Chapter 1: Introduction

In this modern era, due to the exponential growth rate in industrialization and upgrading in the living standards of society, there has been an exponential rise in the demand for global energy. This excess demand for energy eventually leads to an increase in the average temperature of the earth and climate changes. Many developed countries are already started the process of abandoning use of fossil fuels, natural gas can be substituted by biogas and biochar addition [1]. The different scientific community at a global level often discusses this severe issue. The world community is now more inclined toward energy that should be clean and green and can contribute to the sustainable development of society. World Energies Outlooks 2018 reproduced by IEA (International Energy Agencies) [2] predicted the global energy demand rise approximately 40% between the years (2007 and 2030) around 1.3*108 kWh in 2007 to around 1.95 * 108 kWh in 2030. Despite this fact, the contribution of worldwide renewable energies to the total electricity generation was only 23% in 2015 [3]. The Global energy consumption in 2019 and the total energy demand of India are depicted in Fig.1.1. Presently 80% of the total global energy is reliant on fossil fuels like coal, petroleum products, and natural gas. It causes detrimental environmental problems, globally. Among all the renewable sources of energy, biomasses are considered to be the well-known source of energies and it shares a substantial percentage (10-15) % of the global energy requirement. It has been projected that 90% of the global population will be residing in developing nations by 2050. On the other side, Biomass has a foremost segment of up to 90% of the entire power supply in rural areas. This could be due to the possession of lower energy density per unit weight for a specific purpose.

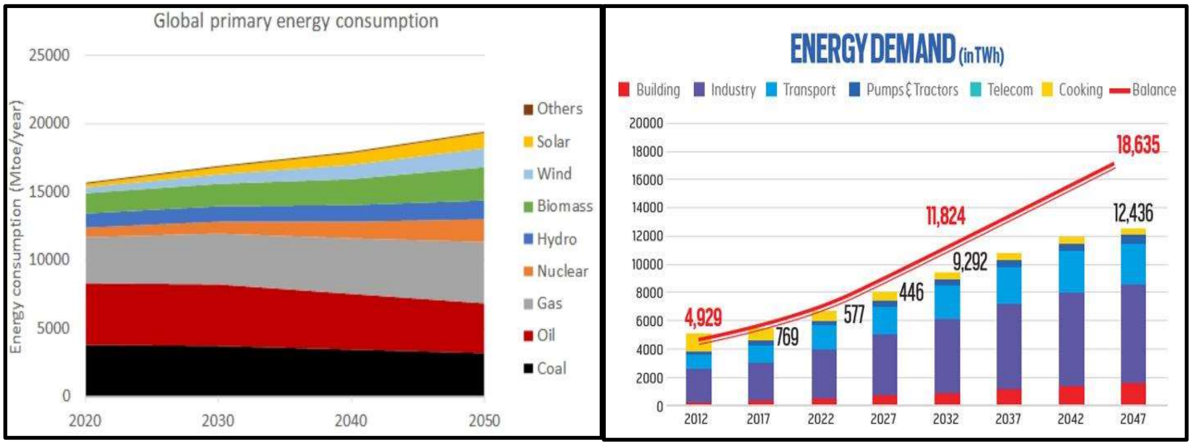


Fig. 1.1. Global energy consumption (Left) and Indian energy demand in different sector (Right) [4]

