CHAPTER 2

LITERATURE REVIEW

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2. LITERATURE REVIEW

This chapter expands on brief journey of gasification and some of the milestones achieved in this field. Furthermore, some of the concepts presented in chapter 1 are briefly reviewed on feed stock materials and its pretreatment for existing gasification technologies used for the production of fuel gas. Furthermore, gasification technologies have been studied for fixed bed and fluidized bed under air, steam and CO_2 as gasifying medium as an oxidizing agent. Within this content the chapter is outlined for understanding the current state of gasification technologies. And these are briefly reviewed below and the impacts of types of gasification bed, gasifying medium and catalyst on production yield, quality and up gradation of produced fuel gas have been enumerated.

2.1. Brief journey of gasification

Biomass can be utilized as energy feedstock through various conversion processes to generate heat, electricity, liquid fuels and synthetic gases. The thermochemical process used for generating power, heat, coke and chemicals are combustion, pyrolysis, gasification and liquefaction. Thermochemical conversion started in 1669. The followings are the journey of gasification with some milestones (Kaupp et al., 1984):

Table 2.1 Some milestones in the field of gasification

Year	Researcher/scientist	Developments/milestones
1669	Thomas Shirley	Carburated hydrogen
1699	Dean Clayton	Coal gas from pyrolitic experiments
1788	Robert Gardner	1st patent in gasification - Suggested the application of waste heat of furnaces to raise steam by combusting the heated products in a boiler
1791	John Barber	Mentioned the use of producer gas to drive an internal combustion engine
1792	Murdock	1st confirmed use of producer gas from coal to light a room in his house For many years coal gas was one of the principal fuels used for lighting purpose in England
1798	Lebon	Gasify wood
1801	Lampadius	Proved the possibility of using the waste gases escaping from charring of wood
1804	Fourcroy	The process of generation of water gas by reaction of water with a hot carbon bed was mentioned
1809	Auberto	Realised that stack gases of blast furnaces can be combusted and used to roast ore and burn lime
1812	Auberto	Received a patent on above realization
1815	J. Taylor	1st producer gas unit was built - Design and operated the unit of producer gas and got a patent - Used oil as a fuel
1815-1839		Many patents were issued for utilization of waste heat and stack gas from blast furnace
1840	Bischof	1st commercially used producer gas plant - Built a large unit at the iron works of Audioncourt, France
Up to		Many researchers and engineers tried to improve

1860		the technology by using low grade fuel etc.
1861	Siemens gas producer	1st successful commercial units
1878	Dowson gas producer	1st which successfully used for stationary power engines
1889	Mond	Recognised 1st time to obtain other products such as ammonia via gasification
1895	Bernier suction gas producer	Beginning of the use of gas producer in small compact units
1901	Brush Koela plant	1st introduction as patented device designed for import to India and other developing countries
1901 to 1905	J. W. Parker	Covers 1000 miles with 2.5 & 25 hp automotive gas producer in Scotland
1914-1918	Porter and Smith in England	Developed automotive producer gas and successfully used during 1st world war.
1919	British Government	British taxation system assigned taxes to cars which included the producer gas
December 1939		About 2,50,000 producer gas based vehicles registered in Sweden

Producer gas was extensively used during the 2nd world war for the production of chemicals and energy. But after 2nd world war all the producer gas production units put on hold because of cheaply and abundantly available of natural gas, gasoline and petroleum oil. However, again the shortage of supply of gasoline and petroleum based fuels were experience and thus the research on gasification restarted again to become independency on fossil fuels as well as for combats the pollution.

2.2. Biomass preparation and characterization

Currently there is lower utilization of non-woody biomass as compared with woody biomass for the production of energy. This is all because of uneven particle size,

specific fuel content, lower energy content and density. The considerations that should be taken for an operative gasification process of selected non-woody biomass are:

• Biomass pre-treatment

• Gasification process parameters and constraints.

2.2.1. Biomass pre-treatment

The main objective of pre-treatment is to prepare the selected biomass suitable as a feedstock for gasification. Due to variety of non-woody biomass with wide range of properties, the pre-treatment becomes a crucial aspect of curtailing failure of gasification process. These may include either a single process or a combination of several steps such as drying, size reduction and densification.

2.2.1.1. Drying

Ideally the moisture content should be in between 10-15 % for the purpose of gasification (Basu, 2010). Non-woody biomass like cotton gin waste, rice husk, etc. contains low moisture content and it does not require drying. However, Non-woody biomass like unripe coconut, green algae, etc. has very high initial moisture content. Thus, drying becomes mandatory in pre-processing stage for these types of biomass to be used as a feedstock. Approximately 2.3 MJ is required for the vaporization of one kilogram of moisture content (Basu, 2010). Thus, moisture can reduce the overall efficiency of the process. However, sun drying may be opted for the drying in pre-processing stage to reduce the energy during the process of drying. Also, heat could be recovered from the heat content of exit gas during gasification process.

2.2.1.2. Size reduction

Non-woody biomass is found with irregular shape and size. Thus, for appropriate size of feed stock its size reduction is often required. Uniform size is required for the other pretreatment process named densification such as pelleting. It also provides uniform size of the particles for the gasification. In general, large amount of surface area is found in smaller particles which allow better heat transfer. The feedstock size is dependent on the type and mode of operation of the gasifier used. However, the most common feedstock size varies from 1 μm to 1 cm (Souza-Santos, 2010). Additionally, for the easy handling of fluidized bed and to maximize the contact of the surface of feedstock with the oxidant during fluidization, sizing of feedstock becomes very important. Furthermore, finer particles are preferred in entrained bed type fluidization. Whereas, biomass reduction takes place at slower rate in fixed bed gasification thus it requires particle size in the range of 1 cm. This size of particle is also required for delaying the rapid combustion while allowing the process of effective devolatization.

2.2.1.3. Densification

Low bulk density, irregular size and shape are some of the demerits of non-woody biomass, which create problems in storing and handling. Additionally, it cannot be used in its current original form. Densification would be a best solution to eradicate the above problems. Torrefaction and pelleting are the general two methods available for the purpose of feedstock densification (Samy, 2013, Tchapda et al., 2014). The combination of these two processes can also be used for densification which increases the density and thus improves the efficiency of the gasification process.

2.2.1.3.1. Torrefaction

Torrefaction is a thermal process which converts biomass in coal like material which has better fuel characteristics than the original biomass. It is achieved by heating the biomass in inert atmosphere at temperature ranges of 200-400 °C. During this process the structure of biomass changes and it becomes more hydrophobic and brittle. It removes moisture content, volatiles materials and reduces the level of mineral content (Sarkar et al., 2014) in the biomass. Reduction of mineral contents reduces the mineral oxides which would be responsible of slagging or caking of ash during gasification process (Sadaka and Negi, 2009). Also, torrefied biomass has many improved properties over untreated material such as higher energy density, lower oxygen-to-carbon ratio, greater grindability, reactivity and ignitability. Furthermore, torrefied biomass offers low transportation and storage costs (Kuo and Wu, 2016; Thanapal et al., 2014; Sarvaramini et al., 2014).

2.2.1.3.2. Pelleting

Another method of densification of biomass is pelleting or briquetting. Briquette particle size range of 1-2 cm is the best for fixed bed biomass gasifier. Conventional pelletiser is typically used for the process of pelletizing. Loose biomass is fed into the pelletiser and pressure is applied on the biomass in the presence of mould. Pelletisers are equipped with blades to cut the pellets in desired size (Chen et al., 2008). Lignin present in the biomass has the ability to bind the fibers (Kalish, 2012). Temperature of the pellets leaving pelletiser is in between 80 to 90 °C, thus cooling becomes very important process for the pelleting. Lignin stabilization takes place during the cooling period and the pellets become hard (Chen et al., 2008). The process of pelleting constructs a uniform sized fuel with many fold higher bulk density and thus it allures for

the energy process. In addition, ash is decreased in the thermochemical conversion if the non-woody biomass is used in pellet form. It is reported that ash was decreased by 2 to 3 folds during the combustion of cotton gin waste pellet compared with unpelleted cotton gin waste (Holt et al. 2006). Furthermore, another category of non-woody biomass pellet has been considered for the industrial purposes (Vinterback, 2004). However, the moisture content, die temperature and configuration, pressure, and feed rate are the different properties on which the efficiency of the equipment depends. Thus, wide variation in the properties of biomass requires specific development of appropriate pelleting processes for each range of feedstock's (Uslu et al., 2008; Holt et al., 2006).

2.2.1.3.3. Combined torrefaction and pelleting

Densification can also be achieved by torrefaction and then pelleting. It also increases the rate of devolatilisation. Sarkar et al. (2014) worked on raw, torrefied, and combination of torrefied and pelleted switchgrass, as pre-treatment process. They had worked in both the inert and oxidizing atmospheres. They found the highest devolatilisation rate for torrefied and pelleted switchgrass and the lowest devolatisation rate was achieved for raw-torrefied switchgrass. Thus, it could be surmised that devolatilisation was increased via pelleting process. However, torrefaction and pelleting consumes extra energy and power.

