones with Olivine and Dolomite as Downstream Catalysts. *Fuel Process Technol* **2006**, *87*, 375-382, https://doi.org/10.1016/j.fuproc.2005.07.008.
121. Han, L.; Wang, Q.; Ma, Q.; Yu, C.; Luo, Z.; Cen, K. Influence of CaO Additives on Wheat-Straw Pyrolysis as Determined by TG-FTIR Analysis. *J Anal Appl Pyrolysis* **2010**, *88*, 199-206, https://doi.org/10.1016/j.jaap.2010.04.007.
122. Escobedo Bretado, M.A.; Delgado Vigil, M.D.; Gutiérrez, J.S.; López Ortiz, A.; Collins-Martínez, V. Hydrogen Production by Absorption Enhanced Water Gas Shift (AEWGS). *Int J Hydrogen Energy* **2010**, *35*, 12083-12090, https://doi.org/10.1016/j.ijhydene.2009.07.025.
123. Miyazawa, T.; Kimura, T.; Nishikawa, J.; Kado, S.; Kunimori, K.; Tomishige, K. Catalytic Performance of Supported Ni Catalysts in Partial Oxidation and Steam Reforming of Tar Derived from the Pyrolysis of Wood Biomass. *Catal Today* **2006**, *115*, 254-262, https://doi.org/10.1016/j.cattod.2006.02.055.
124. Richardson, Y.; Blin, J.; Volle, G.; Motuzas, J.; Julbe, A. In Situ Generation of Ni Metal Nanoparticles as Catalyst for H2-Rich Syngas Production from Biomass Gasification. *Appl Catal A: Gen* **2010**, *382*, 220-230, https://doi.org/10.1016/j.apcata.2010.04.047.
125. Tursun, Y.; Xu, S.; Abulikemu, A.; Dilinuer, T. Biomass Gasification for Hydrogen Rich Gas in a Decoupled Triple Bed Gasifier with Olivine and NiO/Olivine. *Bioresour Technol* **2019**, *272*, 241-248, https://doi.org/10.1016/j.biortech.2018.10.008.
126. Kong, M.; Fei, J.; Wang, S.; Lu, W.; Zheng, X. Influence of Supports on Catalytic Behavior of Nickel Catalysts in Carbon Dioxide Reforming of Toluene as a Model Compound of Tar from Biomass Gasification. *Bioresour Technol* **2011**, *102*, 2004-2008, https://doi.org/10.1016/j.biortech.2010.09.054.
127. Efika, C.E.; Wu, C.; Williams, P.T. Syngas Production from Pyrolysis-Catalytic Steam Reforming of Waste Biomass in a Continuous Screw Kiln Reactor. *J Anal Appl Pyrolysis* **2012**, *95*, 87-94, https://doi.org/10.1016/j.jaap.2012.01.010.
128. Mohd Salleh, M.A.; Kisiki, N.H.; Yusuf, H.M.; Wan Ab Karim Ghani, W.A. Gasification of Biochar from Empty Fruit Bunch in a Fluidized Bed Reactor. *Energies* **2010**, *3*, 1344-1352, https://doi.org/10.3390/en3071344.
129. Wei, L.; Xu, S.; Zhang, L.; Liu, C.; Zhu, H.; Liu, S. Steam Gasification of Biomass for Hydrogen-Rich Gas in a Free-Fall Reactor. *Int J Hydrogen Energy* **2007**, *32*, 24-31, https://doi.org/10.1016/j.ijhydene.2006.06.002.
130. Karmakar, M.K.; Mandal, J.; Haldar, S.; Chatterjee, P.K. Investigation of Fuel Gas Generation in a Pilot Scale Fluidized Bed Autothermal Gasifier Using Rice Husk. *Fuel* **2013**, *111*, 584-591, https://doi.org/10.1016/j.fuel.2013.03.045.
131. Pinto, F.; Franco, C.; André, R.N.; Tavares, C.; Dias, M.; Gulyurtlu, I.; Cabrita, I. Effect of Experimental Conditions on Co-Gasification of Coal, Biomass and Plastics Wastes with Air/Steam Mixtures in a Fluidized Bed System. *Fuel* **2003**, *82*, 1967-1976, https://doi.org/10.1016/S0016-2361(03)00160-1.