There are many methods to transform biomass into advantageous products having higher heating value but this transformation of biomass is dependent on the different parameters like biomass characteristics and its application. Heating values of biomasses can also be enhanced by the unique method of pre-treatment like torrefaction, biomass briquettes, etc. Fig.1.2 reviews the different existing processes for the possible production of liquid fuel and gaseous fuels from the biomass feedstocks (seed, flower, stems, etc.), waste material, and industrial by-products. This Fig.also shows the three different routes for thermo-chemical conversion as biomass gasification, biomass liquefaction, and biomass pyrolysis. Out of all the three routes, biomass gasification has been considered superior for transforming biomass into producer gas having high calorific value with better conversion efficiency. Solid biofuel is one of the other technique of conversion [5]. Other benefit of this technology lies in the development of pyrolytic gas shower cooler that would be included into the pyrolysis unit to decrease PM leakage, which distributes harmful pollutants to the environment [6] . Currently, conventional downdraft biomass gasifier is considered as a prominent technology to make the rural sectors self-sufficient for electricity. It is the most efficient reactor for small-scale application and having high carbon conversion efficiency for generating power [7]. Due to the detrimental and negative effect of non-renewable sources of energy, extensive research must be done to optimize the different parameters of the gasifier to possess effective utilization of any kind of biomass. Different types of biomass feedstock or waste material can be transformed into syngas by the process of gasification which is mainly composed of hydrogen, carbon dioxide, carbon mono oxide, and methane. Wood, Forest, and Agriculture residues, Waste from the wood and food industries, Kernel Shell, Algae, Energy grasses, Straw, Bagasse, Recycled Paper, Sewage Sludge, and other bio-materials and wastes are examples of feedstocks for gasification. Fig.1.3 depicts a schematic of the gasification process from the harvesting of various feedstocks to potential products. The utilization of different feedstocks has its different limitations and challenges corresponding to harvesting, transportation, storage and feeding, and finally gasification operation with the cleaning of produced gas. Out of all biomass, Rice straw has a very high potential for electric power generation. [8] Along with the generation of syngas, its filtration needs to be very effective and efficient. The main impurities in the producer gas are fly ash particles and tar. Other impurities are also present but they are of lower magnitude like Sulphur compounds, Ammonia, Hydrogen-chloride, and Ammonia. Condensation of tar at a lower temperature can create problems like clogging or pipe blockage. It also lowers the heating value of syngas and their yield. This study includes the syngas as an energy carrier and processing like heat, biofuel, biomethane, power, and hydrogen for the distributed power generation. Subsequently, Syn gas from gasification leads to increase energy density in terms of the Synthesis of Fischer Tropsch (FT) diesel, dimethyl ether (DME), methanol, and methane fuel conversion.