2.2.2. Biomass characterization

Proximate and ultimate analyses are generally used to characterize solid fuel composition. Proximate analysis is used to determine fixed carbon, moisture, ash and volatile matter. Whereas, ultimate analysis is used for the determination of the main chemical elements i.e. C, H, O, N and S. Thermochemical reactions take place with these main chemical elements. Some mineral contents are also present in biomasses

which are converted into ash during thermochemical processes. Ash is an inert material left over after gasification as solid residue which decreases the operational energy significance of a feedstock. Because of higher ash and tar content gasification of non-woody biomass faces technical issues like ash sintering, bed bridging and tar collection (Guo et al., 2014; Gai and Dong, 2012).

Table 2.2 The ultimate and proximate analysis of various lignocellulosic biomasses.

Biomass type	Ultimate analysis (db, % w/w)					Proximate analysis (% w/w)				HHV (MJ/kg)	References
	C	H	O	N	S	Ash	VM	FC	M		
Peach stone	41.0	5.7	48.4	4.9	0	1	63	29	7	18.8	Ismail et al., 2018
Pine wood chips*	52.90	6.30	37.60	0.50	0.05	2.90	72.90	24.2	db	22.51	Dıaz and Martınez, 2019
Pine grass	48.20	5.56	45.19	0.36	0.07	6.90	76.60	16.5	db	21.17	Dıaz and Martınez, 2019
Miscanthus	44.5	5.2	45.0	5.3	0	2.1	64.4	22.1	11.4	18.6	Ismail et al., 2018
Rice husk*	35	5.5	36	1.53	0.08	21.89	55.85	15.24	7.12	dna	Bharath et al., 2018
Waste wood*	47.9	5.45	40.6	1.9	0.10	4	dna	dna	8.8	20.06	Valin et al., 2019
Beach wood	49.6	5.69	44	0.3	410 ppm	0.7	dna	dna	8.3	20.56	Valin et al., 2019
Pine saw dust	51.4	5.1	42.4	1.1	-	0.5	74.7	13.2	11.6	19.5	Ma et al., 2019
Ground seed corn	48.91	5.95	41.46	1.73	0.16	1.79	86.44	11.77	db	dna	Timmer and Brown, 2019
Waste wood pellets	47.26	6.14	44.99	0.11	dna	1.5	77.3	14.9	db	19.05	Shen at al., 2019

Torrefied soft wood chip	47.7	5.7	45.5	1.0	0.16	0.6	76.5	22.9	db	22.3	Mafu et al., 2018
Torrefied soft wood chip	46.6	5.5	48.0	0.1	0.01	0.6	77.3	22.1	db	22.4	Mafu et al., 2018
Torrefied sweet sorghum baggasse	43.5	5.6	50.5	0.3	0.13	6.5	69.8	23.7	db	23.0	Mafu et al., 2018
Palm oil empty fruit bunch	42.08	5.72	49.93	0.99	dna	3	83	9	5	18.46	Ariffin et al., 2017
Cedar wood	51.10	5.90	42.50	0.12	0.02	0.3	80–82	18–20	db	21.72	Asadullah et al., 2004
Wood sawdust	46.2	5.1	35.4	1.5	0.06	1.3	70.4	17.9	10.4	21.27	Cao et al., 2006
Olive oil residue*	50.7	5.89	36.97	1.36	0.3	4.6	76	19.4	9.5	23.66	Arvelakis et al., 2003
Rice husk	45.8	6.0	47.9	0.3	dna	0.8	73.8	13.1	12.3	15.82	Velez et al., 2009
Rice straw*	38.61	4.28	37.16	1.08	0.65	12.64	16.55	65.23	5.58	16.86	Li at al., 2009
Pine sawdust*	50.54	7.08	41.11	0.15	0.57	0.55	17.16	82.29	db	23.00	Lv et al., 2004
Spruce wood pellet*	49.3	5.9	44.4	0.1	dna	0.3	17.1	74.2	8.4	20.96	Miccio et al., 2009
Coffee husk	46.8	4.9	47.1	0.6	0.6	1.0	14.3	74.3	10.4	18.9	Li at al., 2009
Coffee ground*	52.97	6.51	36.62	2.8	0.05	1.0	16.7	71.8	10.5	24.46	Murkami et al., 2007
Larch wood	44.18	6.38	49.32	0.12	dna	0.12	14.86	76.86	8.16	21.91	Weerachanchai et al., 2009
Grapevine pruning waste*	46.97	5.8	44.49	0.67	0.01	2.06	19.78	78.16	db	20.37	Lapuerta et al., 2008
Jute stick*	49.79	6.02	41.37	0.19	0.05	0.62	21.4–23.4	76–78	db	22.12	Asadullah et al., 2004

	C	H	O	N	S	Ash	FC	VM	M	HHV	Reference
Sugar-cane bagasse	48.58	5.97	38.94	0.2	0.05	1.26	28.74 – 30.74	67–70	db	21.51	Asadullah et al., 2004
Corn cob	40.22	4.11	42.56	0.39	0.04	2.97	16.11	71.21	9.71	19.11	Lu et al., 2004
Peach stone	51.95	5.76	40.7	0.79	0.01	0.65	18.1	81.3	8.53	24.06	Arvelakis et al., 2005
Straw*	36.57	4.91	40.70	0.57	0.14	8.61	17.91	64.98	8.5	17.06	Shen et al., 2008
Camphor wood*	43.43	4.84	38.53	0.32	0.1	0.49	14.75	72.47	12.29	19.94	Zhou et al., 2009
Beech wood	48.27	6.36	45.2	0.14	dna	0.8	18	81	db	21.66	Radmanesh et al., 2006
Switchgrass*	47	5.3	41.4	0.5	0.1	4.6	17.1	58.4	20	21.16	Jin et al., 2006

*: ultimate analysis on ash free basis; db: dry basis; C: carbon; H: hydrogen; O: oxygen; N: nitrogen; S: sulphur; VM: volatile matter; FC: fixed carbon; M: moisture content; dan: data not available

Table 2.2 shows the characteristics of some woody and non-woody biomass which was taken as feedstock for gasification by researcher available in literature. Generally the higher energy content in solid fuels is found with higher carbon content. However, in reverse, high amount of moisture and ash would lead to decrease of energy content in non-woody biomass. Beside these, the gasification is not only influenced by the carbon content but component of moisture in elemental form (hydrogen and oxygen) also with some other oxidants present in gasification process. These are altogether responsible to form H_2, CH_4, and CO in the produced fuel gas. Furthermore, low density is generally one additional issue with non-woody biomass particularly with herbaceous plant or the biomass initiating from grasses. This would create problems in handling mostly to control feed movement rate.

Alkali like sodium, potassium and alkaline earth minerals such as calcium and magnesium are found in biomass. It also includes some other minerals such as Fe, Si, Al, Cl, and P. Some minerals such as alkali and alkaline present in the biomass may act as catalyst for the process of thermochemical conversion. Moreover, these may form alkali silicate with silica, which would cause bridging and agglomeration inside gasifier resulting to affect gas production. Furthermore, some other minerals can possibly form ash during the gasification process (Fryda et al., 2008; Lahijani and Zainal, 2011).

2.3. Biomass gasification

Conversion of biomass via thermochemical conversion in the presence of gasifying media by which, biomass is converted into a mixture of gaseous products mainly H_2, CO, CH_4 and CO_2. Air, steam, oxygen, carbon di-oxide or mixture of these could be the gasifying media for the process of gasification. Biomass feedstock, gasifying medium, gasifying temperature, bed material, presence of catalyst, and the operational conditions are the main process parameters. There are different types of gasifiers like fixed bed, moving bed, fluidized bed and the entrained flow gasifier. It may also be categorized based on flow of biomass and oxidant, the way by which biomass is supported inside the gasifier and the mode of supply of heat for the gasification. However, broadly two types of gasifier are used for the gasification purposes, i.e., fixed bed gasifier and fluidized bed gasifier, which are known as fixed bed gasification and fluidized bed gasification. Followings are the some literature reviews based on above operational process parameters.

Numerous studies were performed by several researchers comparing pros and cons of fixed and fluidized bed gasification. Environmental and economic factor were considered along with the use of material and energy by Warnecke (2000), and he found

only marginal advantages of fluidized bed gasification over fixed bed gasification. However, Alauddin et al. (2010) reported a lot of drawbacks like, low and non-uniform heating, low mass transfer between gasifying media and biomass in fixed bed gasification over fluidized bed gasification. It results large tar quantities and thus it lowers the efficiency of gasifier. On the other hand, good mixing with gas-solid contact is the advantage of fluidized bed gasification, which infers good rate of conversion reaction and thus ultimately it produces very low amount of tar. Additionally, because of its efficient mass and heat transfer properties, various types of biomass can be feed into the fluidized bed gasifier (Alauddin et al., 2010, Yassin et al., 2009).