132. Meng, X.; de Jong, W.; Fu, N.; Verkooijen, A.H.M. Biomass Gasification in a 100 KWth Steam-Oxygen Blown Circulating Fluidized Bed Gasifier: Effects of Operational Conditions on Product Gas Distribution and Tar Formation. *Biomass and Bioenergy* **2011**, *35*, 2910-2924, https://doi.org/10.1016/j.biombioe.2011.03.028.
133. Erkiaga, A.; Lopez, G.; Amutio, M.; Bilbao, J.; Olazar, M. Influence of Operating Conditions on the Steam Gasification of Biomass in a Conical Spouted Bed Reactor. *Chem Eng J* **2014**, *237*, 259-267, https://doi.org/10.1016/j.cej.2013.10.018.

134. Campoy, M.; Gómez-Barea, A.; Vidal, F.B.; Ollero, P. Air-Steam Gasification of Biomass in a Fluidised Bed: Process Optimisation by Enriched Air. *Fuel Process Technol* **2009**, *90*, 677-685, https://doi.org/10.1016/j.fuproc.2008.12.007.
135. Peng, W.X.; Wang, L.S.; Mirzaee, M.; Ahmadi, H.; Esfahani, M.J.; Fremaux, S. Hydrogen and Syngas Production by Catalytic Biomass Gasification. *Energy Convers Manag* **2017**, *135*, 270–273, https://doi.org/10.1016/j.enconman.2016.12.056.
136. Islam, M.W. A Review of Dolomite Catalyst for Biomass Gasification Tar Removal. *Fuel* **2020**, *267*, 117095, https://doi.org/10.1016/j.fuel.2020.117095.
137. Woolcock, P.J.; Brown, R.C. A Review of Cleaning Technologies for Biomass-Derived Syngas. *Biomass and Bioenergy* **2013**, *52*, 54-84, https://doi.org/10.1016/j.biombioe.2013.02.036.
138. Shen, Y. Chars as Carbonaceous Adsorbents/Catalysts for Tar Elimination during Biomass Pyrolysis or Gasification. *Renewable and Sustainable Energy Reviews* **2015**, *43*, 281-295, https://doi.org/10.1016/j.rser.2014.11.061.
139. Di Blasi, C. Modeling Intra- and Extra-Particle Processes of Wood Fast Pyrolysis. *AIChE J* **2002**, *48*, 2386-2397, https://doi.org/10.1002/aic.690481028.
140. Han, J.; Kim, H. The Reduction and Control Technology of Tar during Biomass Gasification/Pyrolysis: An Overview. *Renewable and Sustainable Energy Reviews* **2008**, *12*, 397-416, https://doi.org/10.1016/j.rser.2006.07.015.
141. Tregrossi, A.; Ciajolo, A.; Barbella, R. The Combustion of Benzene in Rich Premixed Flames at Atmospheric Pressure. *Combust Flame* **1999**, *117*, 553-561, https://doi.org/10.1016/S0010-2180(98)00157-6.
142. Shen, Y.; Yoshikawa, K. Recent Progresses in Catalytic Tar Elimination during Biomass Gasification or Pyrolysis-A Review. *Renewable and Sustainable Energy Reviews* **2013**, *21*, 371-392, https://doi.org/10.1016/j.rser.2012.12.062.
143. Makwana, J.P.; Pandey, J.; Mishra, G. Improving the Properties of Producer Gas Using High Temperature Gasification of Rice Husk in a Pilot Scale Fluidized Bed Gasifier (FBG). *Renew Energy* **2019**, *130*, 943-951, https://doi.org/10.1016/j.renene.2018.07.011.
144. Schmid, M.; Beirow, M.; Schweitzer, D.; Waizmann, G.; Spörl, R.; Scheffknecht, G. Product Gas Composition for Steam-Oxygen Fluidized Bed Gasification of Dried Sewage Sludge, Straw Pellets and Wood Pellets and the Influence of Limestone as Bed Material. *Biomass and Bioenergy* **2018**, *117*, 71-77, https://doi.org/10.1016/j.biombioe.2018.07.011.