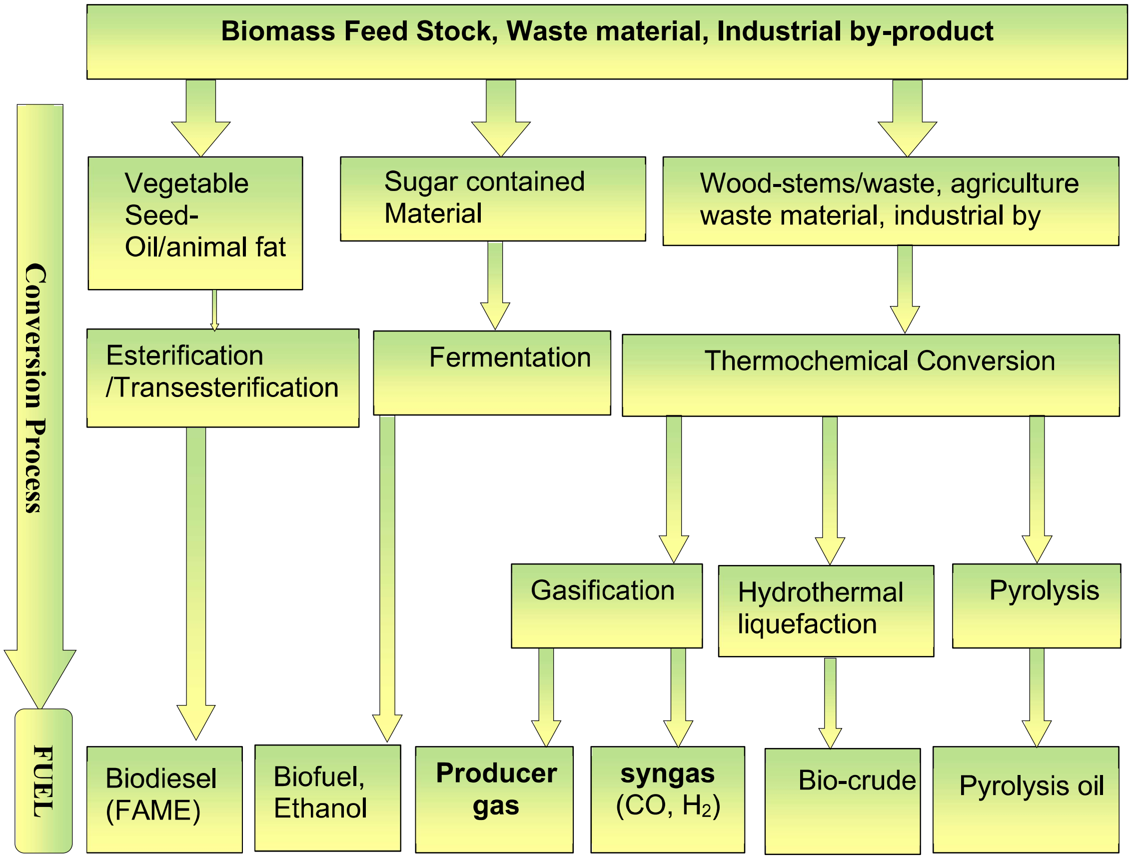


Fig. 1.2. Conversion route of biomass to fuel

Gasification is the thermo-chemicals transformation of any raw biomass into gaseous fuel by the process of partial oxidation with the gasifying agents like air, steam, oxygen, or their mixtures [9-13]. The process of gasification takes place always below the stoichiometric values like 0.2 to 0.4 [14]. This incomplete combustion precludes the complete transformation of carbon and hydrogen present inside the biomass into CO_2 and H_2O respectively and thus eventually it leads to the emergence of combustible products like H_2, CO, and CH_4. Higher the magnitude of these combustible components, the higher will be the calorific value of producer gas. Besides these component hydrocarbons like C_2H_4 and C_2H_6 are also existed in very trivial magnitude. The thermochemical reaction in the gasifier comprises different zones namely drying, pyrolysis, oxidation, and reduction zone. Several works have been published on the outcomes of experimental and theoretical investigation performed on the different parameters of downdraft gasifier such as variable equivalence ratio, feedstock particles size, the magnitude of moisture content, the composition of producer gas, higher heating values, carbon conversion, and temperature profile, they are [15], [16] and [17], [18]. Most of them have carried out a techno-economic analysis of variable gasifying agents like steam and oxygen for the gasification of biomass using the Aspen plus model and concluded that cleaner and economic products can be generated using steam alone. Techno-economic assessment of potato waste management in developing economies was investigated by [19]. By- product of gasification i.e. bio char can be modified to phosphate management in wastewater treatment plants by fixing Inexpensive Ca and Fe sorbents [20]. Bio-char farming also increasing its attention to the researcher around the world [21] Other factors like calorific values of syngas, the total cost of steam as compared to air and oxygen, etc. were considered in the analysis. The influence of all these gasifying agents like air, O_2 and steam on the quality of syngas has been covered in this present work. [22] experimented on the generation of producer gas from the downdraft gasifier using sewage sludge and reported that sewage sludge can be treated as a renewable source for gasification. Biomass gasifier can be simulated in Aspen plus [23]. The composition of combustible gas reported by the Adnan Midilli was in the range of 19-23 %. The main problem associated with the gasification when the producer gas is used as the IC engine fuel is the formation of tar. It is very crucial to eliminate or reduce tar content in the producer gas in order to counter the problem during the running mode of engine. The maximum permissible quantity of tar content in the producer gas for the usage as the fuel in IC engine is 100.0 mg/Nm^3. Method of tar removal can be classified into two parts namely primary method and secondary method. Primary method of tar reduction process can be attained by high temperature of gasification processes and it generally takes place inside the reactor. On the other hand in the secondary process, tars removal technique is carried out outside the reactor by the treatment of producer gas. Secondary method is further categorized into two methods, namely physical method and chemical method. Out of both of these physical method is more cost-effective and effective in nature. Physical method is further categorized into wet systems such as filter, spray towers, venture scrubber, packed columns scrubbers and dry systems. The most common technique adopted for the tar reduction in producer gas is bio oil scrubbers and char filters [24] investigated the effect of variable input parameters on the gasification of biomass in Circulating fluidized bed using olivine as the material of bed. They revealed that the optimized composition of PG with low yield of tar can be acquired at ER approximately 0.30, steam to biomass ratio 0.70 and particle size of biomass around 0.3 cm and moisture content around 9%. Similarly, other influencing parameters also analyzed to enhance the quality of produced gas in the present investigation.