2.3.1. Fixed bed gasification

The biomass bed is kept stationary in fixed bed gasifier, while gasifying media passes through it. Updraft and downdraft gasification are the two common configuration of this type of gasifier. Fixed bed gasifier is the oldest and simplest form of a gasifier, which allows low cost installation investment as well as relatively low operating cost and simple in operation. Furthermore, both downdraft and updraft gasification use the same mechanical configuration but it varies in the operation of feeding biomass and gasifying agent.

Shen et al. (2019) used air and mixture of air and CO_2 as oxidizing agent during gasification. At first gasification was performed using 100% air as gasifying media, furthermore, 15% CO_2 was added in gasifying media with 85% air. Then after the results of this comparative study was reported. Since, CO_2 behaves as an inert gasifying media at low temperature and it could be converted to CO at high temperature. It was reported that CO_2 as gasifying agent has comparable energy of produced fuel gas as that of air as gasifying media, also, use of CO_2 has reduced the N_2 fraction in the produced

fuel gas. The energy generation of produce fuel gas per gram of wood pallet were 6.67 kJ with 15% CO_2 and 85% air as gasifying media, whereas, 7.45 kJ of energy was found with 100% air as gasifying media at 800 ℃ gasifying temperature. In addition, CO_2 air mixture with gasifying media was also conducted in small scale gasification experiments and it was found that CO concentration in produced fuel gas was enhanced due to Boudouard reaction. On the other hand, CH_4 concentration was suppressed owing to CO_2 dry reforming and the produced gas has a high $CO:H_2$ ratio due to reverse water-gas shift reaction. CO_2 addition with gasifying media also enhanced carbon conversion efficiency and cold gas efficiency by 6 % and 5.8%, respectively.

Prasertcharoensuk et al. (2019) studied the behaviour of lignocellulosic material after pyrolysis. Pyrolysis was performed in the temperature range of 600 to 900 ℃, which significantly influenced the char properties and the total pore size was increased by up to 2.5 to 3 times. Increasing the surface area and pore size enhanced the surface area for gas-solid reaction during the gasification process. It was found that unstable compounds like levoglucoan and its derivatives decomposed and phenolic compounds formation enhanced after pyrolysis above the temperature of 700 ℃. The composition of H_2 was increased from 49 to 67 mol % when gasification was performed without pyrolysis and after pyrolysis at 900 ℃. Steam to carbon in biomass ratio was used 5.7 at 1000 ℃ gasifying temperature and the particle volume was in the range of 0.5 to 1 cm^3. It was attributed that amount of volatiles affected the properties of produced fuel gas, thus pyrolysis is a crucial step for gasification.

Co-gasification of two biomasses was performed by Diaz and Martinez (2019). The mixture of pine wood and pinewood-grass was taken as a feedstock and it was mixed by weight as 100-0%, 90-10%, 80-20%, and 70-30%, respectively. The experiments were conducted in a laboratory scale updraft gasifier using air as a gasifying medium. The

experiments were performed in the equivalence ratios of 0.25, 0.30, and 0.34. And gasification temperature was varied from 800 to 1100 °C. An increase of about 20 % for H_2, 20 % for CO and 30 % for CH_4 by volume was observed in the gasification of combined 80 pine wood and 20 % pine grass with respect to the 100 % pine wood. In addition, the mixture of 80 % pine wood and 20 % pine grass was found to be most promising in terms of improving carbon conversion and reducing the amount of char. It was surmised that the improvement in H_2, CO and CH_4 concentration was due to presence of K_2O in the 20 % pine grass, which acted as catalyst. However, it was prone to combustion rather than gasification when more than 20 % amount of pine grass was used. Lower heating value of the produced fuel gas was found between 4.0 MJ/Nm^3 to 5.5 MJ/Nm^3 by the mixture of 80-20 % biomass.

Thengane et al. (2019) worked on co-gasification of high ash biomass and high ash coal. Biomass taken for study contained dry litter of jackfruit, raintree, mango and eucalyptus tree, which showed ash content ranging from 20 to 25 %. Cylindrical shape pellets are made from these garden wastes with the dimensions as length 40 mm, diameter 15 mm. High ash coal was collected from Western Coalfields Limited, Chandrapur area, which was taken in the form of chips with 10-40 mm and 5-10 mm dimensions. The highest cold gas efficiency, thermal efficiency and lower heating value of produced fuel gas were found as 57.5 % , 72.63 % and 3.05 MJ/Nm^3, respectively for biomass ratio 0.75. Whereas it was formed lowest for coal with cold gas efficiency 33.06 % and thermal efficiency 49.38%. It was found that carbon conversion of feedstock to gas was increased with the increase of the amount of biomass. Furthermore, the presence of coal enhanced the rate of reaction by increasing the temperature.

Mafu et al. (2018) also used CO_2 as gasifying agent for the gasification of biomass derived char samples in thermogravimetric analyser. The biomasses taken were softwood chips, hardwood chips and sweet sorghum bagasse and the selected temperature range was 850- 950 °C. Reactivity of sub bituminous coal char was also compared with the reactivity of all three biomass char under CO_2 atmosphere. The reactivity of hard wood was found lowest whereas the reactivity of sweet sorghum bagasse was highest among all biomass char. However, the reactivity of sub-bituminous coal was lowest amongst all. Furthermore, addition of biomass form 10 to 30 % by weight was also made for coal char gasification. It was found that 20 and 30 % addition of biomass with coal char increased the gasification rate whereas; addition of 10% biomass had no any significant effect on the gasification reactivity of coal char.

A comparative study of steam gasification under Fe_2O_3 as catalyst and without catalyst was investigated by Shen et al. (2018) taking feedstock as a mixture of Indonesian Adaro coal and Japanese cedar in the ratio of 1:1 by weight. 10 wt% Fe_2O_3 with the mixture of Japanese cedar and coal was taken in 50 % of H_2O by vol and subjected to 800 °C for 1 hour. The evolution of H_2 during gasification of Indonesian Adaro coal and Japanese cedar without catalyst was 100 mmol/g of feedstock, and the evolution was raised to 152 mmol/g of feedstock in the presence of Fe_2O_3 as a catalyst. It was also found that the carbon conversion was 38 % for Adaro coal and reached to 70 % for the mixture of Japanese cedar and Adaro coal in presence of Fe_2O_3 during first 30 min of gasification.

Furuso et al. (2018) studied on alkali addition in entrained flow biomass gasification and did the thermodynamic equilibrium calculations. Four different forest wastes were taken for the study, i.e., pine stemwood, pine bark, spruce forest residue and pine forest residues which were further impregnated with 2, 4 and 8 % of Na or K. It was reported

that 2 to 8 % addition of alkali catalyst was changed the biomass gasification and the cleaner fuel gas was found. And the impregnation of Na was more promising candidate to get cleaner fuel gas.

Arifin et al. (2017) performed gasification on a medium-scale downdraft fixed bed gasifier with a feed rate of 162 kg/h and the feedstock was palm oil empty fruit bunch. The gasification temperature was kept in the range of 850 to 950 ℃. It was attributed that the ideal gasification temperature for palm oil empty fruit bunch was between 850 to 950 ℃, furthermore, the cold gas efficiency and fuel gas heating value were increased with the increase of gasification temperature. Heating value of fuel gas varied from 4.10 to 6.42 MJ/Nm^3 and cold gas efficiency (CGE) was varied from 61 to 67 %. It was also attributed that the fuel gas generated from the gasification of oil palm empty fruit bunch with feed rate of 126 kg/h at gasification temperature 900 ℃ has the capacity to generate 106 kilo watt equivalent (kWe) electricity.

Balanco et al. (2013) worked on steam reformation after pyrolysis of municipal solid waste derived fuel. The feedstock particle size was approximately 1.0 mm which has 40, 6, 32 and 0.5 wt% of carbon, hydrogen, oxygen and, nitrogen, respectively. Ni based catalysts were prepared by sol-gel method with support metal Al, Mg and Ce for the Ni loading of 5, 10, 20, and 40 wt%, respectively. Initially, pyrolysis of refused derived fuel was performed at 600 ℃ then it was reformed at 800 ℃ under the gasifying agent steam. 20 wt% loading of Ni on Ni/SiO$_2$ catalyst was found highly efficient for tar destruction and the highest concentration of H$_2$ was 57.9 vol% at this loading. Alcohol functional groups and alkenes were mainly found in the gas chromatography- mass spectroscopy of the tar with major concentration of phenol, cresols, styrene, fluorine, naphthalene and phenanthrene.