145. Win, M.M.; Asari, M.; Hayakawa, R.; Hosoda, H.; Yano, J.; Sakai, S-ichi. Characteristics of Gas from the Fluidized Bed Gasification of Refuse Paper and Plastic Fuel (RPF) and Wood Biomass. *Waste Manag* **2019**, *87*, 173-182, https://doi.org/10.1016/j.wasman.2019.02.002.
146. Koppatz, S.; Pfeifer, C.; Rauch, R.; Hofbauer, H.; Marquard-Moellenstedt, T.; Specht, M. H_2 Rich Product Gas by Steam Gasification of Biomass with in Situ CO_2 Absorption in a Dual Fluidized Bed System of 8 MW Fuel Input. *Fuel Process Technol* **2009**, *90*, 914-921, https://doi.org/10.1016/j.fuproc.2009.03.016.
147. Corella, J.; Toledo, J.M.; Padilla, R. Olivine or Dolomite as In-Bed Additive in Biomass Gasification with Air in a Fluidized Bed: Which Is Better? *Energy Fuels* **2004**, *18*, 713-720, https://doi.org/10.1021/ef0340918.
148. Porcu, A.; Sollai, S.; Marotto, D.; Mureddu, M.; Ferrara, F.; Pettinau, A. Techno-Economic Analysis of a Small-Scale Biomass-to-Energy BFB Gasification-Based System. *Energies* **2019**, *12*, 494, https://doi.org/10.3390/en12030494.
149. Liu, C.; Huang, Y.; Niu, M.; Pei, H.; Liu, L.; Wang, Y.; Dong, L.; Xu, L. Influences of Equivalence Ratio, Oxygen Concentration and Fluidization Velocity on the Characteristics of Oxygen-Enriched Gasification Products from Biomass in a Pilot-Scale Fluidized Bed. *Int J Hydrogen Energy* **2018**, *43*, 14214–14225, https://doi.org/10.1016/j.ijhydene.2018.05.154.
150. González, J.F.; Román, S.; Bragado, D.; Calderón, M. Investigation on the Reactions Influencing Biomass Air and Air/Steam Gasification for Hydrogen Production. *Fuel Process Technol* **2008**, *89*, 764-772, https://doi.org/10.1016/j.fuproc.2008.01.011.
151. Khezri, R.; Ghani, W.A.W.A.K.; Biak, D.R.A.; Yunus, R.; Silas, K. Experimental Evaluation of Napier Grass Gasification in an Autothermal Bubbling Fluidized Bed Reactor. *Energies* **2019**, *12*, 1517, https://doi.org/10.3390/en12081517.
152. Bandara, J.C.; Jaiswal, R.; Nielsen, H.K.; Moldestad, B.M.E.; Eikeland, M.S. Air Gasification of Wood Chips, Wood Pellets and Grass Pellets in a Bubbling Fluidized Bed Reactor. *Energy* **2021**, *233*, 121149, https://doi.org/10.1016/J.ENERGY.2021.121149.
153. Natarajan, E.; Nordin, A.; Rao, A.N. Overview of Combustion and Gasification of Rice Husk in Fluidized

Bed Reactors. *Biomass and Bioenergy* **1998**, *14*, 533-546, https://doi.org/10.1016/S0961-9534(97)10060-5.
154. Kim, J.-W.; Jeong, Y.-S.; Kim, J.-S. How to Avoid Bed Agglomeration in the Bubbling Fluidized Bed Biomass Gasification: Two-Stage Gasification at 600 °C. *Energy* **2022**, *250*, 123882, https://doi.org/10.2139/SSRN.3971593.
155. Nascimento, F.R.M.; González, A.M.; Silva Lora, E.E.; Ratner, A.; Escobar Palacio, J.C.; Reinaldo, R. Bench-Scale Bubbling Fluidized Bed Systems around the World - Bed Agglomeration and Collapse: A Comprehensive Review. *Int J Hydrogen Energy* **2021**, *46*, 18740–18766, https://doi.org/10.1016/J.IJHYDENE.2021.03.036.
156. Materazzi, M.; Lettieri, P.; Taylor, R.; Chapman, C. Performance Analysis of RDF Gasification in a Two Stage Fluidized Bed-Plasma Process. *Waste Manag* **2016**, *47*, 256–266, https://doi.org/10.1016/j.wasman.2015.06.016.