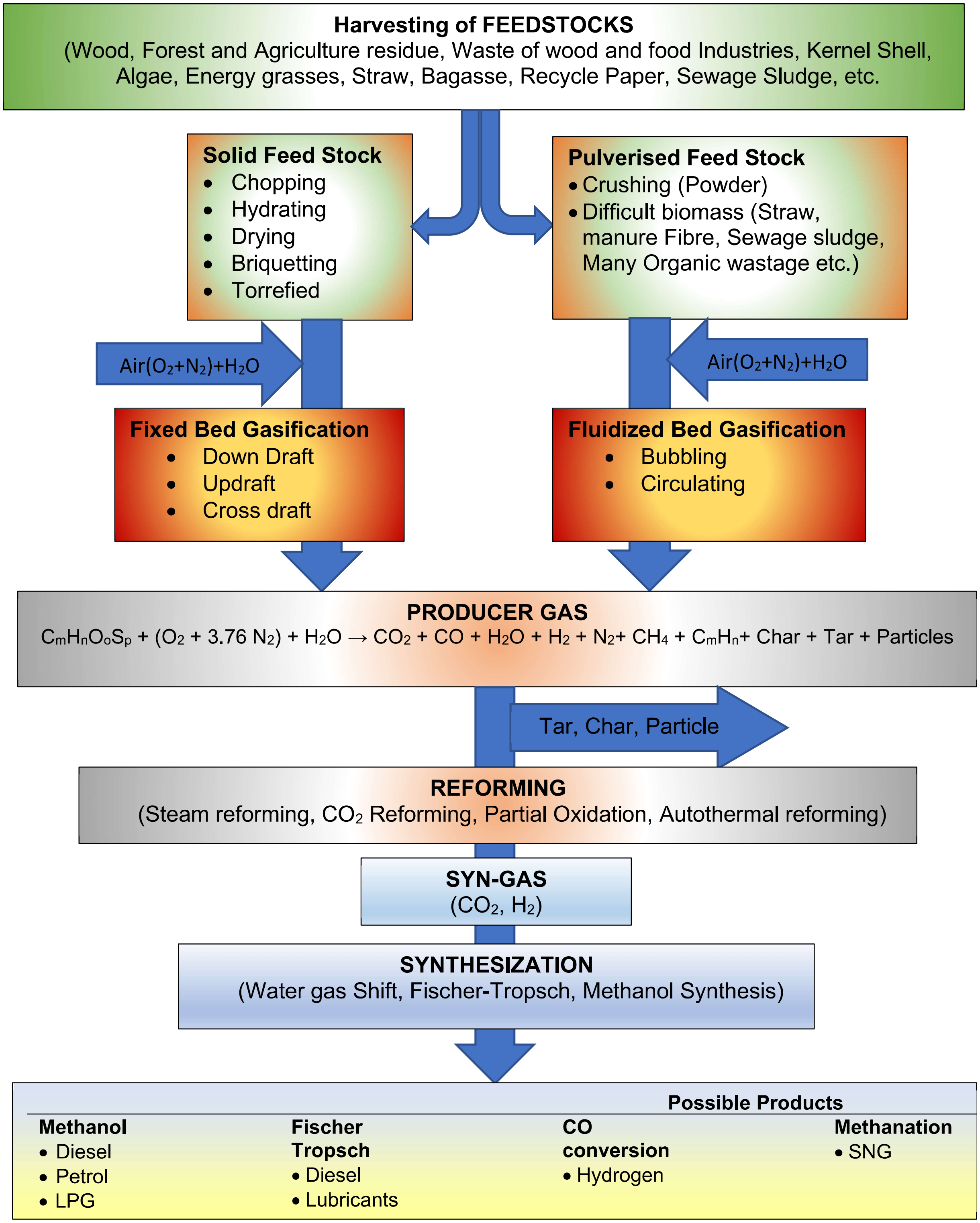


Fig. 1.3. Schematic of the gasification process from harvesting feedstock to possible products

To encourage the deployment of biomass gasification, advanced concepts are obligatory which includes possession of higher syngas heating value, intensification of the purity of gas, enhancement of the overall process efficiency, and development of the economic viability by declining system and production costs. The present study mainly intended for all the researchers, technicians, and stakeholders who investigating the biomass gasifier, to comprise an understanding of the effective use of conventional as well as the latest gasifier, pre-treatment of syngas as well as biomass, for the rural development and objectify the possibility of improvement in this domain.