Ciferno and Maranao (2002) found a little bit methane and H_2 and CO production was maximised at temperature greater than 1200 °C. Li at al. (2009) performed gasification of empty fruit bunch (EFB). They used tri-metallic material as catalyst and steam as a gasifying media and worked in the temperature range of 750 to 900 °C. They attributed higher production of hydrogen and total gas yield at higher temperature. At 900 °C, the H_2 and total gas yield were 1.481 and 2.48 m^3/kg of EFB, respectively, which was highest production. The concentration of H_2 and CO_2 increased with increase of temperature from 700 to 900 °C. While, the concentration of CO and CH_4 decreased with the increase of temperature. HHV also decreased with increase of temperature and it reached to 11.39 MJ/Nm^3 at 900 °C from 13.52 MJ/Nm^3.

Similarly, Li et al. (2009) also performed gasification of EFB on the four different particle size, i.e., <0.15, 0.15-1, 1-2, 2-5 mm under steam as a gasifying medium. They found added H_2 and CO_2 production and fewer CH_4 and CO concentrations in fuel gas for smaller particles than the larger one. However, the value of HHV increased with increasing particle size and maximum HHV was found as 12.54 MJ/kg for EFB of particle size 2-5 mm.

Luo et al. (2009) worked on pine saw dust and steam as gasifying media. Particle size of pine saw dust was from 0.075 to 1.2 mm in group of 0.075-0.15, 0.15-0.3, 0.3-0.6, 0.6-1.2 mm. In the research the gasification temperature was taken as 900 °C. During the study, increase of char and tar yield was formed with the increase of particle size, and hence decrease of H_2 and total gas yield was noted. Carbon conversion efficiency was also found to be decreased with the increase of particle size. The highest H_2 and total gas yield was noted as 0.8 and 1.62 m^3/kg of pine saw dust, respectively for the particle size of less than 0.075 mm, which was smallest size. Production of more CO and less CO_2 in the smaller particle than the larger particle was also reported by this study.

Yan et. al. (2010) observed a different trend in the study of char derived from cyanobacterial blooms of the size of < 0.15, 0.15-0.3, 0.3-0.45, 0.45-0.9, 0.9-3 mm. Gas yield was observed increasing trend from 1.72 to 1.84 Nm^3/kg of biomass with the increase of the particle size form less than 0.15 mm to the range of 0.45-0.9 mm. Gas yield was further decreased slightly and observed as 1.81 Nm^3/kg as the particle size was increased. However, the product gas composition was nearly same at gasification temperature 850 °C for all the particle size of biomass, which shows no effect on the fuel gas composition with the variation of particle size.

Lv et al. (2007) made a comparative study on gasifying media between oxygen/steam and air for pine wood block as a feedstock. The composition of H_2 and CO was 52.19 and 63.31 vol% and 52.19 and 63.31 vol % for air and oxygen/steam as gasifying media, respectively. It was also observed that the hydrogen yield was highest 0.49 m^3/kg of biomass under steam as oxidizing agent.

Li et al. (2009) had also performed analysis varying steam to biomass ratios (SB) from 0 to 1.33. Increasing SB resulted in increase of total gas and hydrogen gas yield, and the highest values were 1.481 and 2.48 m^3/kg biomass for hydrogen and total gas yield, respectively. However, hydrogen yield and total gas started to decrease as SB increased from 1.33 to 2.67 and the same trend was followed by the hydrogen in fuel gas composition.

As per the study of Skoulu et al. (2009), amount of tar and char decreased slightly as ER was increased from 0.14 to 0.42. Maximum gas yield was found 0.8 wt % at equivalence ratio (ER) of 0.21. Both the H_2 gas composition and HHV was found highest at ER 0.21. Increasing ER from 0.21 to 0.42 resulted slightly decrease in total

gas yield but lowest values were observed for both H_2 gas composition and HHV at ER of 0.42.

Mahishi and Goswami (2007) conducted experiments on pine bark using calcium oxide as a sorbent to absorb CO_2. During the experiments biomass and calcium oxide ratio taken in equal molal ratio. At gasifying temperature 600 ℃, the composition of product gas without CaO was H_2: 60, CO: 9.1, CH_4: 3.2, CO_2: 27.7; and with CaO, H_2: 64.5, CO: 5.9, CH_4: 2.8, CO_2: 27.7 in vol %. It was observed that concentration of hydrogen increased significantly by using sorbent. It could be surmised from the results that CaO played a dual role in the gasification first as a CO_2 sorbent and the second as a catalyst.

Other researcher Hanoaka et al. (2005) also used calcium oxide as a CO_2 sorbent in the gasification of Japanese oak under steam as an oxidizing agent. The presence of CO_2 in produced fuel gas was found when gasification was carried out without the presence of CaO. Conversely, there was no any sign of presence of CO_2 in fuel gas when CaO was used as a CO_2 sorbent. H_2 yield was increased with the increase of [Ca]/[C] in molar form from 0 to 2, however, it decreased with increasing the molar ratio of [Ca]/[C] from 2 to 4 and fell down from maximum 0.8 to 0.55 m^3/kg of biomass.

Li et. al. (2009) prepared a new tri-metallic nano catalyst (nano-NiLaFe/γ-Al_2O_3) and compared with calcined dolomite. In the absence of catalyst the gas yield was lowest (1.21 m^3/kg) and tar yield was highest (37.8 g/Nm^3). However, gas yield showed increasing trends in the presence of nano tri-metallic catalyst and highest gas yield was found as 2.11 m^3/kg of biomass and lowest tar yield was found as 0.28 g/Nm^3 of produced fuel gas. Highest concentration of H_2 was also found in the presence of newly developed tri-metallic catalyst and at this point CO_2 concentration was very low.

Research work conducted by several researchers on fixed bed gasification was tabulated in Table 2.3.

2.3.2. Fluidized bed gasification

The major issues with fixed bed gasification are non-uniform heating and improper contact between solid surfaces and gasifying media. Due to which more amount of tar generated in fixed bed gasification with respect to fluidized bed gasification. However, a bed material is required for the proper fluidization. Several studies are available in regard to bed material such as sand, which does not play an active role in gasification but helps in attaining proper pressure difference and in uniform heating during fluidization process. Other types of research are available where only catalysts were used as a bed material, but it increases the cost of the process and also recovery of catalyst becomes a challenging task. Bubbling fluidized bed and circulating fluidized bed type of gasifiers are generally used by several researchers. However, bubbling fluidized bed is simple in design and quite easy in operation with respect to circulating fluidized bed gasifier.

The fluidized bed gasifiers are categorized based on the mode of heat transfer and their fluid dynamics. Generally fine inert silica sand or alumina is used as bed material in bubbling fluidized bed. A gasification media is forced through these fine particles, and due to gas velocity particles start uplifting and coming back to bed. A point is achieved when weigh of the solid is counterbalanced by the frictional forces between the gas and particles. At this gas velocity the solid particles behave like fluid which is known as bubbling fluidized bed.

Maa et al. (2019) used olivine and dolomite to be act as natural catalyst in the fluidized bed gasification. The experiments were conducted to study the effect of operating

parameters in bubbling fluidized bed co-gasification of pine saw dust and brown coal. The gasification temperature varied from 700 to 1000 °C and the feed particle size varied from 2 to 3.5 mm. Furthermore, steam/fuel ratio, equivalence ratio, biomass ratio and the catalyst loading were varied from 0.5-0.8, 0.1 to 0.4, 0 to 100 % and 3.0 to 12.0 wt %, respectively. H_2 yield was reached to 55.5 (g/kg-fuel) with the dolomite loading 12 wt% from 52.9 (g/kg-fuel) with the dolomite loading 3 wt% and the yield was increased from 47.5 to 52.1 (g/kg-fuel) for olivine loading. Whereas, tar yield decreased drastically from 5.4 to 0.4 (g/Nm^3) and from 7.0 to 0.8 (g/Nm^3), respectively with the presence of dolomite and olivine. It was attributed that dolomite and olivine have high potential to be used as catalyst because of its natural occurrence and capability to enhance the H_2 production and tar up gradation.

In an another research, the effects of gasification temperature, biomass particle size, equivalence ratio, superficial velocity and the steam addition on ground nut corn in fluidized bed were studied by Timmer and Brown (2019). During the study the feed rate, equivalence ratio, and temperature were varied from 0.518 to 1.061 g/sec and, 0.247 to 0.370, from 715 to 805 °C, respectively. Higher carbon conversion was achieved with decreasing both superficial gas velocity and particle size, and with increasing equivalence ratio. And negligible effect was recorded on carbon conversion with the change of steam concentration. The highest gas-solid chemical reaction coefficient was found as 6.32×10^{-4} sec^{-1}, which was achieved at equivalence ratio 0.252, feed rate 0.724 g/ sec and gasification temperature 797 °C.