157. Van Der Drift, A.; Van Doorn, J.; Vermeulen, J.W. Ten Residual Biomass Fuels for Circulating Fluidized-Bed Gasification. *Biomass and Bioenergy* **2001**, *20*, 45-56, https://doi.org/10.1016/S0961-9534(00)00045-3.
158. Fryda, L.E.; Panopoulos, K.D.; Kakaras, E. Agglomeration in Fluidised Bed Gasification of Biomass. *Powder Technol* **2008**, *181*, 307-320, https://doi.org/10.1016/j.powtec.2007.05.022.
159. Bartels, M.; Lin, W.; Nijenhuis, J.; Kapteijn, F.; van Ommen, J.R. Agglomeration in Fluidized Beds at High Temperatures: Mechanisms, Detection and Prevention. *Progress in Energy and Combustion Science* **2008**, *34*, 633-666, https://doi.org/10.1016/j.pecs.2008.04.002.
160. Atakül, H.; Hilmioğlu, B.; Ekinci, E. The Relationship between the Tendency of Lignites to Agglomerate and Their Fusion Characteristics in a Fluidized Bed Combustor. *Fuel Process Technol* **2005**, *86*, 1369-1383, https://doi.org/10.1016/j.fuproc.2005.01.021.
161. Zhou, C.; Rosén, C.; Engvall, K. Biomass Oxygen/Steam Gasification in a Pressurized Bubbling Fluidized Bed: Agglomeration Behavior. *Appl Energy* **2016**, *172*, 230-250, https://doi.org/10.1016/j.apenergy.2016.03.106.
162. Xue, G.; Kwapinska, M.; Horvat, A.; Li, Z.; Dooley, S.; Kwapinski, W.; Leahy, J.J. Gasification of Miscanthus x Giganteus in an Air-Blown Bubbling Fluidized Bed: A Preliminary Study of Performance and Agglomeration. *Energy and Fuels* **2014**, *28*, 1121-1131, https://doi.org/10.1021/ef4022152.
163. Kittivech, T.; Fukuda, S. Investigating Agglomeration Tendency of Co-Gasification between High Alkali Biomass and Woody Biomass in a Bubbling Fluidized Bed System. *Energies* **2020**, *13*, 56, https://doi.org/10.3390/en13010056.
164. Esa Kurkela. Review of Finnish Biomass Gasification Technologies. *OPET Report 4*, Technical Research Centre of Finland, ESPOO **2002**.
165. Kari Salo & Andras Horvath. Biomass Gasification in Skive: Opening Doors in Denmark. *REW* **2009**, *11*.
166. Huynh, C. Van; Kong, S.C. Performance Characteristics of a Pilot-Scale Biomass Gasifier Using Oxygen-Enriched Air and Steam. *Fuel* **2013**, https://doi.org/10.1016/j.fuel.2012.09.033.
167. Motta, I.L.; Miranda, N.T.; Maciel Filho, R.; Wolf Maciel, M.R. Biomass Gasification in Fluidized Beds: A Review of Biomass Moisture Content and Operating Pressure Effects. *Renewable and Sustainable Energy Reviews* **2018**, *94*, 998-1023, https://doi.org/10.1016/j.rser.2018.06.042.
168. Pio, D.T.; Tarelho, L.A.C.; Matos, M.A.A. Characteristics of the Gas Produced during Biomass Direct Gasification in an Autothermal Pilot-Scale Bubbling Fluidized Bed Reactor. *Energy* **2017**, *120*, 915-928, https://doi.org/10.1016/j.energy.2016.11.145.
169. Arena, U.; Di Gregorio, F. Fluidized Bed Gasification of Industrial Solid Recovered Fuels. *Waste Manag* **2016**, *50*, 86-92, https://doi.org/10.1016/j.wasman.2016.02.011.
170. Di Carlo, A.; Savuto, E.; Foscolo, P.U.; Papa, A.A.; Tacconi, A.; Del Zotto, L.; Aydin, B.; Bocci, E. Preliminary Results of Biomass Gasification Obtained at Pilot Scale with an Innovative 100 KWth Dual Bubbling Fluidized Bed Gasifier. *Energies* **2022**, *15*, 4369, https://doi.org/10.3390/en15124369.