Valin et al. (2019) experimented several types of feed stocks like bulky furniture waste, plastics, cardboards, paper and textiles. Mixture of all these were named as solid refused fuel (SRF), which were pelletized and gasified in fluidized bed. Furthermore gasification was done with waste wood and stem beech wood sawdust. The temperature

was varied from 800 to 910 °C and the equivalence ratio was varied from 0 to 0.34. Gasification was performed with a solid feeding rate of 1-3 kg/h in a bubbling fluidized bed at 1.5 bar. With the agreement of other researchers, it was found that yield of H_2 and CO in produced gas was influenced with the temperature. Furthermore, it was found that addition of steam enhanced the yield of CO and CO_2. The optimum temperature found for the gasification of SRF was 908 °C and the yield of H_2, CO, CH_4, and CO_2 at optimum temperature were 0.2, 0.16, 0.13, and 0.36, respectively.

Tian et al. (2018) used *Enteromorpha intetinalis* biomass as a feedstock for the gasification using air and steam as oxidising agent in fluidized bed. During this study, calcined dolomite, limestone and olivine were used as catalysts to crack the tar and to increase the H_2 content in produced gaseous product. To study the effect of all three natural catalysts, all the experiments were performed at equivalence ratio 0.14 and steam to biomass ratio at 0.5 (wt/wt). When calcined dolomite was added to the reactor, a significant amount of tar reduction was observed and fuel gas yield was increased by more than 14 %. Furthermore, the gasification temperature was varied from 800 to 1000 °C and the maximum yield of H_2 was found at 1000 °C and the value was 49.1 vol %. Calcined dolomite was found most effective for the tar destruction. Increase in biomass particle size also increased the tar content however; the variation was only for an insignificant amount. However, the char yield was almost same for all the types of catalysts, thus it was attributed that char yield was dependent on char content in devolatization step and the rate of reactions. At optimum temperature, the carbon conversion was found to be 60.8 % and yield of other gases were found as CO: 26.4, CH_4: 0.8 and CO_2: 23.7.

Another study was carried out by Ismail et al. (2018) in a fluidized bed using pilot plant gasifier. The biomass used as a feed stock for the study was peach stone and

miscanthus. Ismail et al., 2018 also used dolomite and olivine as catalysts to enhance the tar cracking and to increase the gas yield. Study was carried out at three different gasification temperatures, i.e. 750, 800 and 850 °C in air as gasifying media with 45 kg/h of constant feed rate. Furthermore, the operating process parameters were optimised by two dimension COMMENT code. Furthermore, numerical results were compared with the experimental results and it was found in agreement with each other. Modelling was made using Eulerian approach on mass, energy and momentum exchange. It was stated that increased gasification temperature decreased the tar production. At lower temperature, the formation of CO was high resulting the increased value of fuel gas heating value. It had been attributed that mathematical model can be used for biomass gasification.

Research on co-gasification of Indian rice husk and Indian coal was performed by Bharath et al. (2018) using lab-scale bubbling fluidized bed reactor. Air and steam were used as oxidizing agents at atmospheric pressure. Air to solid ratio was varied from 1.02 to 1.72. The high amount of fly ash was observed when the experiment was started at equivalence ratio of 0.3, and then the equivalence ratio was reduced to 0.22 for rice husk. It was found that addition of rice husk increased the carbon conversion, heating value and cold gas efficiency of produced fuel gases. Contribution of rice husk was varied to share 0 to 90% of the power. The heating value was found to be increased from the range of 2.14 - 2.68 MJ/Nm^3 to the range of 5.21- 5.4 MJ/Nm^3 depending on the operating parameters for the case of 0% rice husk and 75 % rice husk, respectively. At the share of 50 to 75 % of total power by rice husk the cold gas efficiency, total carbon conversion, and heating value of produced fuel gases were found to be 78 %, 89 % and 5.4 MJ/m^3 with steam. The carbon conversion was 85.7 % when only air was used as gasifying medium. There was a trace amount of methane when 8.37 % of rice

husk was used; however no evidence of methane was detected when the rice husk percentage was increased to 75 %.

Singh et al. (2018) used naturally available sand as bed material and groundnut shell as feedstock. This groundnut shell was gasified in the bubbling fluidized bed reactor in the presence of air as gasifying medium. During the research the equivalence ratio was varied from 0.29 to 0.33, feedstock feeding rate from 36 to 31.7 kg/h and gasification temperature from 650 to 800 °C. Higher heating value was decreased with the increase of equivalence ratio. Also, suspended particulate matters were high at higher equivalence ratio. The lowest equivalence ratio was also not favourable because of choking and burning of tar happened with the incipient of ground nut shell gasification. Therefore, the most suitable equivalence ratio was attributed as 0.31. And cold gas efficiency and carbon conversion efficiency at optimal equivalence ratio were found as 71.8 and 88 %, respectively at equivalence ratio of 0.31.

Peng at al. (2017) also worked on co-gasification of wood residue and coal in fluidized bed and catalysts were also used during these experiments of gasification. Wood residue was received from a wood product manufacturer which was mixed with high volatile bituminous coal taken from east part of Iran. Alkali metals of $NaHCO_3$, K_2CO_3 and $KHCO_3$ prepared by one-step polymerization method were taken as catalysts and its effects onto the products had been reported. Pure oxygen and steam were used for the gasifying medium as oxidising agent. With the agreement of Bharath et al. (2018), Peng et al. (2017) also reported that addition of coal to biomass had a positive impact on the gasification process. The overall conversion was increased from 81 to 94% with the increase of the coal/biomass ratio from 0.1 to 0.5. In addition, the results also showed that increasing the catalyst mass ratio was responsible for increased CO_2 and H_2 yield. As the catalyst mass ratio increased the tar yield decreased from 13.38 to 9.27 for

Al_2O_3/K_2CO_3, from 14.87 to 10.47 for $KHCO_3$ and from 14.18 to 9.62 for $Al_2O_3/NaHCO_3$. Furthermore, K_2CO_3 was found most promising catalyst with the lowest catalyst deactivation and highest conversion to gaseous products as compared to $NaHCO_3$ and $KHCO_3$.

Ahmed et. al. (2016) reported that direct heated bubbling fluidized bed gasifiers are mostly used. If offers broad span of parameters like temperature, pressure, etc. Mohammed et al., (2011) performed gasification of empty fruit bunch in fluidized bed, under the influence of air as gasifying media. The range of temperature taken during the experiment was from 700 to 1000 °C. As the gasification temperature was increased, the H_2 and CH_4 concentrations were increased and H_2 reached to 38.02 vol % from 10.27 and CH_4 reached to 14.72 vol % from 5.84. The concentration of CO was also increased with the increase of gasification temperature. In contrary, the concentration of CO_2 decreased with the increase of temperature. With the effect of higher temperature, tar and char percentage were also decreased. 92 wt% highest gas yield was observed at the temperature 1000 °C which had maximum HHV and the value was 17.81 MJ/ Nm^3.

In another research on sawdust as feedstock, Lv et al. (2004) varied the gasification temperature from 700 to 900 °C in fluidized bed. The results were in agreement with Mohammed et al., (2011) for gas yield and hydrogen production. The gas yield was increased from 1.43 to 2.53 Nm^3/kg of biomass with the gasification temperature moving from 700 to 900 °C. The composition of hydrogen was also increased with the temperature and reached to maximum 39 vol% at 900 °C from 21 vol% at 700 °C. The value of HHV first decreased from 700 to 750 °C but reached to maximum value at gasification temperature of 800 °C which was 10.82 MJ/Nm^3. However, the HHV was further reported with decreasing trend and reached to lowest value at 900 °C.

However, Wongsiriamnuay et al. (2013) differ from the outcomes of Lv et al. (2004) and Mohhamad et al. (2011) in regard to effect of temperature on gas yield and H_2 concentration. Bamboo was taken as feedstock by Wongsiriamnuay et al. 2013. Gasification of bamboo was performed from the temperature 400 to 600 ℃ using air and steam as gasifying media. It was reported that a decrease in the concentration of H_2 and CO was observed with the increase of gasification temperature. However, the CO_2 concentration was increased with the increase of temperature. Furthermore, the total gas yield remained about constant and maximum HHV and carbon conversion equivalence (CCE) were found at gasification temperature of 500 ℃ with the value of 4.1 MJ/Nm^3 and 67.4 %, respectively.

Mohammad et al. (2011) also performed experiments taking different particle size of empty fruit bunch. The particle size considered in this study was <0.3, 0.3-0.5, and 0.5-1.0 mm. It was found that increasing particle sizes generated more tar and char. And the highest 74.79 wt % gas yield was reported which was from the smallest particle size biomass. The largest particle size is responsible for the lowest gas yield with typical value 72.74 wt%. The concentration of H_2 was almost same with the variation of approximately 1 vol% in the particle size range of less than 0.3 mm and 0.3 to 0.5 mm. However, the further increase of particle size decreased the H_2 concentration to the lowest value (21.57 vol%). Furthermore, the highest HHV was reported for the particle size ranges from 0.3-0.5 mm. In another study by Lv et al. (2004), more CO and CH_4 were generated in smaller particle sized feedstock and in contrary CO_2 were decreased with the decrease of feedstock particle size. Lv et al. (2004) observed highest HHV, carbon conversion efficiency and gas yield for the smallest feedstock particle size and the values were 10.9 MJ/Nm^3, 95.10% and 2.57 Nm^3/kg of biomass, respectively. In an another study ER was varied from 0.15 to 0.35 and with the increase of ER tar and char

yield decreased which were reached from 9.53 to 2.82 wt% and 13.65 to 2.12 wt%, respectively. The highest gas yield was reported as 86.46 wt% at ER 0.35; however, the HHV was reported as lowest 14.61 MJ/Nm^3 at this ER. The maximum concentration of H_2 was found as 27.42 vol% at an ER of 0.25 which was decreased continuously till the ER of 0.35.

The same trend depicted by Lv et al. (2004) was observed by Wongsiriamnuay et al. (2013) on the experiments conducted for bamboo under the gasifying media air and air-steam mixture. Furthermore, mixture of air-steam as gasifying media generated high gas yield and higher value of CCE with respect to using air as gasifying media. In addition, the concentration of H_2 and CO in the produced fuel gas also increased by using the mixture of air and steam as gasifying media during gasification for the oxidizing agent. In another research, Wongsiriamnuay et al. (2013) used calcined dolomite as a catalyst and the gasification was carried out by varying catalyst to biomass ratios as 0:1, 1:1 and 1.5:1. The yield of H_2 and CO increased with the increase of coal to biomass ratio (CB) at higher temperature whereas the yield of CH_4 and CO_2 decreased for a little bit. The carbon conversion efficiency and total gas yield were increased with the presence of catalyst. It was surmised that the presence of catalyst enhanced the tar reforming reaction and hence tar decreased and the gas yield was increased.

Chang et al. (2011) worked on the gasification of α-cellulose under the gasifying media of air and steam. The gasification temperature used was 800 °C by varying steam to biomass ratio (SB) from 0 to 1.5 with a step of 0.5 and equivalence ratio was kept constant at 0.27. Increasing SB from 0 to 1, the H_2 concentration was found to be increased significantly and reached to highest H_2 composition 18.56 vol % from 13.50. Further increase of SB from 1 to 1.5 the H_2 concentration was decreased. The highest

total gas yield 1.02 Nm^3/kg of biomass was shown at SB 1. The lowest HHV was found at SB 1.5, which was 8.81 MJ/Nm^3.

Research work conducted by several researchers on fluidized bed gasification was shown in Table 2.4.

From the above review it may be concluded that the increase of gasification temperature form 700 °C increase the production of gas with H_2 and CO and less amount of char and tar. High gas production can be achieved nearby 900 to 950 °C. Thermal cracking of tar also enhanced at higher temperature (800-900 °C) and hence it assuaged the high production of gas yield (1.9-2.9 Nm^3/kg biomass). In addition, the presence of catalyst engendered the catalytic cracking of tar at relatively lower temperature. Furthermore, the presence of steam as oxidizing agent enhances the rate of steam methane reforming and water gas shift reaction. And thus it increases the composition of H_2 in product fuel gas. However, excessive use of steam in gasifier can cause the system to lose a large amount of energy in the form of heating up of the steam. Thus, wasting of energy to generate energy is not favourable. It was also observed that gasifier produces low gas quality of produced fuel gas because of lowered reaction temperature (400-600 °C) due to excess amount of steam present in the gasifier. Again, higher equivalence ratio produces lower char and tar yield, lower heating value of gases and lower concentration of CO but higher concentration of CO_2 because of combustion instead of gasification. Thus, equivalence ratio is an important parameter and it must be optimised for the higher gas yield and quality.

Some of the naturally occurring materials like CaO, dolomite, gypsum, olivine, etc. acts as CO_2 absorber and the H_2 concentration and thus increase the quality of the produced fuel gases as well. Furthermore, these materials are generally used as bed

materials for the gasification. However, the most popular bed material (BM) is sand, which is used widely in fluidized bed reactor. However, it does not play active role in the cracking of tar. Tar is one of the major issues in the gasification of biomass which may condense during the application of produced fuel gas. Formation of tar also decreases the efficiency of gasifier since it contains hydrocarbon in it. Tar is a complex mixture of condensable single to five ring aromatic compounds. It may also consist of oxygen containing hydrocarbons and complex poly aromatic hydrocarbons (PAH) (Chaiprasert and Viditsant, 2010). For the cracking of tar, several studies were performed by utilizing catalyst as bed material, which decomposes the tar in hydrocarbons. Ni, orthosilicate of magnesium and iron, limestone, egg shell, gypsum, cement, etc. are some of the materials which are used as catalysts for the decomposition of tar. Catalyst based on Ni is considered to be effective (Wo et. al., 2013) compared to other noble metals. But it would be most promising if some waste material could be utilized as a catalyst. In addition, some inherent metals and elements act as a catalyst and increase the total gas yield, carbon conversion, H_2 gas yield, etc.

2.4. Literature gap

Steam gasification in the presence of catalyst is considered to be efficient for higher amount of H_2 yield due to tar cracking and steam reforming. The energy required to generate steam and, and deactivation of catalyst (Sansaniwal et al., 2017, Chen et al., 2015, Rui et al., 2014) are the major constraints on the efficiency of steam gasification process. However, H_2O in gaseous form can be provided by humidified air. A large amount of humidified air can be obtained from the cooling towers of any thermal power plant. Therefore, humidified air can be a potential candidate to be utilized as gasifying medium as gasifier already working at higher temperature. Moreover, no research was found taking humidified air as a gasifying medium.

The outer part of green coconut is a problem for the society as it does not degrade easily. On the other hand it cannot be left in the agricultural field. Thus it adds negative economic value as farmers need to spend money for its disposal. Also, coconut husk contains a high amount of lignin composition, so it cannot be easily hydrolysed by enzymes. Thus, it cannot be used for energy production through biochemical route. Very limited numbers of researches have been found for the utilization of unripe coconut fibre husk (Rodrigues et al., 2018; Gonçalves et al., 2015).

Furthermore, special arrangement, precautions and money are required for steam generation and catalyst synthesis. Some researches were found using inherent element as a catalyst. However, none of the research has been found on gasification utilizing industry waste product like paper and pulp waste water as a source of catalyst since it may contains metals like Ni, Fe, Zn and Na, etc. (Thompson et al., 2001; Lacorte et al., 2003) which could be impregnated into the biomass to enhance the H_2 content in the fuel gas.

The whole Ph.D. was executed as per the objectives of the present work as given in previous chapter.

Table 2.3 Summary of biomass gasification in fixed bed

Sl. No.	Feed stock	Gasification media (GM) and gasification column specification (GCS)	Operating conditions	Gas composition (vol %/ wt %)/ Gas yield (m^3/kg boiomass)	Optimum condition	Efficiency/ energy recovery	Gas HHV/ LHV (MJ/Nm^3)	Reference
1.	F: High ash biomass (garden waste) and high ash coal	GM: CO_2 GCS: H:1.2 m OD: 0.5 m	GT: 450-650 °C Biomass to coal ratio: 0, 0.25, 0.5, 0.75, 1	Vol % H_2: 7.2-9.6 CO: 6.8- 11.7 CH_4: 1.3- 1.7 CO_2: 11.2- 14.8	Biomass to coal ratio: 0.75	dna	HHV: 5.51	Thengane et al., 2019
2.	F: Mixture of pine wood chips and pine grass	GM: air GCS: H: 0.8 m ID: 0.32 m	GT: 800-1050 °C ER: 0.25, 0.30, 0.34	Vol % H_2: 4.4- 8.7 CO: 15.5- 23.7 CH_4: 1.6- 4.7 CO_2: 13.6-9.9	Mixture of 80% pine wood and 20 % pine grass	dna	HHV: 5.46- 6.46	Dıaz and Martınez, 2019
3.	F: Waste wood	GM: steam GCS: H:830 mm ID: 33 mm	GT: 1000 °C After pyrolysis at: 600, 800, 900 °C Steam to carbon in biomass ratio: 5.7	Vol % H_2: 48.8-67.2 CO: 4.5-8.8 CH_4: 7.7-2.2 CO_2:39.0-21.8 GY: Total gas: 77.8-95.8 wt%	Pyrolysis at: 900 °C	dna	dna	Prasertcharoensuk et al., 2019
4.	F: wood sample	GM: 100 %air, 15% CO_2 + 85% air	GT: 700-800 °C ER:0.24	Optimum condition H_2: 18.0	Air 85% + CO_2 15%, GT: 800	PER: 56.3 % CCE:	dna	Shen et al., 2019

No.							
	GCS: H: 1.1 m ID: 46 mm		CO: 26.7 CH_4: 3.4 CO_2:14.1 N_2: 37.8 GY: Total gas: 19.8 Nm^3/h	°C	65.2 %		
5.	F: Japanese ceder: coal: 1:1 GM: Air, steam Catalyst: Fe_2O_3 GCS: na	GT: 800 °C	H_2: 100-152 mmol/gm	Presence of Fe_2O_3	CCE 38-70 %		Shen et al., 2018
6.	F: Biomass char (softwood chips, hardwood chips, sweet sorghum bagasse), bituminous coal GM: CO_2 GCS: na	GT: 850, 875, 900, 925, 950 °C	Biomass gasification reactivities decreased in the order: SB > SW > HW and were greater than that of coal.	dna	dna	dna	Mafu et al., 2018
7.	F: palm oil empty fruit bunch GM: air GCS: H: 2 m ID: 1.5 m	FR: 126 kg/h ER: 0.43-4.7 GT: 850- 950 °C	Optimum Vol % H_2: 7.2 CO: 10.9 CH_4: 21.03 CO_2:3.8 N_2: 57.07	T: 900 °C	PER: 61-67%	HHV: 4.02-4.62	Ariffin et al., 2017
8.	F: MSW refused derived fuel GM: steam GCS: na	GT: 800 °C Catalyst: Ni/SiO_2 with Ni	Optimum Vol% H_2: 57.9	$20Ni/SiO_2$	dna	dna	Balanco et al., 2013

				CO: 18.4 CH$_4$: 2.2 CO$_2$: 21.5 GY Total: 68.7 wt%				
9.	F: Palm oil waste, Tri-metallic catalyst	GM: steam GCS: H: 400 mm; 1200 mm ID: 200 mm; 88 mm	ER: 0.3-1 kg/h FS: 0.15-2 mm SB: 1.33 GT: 750, 800, 850, 900 °C	H$_2$: 48-60 CO: 15-26 CH$_4$: 5-5 CO$_2$:20-25 GY Total: 1.79- 2.48 Nm^3/kg biomass H$_2$: 0.861-1.481 Nm^3/kg biomass	GT: 900 °C Maximum total gas and H$_2$ gas yield GT: 750 °C Highest LHV	dna	LHV: 9.13-11.26	Li et al., 2009
10.	F: Pine wood block	GM: air, oxygen-steam GCS: H: 350 mm ID: 60 mm	GT: 774, 798, 850, 886, 934 °C ER: 0.22, 0.24, 0.25, 0.26	Using air H$_2$: 52.19 CO: 63-31 GY: Total gas: 0.82-0.94 Nm^3/kg biomass H$_2$: 0.24-0.33 Nm^3/kg biomass Using O$_2$/steam H$_2$: 63.27 CO: 72.56 GY: Total gas: 1.24-	GM: oxygen-steam	dna	dna	Lv et al., 2007

				1.62 Nm^3/kg biomass H_2: 0.36-0.49 Nm^3/kg biomass				
11.	F: palm oil wastes BM: tri-metallic	GM: steam GCS: H: 400 mm; 1200 mm ID: 200 mm; 88 mm	FS: 0.15-2 mm FR: 0.3 kg/h	H_2: 47-58 CO: 14-33 CH_4: 3-6 CO_2: 14-26 GY Total gas: 1.2-2.48 Nm^3/kg biomass H_2- 0.558-1.481 Nm^3/kg biomass	SB: 1.33 Maximum gas yield and H_2 yield CB: 0 Highest LHV	dna	LHV: 8.73-11.98	Li et al., 2009
12.	F: olive kernel	GM: Air GCS: H: 500 mm ID: 12.5 mm	ER: 0.14, 0.21, 0.42 GT: 950 ℃	Wt% H_2: 20-30 CO: 15-20 CH_4: 10-12 CO_2: 40-55	ER: 0.21 (maximum value of gas yield, H_2 content, and LHV)	dna	LHV: 8.8-10.4	Skoulou and Zabaniotou; 2008
13.	F: palm oil wastes BM: tri-metallic catalyst	GM: steam GCS: H: 400 mm; 1200 mm ID: 200 mm; 88 mm	FR: 0.3-1 kg/h FS: <0.15, 0.15-1, 1-2, 2-5 mm SB: 1.33 GT: 800, 850 ℃	H_2: 55-58 CO: 14-18 CH_4: 3-5 CO_2: 20-23 GY: Total 2.16-2.41 Nm^3/kg biomass H_2: 1.183-1.4	FS: <0.15 Maximum gas and H_2 yield FS: 2-5 mm Highest LHV	dna	LHV: 8.99-10.28	Li et al., 2009

				Nm^3/kg biomass				
14.	F: pine saw dust BM: calcined dolomite	GM: steam GCS: H: 600 mm OD: 219 mm	FR: 0.3 kg/h ER: 1.2 GT: 900 °C FS: <0.075, 0.075-0.15, 0.15-0.3, 0.3-0.6, 0.6-1.2 mm	H_2: 40-51.2 CO: 15-22.4 CH_4: 2-5 CO_2: 12-40 GY: Total gas: 1.38-1.62 Nm^3/kg biomass H_2 gas: 0.55-0.8 Nm^3/kg biomass	FS:< 0.075 Maximum total gas and H_2 gas yield, highest CCE	80-99.87 %	dna	Luo et al., 2009
15.	F: char derived from cyanobacterial blooms	GM: steam GCS: H: 1000 mm ID: 50 mm	GT: 850 °C FS: < 0.15 mm, 0.15-0.3, 0.3-0.45, 0.45-0.9, 0.9- 3mm	H_2:47-49 CO: 14-15 CH_4: 2 CO_2: 30-35	FS: 0.45-0.9 mm Maximum total gas yield	dna	dna	Yan et. al., 2010
16.	F: pine bark BM: CaO reagent (batch type reactor)	GM: steam GCS: dna	GT: 600 °C CaO biomass ratio: 0, 1	Without Cao Vol % H_2: 60 CO: 9.1 CH_4: 3.2 CO_2: 27.7 With CaO Vol% H_2: 64.5 CO: 5.9 CH_4: 2.8 CO_2: 26.8	Using Cao	Without CaO: 30.3 With CaO: 55.6	dna	Mahishi and Goshwami 2007

17.	F: glycerol BM: silicon carbide and Ni/Al$_2$O$_3$ catalyst	GM: steam GCS: H: 500 mm ID: 10.5 mm	FS: 0.20-0.35 mm Catalyst loading: 0-0.8 wt%	Vol % H$_2$: 55.4-68.3 CO: 20.2-36.9 CH$_4$: 2.4-5.9 CO$_2$:1.9-7.7 GY: Total gas: 0.91-1.3 Nm^3/kg biomass	Catalyst loading: 0.8 wt%	dna	dna	Valliyappam et. al., 2008
18.	F: palm oil wastes BM: no catalyst, calcined dolomite, nano-NiLaFe/γ-Al$_2$O$_3$	GM: steam GCS: H: 1200 mm ID: 88 mm	FR: 0.3-1 kg/h FS: 0.15- 2 mm SB: 1.33 GT: 800 °C	Vol % H$_2$: 36.5-53.6 CO: 12.7-25.8 CH$_4$: 4.4-10.2 CO$_2$: 20.9-26.6	BM: nano-NiLaFe/γ-Al$_2$O$_3$ Maximum total gas and H$_2$ gas yield BM: calcined dolomite Highest LHV	dna	LHV: 10.20-12.72	Li et al., 2009

H: height; ID: inner diameter; ER: equivalence ratio; GT: gasification temperature; GM: gasifying medium; GY: gas yield; F: feed material; dna: data not available, FR: feed rate; FS: feed size; SB: steam biomass ratio; GCS: Gasification column specification; PER: potential energy recovery; CCE: carbon conversion efficiency; HHV: higher heating value; LHV: lower heating value

Table 2.4 Summary of biomass gasification in fluidized bed

Sl. No.	Feed stock/ bed material	Gasification media (GM) and gasification column specification (GCS)	Operating conditions	Gas Composition (vol %/ wt %)/ Gas Yield (m^3/kg biomass)	Optimum condition	Carbon conversion efficiency/ Energy recovery	Gas HHV/LHV (MJ/Nm^3)	Reference
1.	F: Ground seed corn char BM: 70% silica 30% calcined limestone	GM: air, wet steam GCS: H: 81.3+ 122 cm ID: 9.5+15.2 cm	FR: ER: 0.24-0.37 T: 700-805 °C	Reaction coefficients was highest at ER 0.25 and Temperature 800 °C	ER: 0.25 GT: 800 °C	dna	dna	Timmer and Brown, 2019
2.	F: Beech wood sawdust, waste wood BM: silicon carbide powder	GM: Air, steam GCS: H: 0.95 m + 1.54 ID: 0.124 m + 0.20 m	FR: 1-3 kg/h ER: 0-0.34 GT: 800-910 °C P: 1.5 bar	At optimum Nm^3/kg H_2: 0.2 CO: 0.16 CH_4: 0.13 CO_2: 0.36	Air:steam 0.24:0.73, GT: 908 °C	PER: 59%	HHV: 6.9	Valin et al., 2019
3.	F: pine sawdust/ coal BM: dolomite and livine	GM: steam GCS: H: 55 cm ID: 8.5 cm	ER: 0.1-0.4 T: 700-1000 °C	Dolomite H_2: 52.9-55.5 g/kg-fuel Olivin H_2: 47.5-52.1 g/kg-fuel	Dolomite	For dolomite PER: 92.3 CCE: 84.2	HHV: 13.8	Ma et al., 2019
4.	F: peach stone, miscanthus BM: dolomite,	GM: air GCSS: H: 4.15 m	FR: 45 kg/h T: 750-850 °C	At optimum (vol %) H_2: 11.03	T: 800 °C	dna	dna	Ismail et al., 2018

	olivine	ID: 0.5 m		CO: 13.2 CH$_4$: 15.8 CO$_2$: 4.3 N$_2$: 55.67			
5.	F: Ground nut shell BM: Sand	GM: air GCS: H:1600 mm ID: 200 mm	ER: 0.29, 0.31 and 0.33 GT: 650-800 °C	At optimum (vol %) H$_2$: 13.77 CO: 12.94 CH$_4$: 5.75 CO$_2$: 13.5 N$_2$: 54.04	ER: 0.31 GT: 714	CCE: 88 % PER: 71.8%	dna	Singh et al., 2018
6.	F: *Enteromorpha intetinalis* Catalyst: Limestone, calcined dolomite, olivine	GM: Air, steam GCS: H: 610 mm OD: 120 mm	ER: 0.14 GT: 800-1000 °C	Optimum (vol%) H$_2$: 49.1 CO: 26.4 CH$_4$: 0.8 CO$_2$: 23.7	GT: 1000°C Steam to biomass ratio: 1 Calcined dolomite	PER: 71.5 CCE: 60.8	HHV: 10.5	Tian et al., 2018
7.	F: blend of Indian rice husk and coal	GM: Air, steam GCS: H: 2.5 m ID: 0.15 m	GT: 750-850 °C Rice husk: coal: 50:50, 75:25 wt%	Optimum (vol %) H$_2$: 8.62 CO: 13.72 CH$_4$: 6.68 CO$_2$: 11.65 N$_2$: 59.33	dna	PER: 78% CCE: 85%	HHV: 5.21	Bharath et al., 2018
8.	F: Wood residue/coal	GM: oxygen, steam	ER: 0.4 GT: 850 °C	Vol % H$_2$: 41.25-	BM: K$_2$CO$_3$	dna	HHV 12.57-	Peng et al., 2017

	BM: NaHCO$_3$, KHCO$_{3,}$ and K$_2$CO$_3$	GCS: H: 1.4 m ID: 60 mm		52.07 CO: 31.47-35.14 CH$_4$: 8.42:5.75 CO$_2$:18.85-7.04			13.36 kJ/Nm^3	
9.	F: bamboo BM: silica sand	GM: air GCS: H: 2000mm ID: 50 mm	FR: 0.6 kg/h	Vol % H$_2$: 6.6-8.16 CO: 23.5-30.6 CH$_4$: 4-5 CO$_2$: 59-63 GY Tota: 1.9-2	GT 400 °C Highest H$_2$ content GT 500 °C Highest CCE and LHV	CCE: 63.6-67.4 %	LHV: 1.6-1.9	Wongsiriamnuay et al., 2013
10.	F: bamboo BM: silica sand	GM: Air and air:steam blends GCS: H: 200 cm ID: 5 cm	FR: 0.6 kg/h ER: 0.4 SB: 0:1 and 1:1 GT: 400, 500 and 600 °C	Using air (vol %) H$_2$: 6.6-8.16 CO: 23.5- 30.6 GY: 1.9-2.0 Nm^3/kg of biomass Using air:steam (vol %) H$_2$: 10.9-16.5 CO: 36.1- 40.3 GY: 2.8-2.9 Nm^3/kg of biomass	GM: air:steam, SB: 1:1 ER:0.4	Using air 63.6- 67.4 % Using air:steam: 87.3-98.5 %	dna	Wongsiriamnuay et al., 2013

11.	F: bamboo BM: silica sand and calcined dolomite	GM: air GCS: H: 2000 mm ID: 50 mm	FR: 0.6 kg/h ER:0.4 FS: 0.10-0.25 mm Calcined dolomite to Biomass ratio: (0:1, 1:1, 1.5:1)	H_2: 3.2-9.1 CO: 21.4-31.7 GY: Total gas: 1.9-2.1 Nm^3/kg of biomass	Calcined dolomite to biomass ratio: 1.5:1 Maximum H_2 content, highest LHV and CCE	CCE:59.5-80.1 %	dna	Wongsiriamnuay et al., 2013
12.	F:Empty fruit bunch BM: inert sand	GM: air GCS: H:600 mm ID: 400 mm	FR: 0.6 kg/h ER:0.15-0.35 GT: 700, 800, 900, 1000 ℃	H_2: 10.27-38.02 CO: 21.87-36.36 CH_4: 5.84-14.72 CO_2: 10-65 GY: Total gas 62.68-91.7 wt%	GT:1000 (maximum total gas yield, highest LHV, and low char and tars)	dna	LHV: 7.5-15.55	Mohammed et al., 2011
13.	F: Empty Fruit Bunch BM: inert sand	GM: Air GCS: H: 600 mm ID: 40 mm	FR: 0.6 kg/h FS: 0.3- 0.5 mm ER: 0.15, 0.20, 0.25, 0.30, 0.35	(Vol %) H_2: 18.37-27.42 CO: 32-45 CH_4: 12-15 CO_2: 16.66-36.05 GY Total: 70.75-86.46 wt %	ER: 0.35 Maximum gas yield ER:0.25 Maximum hydrogen content ER: 0.15 Highest LHV	dna	LHV: 12.35-15.38	Mohammed et al., 2011

No.								
14.	F: EFB BM: inert sand	GM: air GCS: H: 600 mm ID: 40 mm	FR: 0.6 kg/h ER: 0.15-0.35 GT: 850 °C FS: <0.3, 0.3-0.5, 0.5-1.0 mm	(Vol %) H_2: 21.57-33.93 CO: 35-42.5 CH_4: 15-17.5 CO_2: 7.5- 30 GY: Total: 72.74-74.79 wt%	FS: <0.35 mm Maximum gas yield, low char and heavy tar FS: 0.3-0.5 mm Optimum gas composition and highest LHV	dna	LHV: 11.8-15.26	Mohammed et al., 2011
15.	F: α-cellulose	GM: Air-steam GCS: H: 1100 mm ID: 63.9	FS < 0.35 mm ER: 0.27 SB: 0, 0.5, 1, 1.5 GT: 800 °C	(Vol %) H_2: 13.5-18.56 CO: 6.45-11.21 CH_4: 2.21-3.73 CO_2: 26.3-27.77 GY Total: 0.78-1.02 Nm^3/ kg of biomass	SB:1 Maximum gas yield SB:0 Highest LHV	dna	LHV: 6.55-7.61	Chang et al., 2011
16.	F: pine sawdust BM: silica sand	GM: air-steam GCS: H: 1400mm ID: 40 mm	FR: 0.445kg/h FS: 0.3-0.45 mm SB: 2.7 ER: 0.22	(Vol %) H_2: 21-39 CO: 35-43 CH_4: 6-10 CO_2: 18-20	GT:900 °C (maximum gas yield and highest CCE)	78.17-92.59 %	LHV: 7.362-8.56	Lv et al., 2004

			GT: 700, 750, 800, 850, 900 °C	GY: 1.43-2.53 Nm^3/ kg of biomass	GT: 800 °C Highest LHV			
17.	F: pine saw dust BM: silica sand	GM: air-steam GCS: H: 1400 mm ID: 40 mm	FR: 0.512 kg/h SB: 1.56; ER: 0.23 BT: 800 °C FS: 0.2-0.3, 0.3-0.45, 0.45-0.6, 0.6-0.9 mm	(Vol %) H_2: 30-32 CO: 16-20 CH_4: 6-7 CO_2: 16-20 GY- Total: 1.53-2.57 Nm^3/ kg of biomass	FS: 0.2-0.3 mm Maximum gas yield, highest LHV and CCE	77.62-95.10 %	LHV: 7.0-8.7	Lv et al., 2004

F: feed; FR: feed rate; BM: bed material; GM: gasifying medium; ER: equivalence ratio; GT: gasification temperature; GY: gas yield; H: height; ID: inner diameter; ER: equivalence ratio; F: feed material; dna: data not available; FS: feed size; SB: steam biomass ratio; GCS: gasification column specification; PER: potential energy recovery; CCE: carbon conversion efficiency