This study reports several issues and comparative analysis on the advanced as well as conventional concepts of gasification and utilization of different feedstock including waste material and agricultural biomass. Furthermore, the effect of variable input parameters on the output results as produced gas and its performances in the power sector. Comparative assessment between conventional and advanced gasification system are mentioned in table 1.1 The table shows that presently downdraft gasifier is the most populated gasifier among all conventional gasifiers as the composition of syngas generated from the downdraft gasifier is of higher heating value. It may be due to a scant amount of tar concentration due to increased thermal tar cracking. However, the advanced concepts of gasifiers need lots of research and modifications to enhance the gasification efficiency of particular feedstock. The main problems of gasification are the presence of ash particles and tar and some impurities, increment of these quantities reduces the syngas yield and calorific value. Most of the new concepts of biomass gasification such as circulating fluid bed (CFB), Plasma, supercritical water gasification, Viking gasification have shown advantages over the issues on peculiar biomass and waste feedstock. The purpose of this study is to provide technicians, academicians, and other stakeholders working on biomass gasification with an overview of the foundations, developments, and hurdles to commercialization of the technology, particularly in rural and isolated parts of the developing world. Several study on biomass gasifiers have been published, but none of them focused on the design parameter and how it affects the gasifier's performance. Therefore, it is very crucial to present a comparative assessments on the latest and conventional gasifier.

Table. 1.1. Comparative assessment of advanced and conventional gasification technology

Type of Gasifier	Characteristics	Advantages	Present Scenario
Conventional gasifiers			
Updraft gasifier	Gasifying media such as oxygen, steam, and air forced to flow at the bottom of the gasifier to interact with feedstock and combustible gases in opposite current directions	High flexibility in fuel and can able to withstand high content of ash, a higher amount of moisture content in biomass	• More research is required to make it highly efficient • Presently the hearth capacity of an updraft gasifier is mostly limited to 2.8 MW/m^2 or 150 $kg/m^2/h$ for biomass [25]
Downdraft gasifier	Interaction of air with the feedstocks in a downward way	Fuel precise in nature and can operate on any type of biomass	• Commercialized in the market [26] • Lots of downdraft gasification plant has been set up around the world • Downdraft gasification plant along with its capacity has been tabulated in this present paper deeply
Cross-draft gasifier	Air will be forced to move into the gasifier from the side's position	Production of gas is flexible with less time for a startup	• It is in the phase of R&D. [27] • Currently, a very scant commercialized plant is based on a Cross-draft gasifier. • Lots of effort is needed to make it effective for commercialization in the market.

Bubbling bed gasifier	highly pressurized fluidized medium such as O_2, steam, and the air is forced to move through the reactors bed which is having inert bed materials	Design of construction and operation is very simple and gasification of a wide range of biomass can take place with an operating condition of very high pressure	• Tested on a smaller scale; large scale application planned • Presently this type of gasifier is used for a medium-scale process of less than 25 MW. [28]
Circulating bed gasifier	Energy input per unit reactor body cross-sectional area is generally higher	Various biomass handling, high carbon conversion, and gasification efficiency	• Used in scales up to a few MW • Presently this type of gasifier is used for capacity ranging from 10 to 420 MW.[29]
Advance gasifiers			
Plasma gasifier	Process of Gasification is accomplished using a plasma	The disintegration of any organic materials into their fundamental molecules	• Generally used for toxic biomedical waste treatment • Presently it has been commercialized in Wuhan, China with a capacity of 100 ton per day [30], Pune, Maharashtra, India with a capacity of 72 ton per day[31] • Mihama-Mikata, Japan with a capacity of 151 ton per day, National Cheng Kung University - Tainan City, Taiwan with a capacity of 3.3-5.50 ton per day [31]
Supercritical water gasification	Process of Gasification is accomplished using supercritical water	Liquid and biomass with a high magnitude of moisture content can be gasified without pretreatment	

Viking gasifier	Implementation of pyrolysis and Gasification process in a multistage, in a single controlled stage	Gasification efficiency is high and enhancement in the heating value of syngas with ultra-low tar Concentration.	• The apprehension of notions from 100.0 kW to 6.0 MW successful. • It has been working in countries like Denmark, Berlin Currently, this multi-stage gasification is in the phase of development.
FT process integrated with gasifier	Producer gas generated via gasification is utilized for FT-fuels synthesis	Production of clean, carbon-neutral liquid biofuels	• Used in scales up to a few MW • Presently this advanced concept is in the phase of R&D. [33]
Circulating bed gasifier	Energy input per unit reactor body cross-sectional area is generally higher	Various biomass handling, high carbon conversion, and gasification efficiency	• Used in scales up to a few MW • Presently this type of gasifier is used for capacity ranging from 10 to 420 MW.[29]

1.1. Conventional waste biomass feedstock

Feedstock required for the gasification experiments is renewable with environmentally friendly and it is carbon neutral [34]. Different size of biomass is readily available in nature which is a waste for the equatorial countries and in those nations whose economic growth is mainly reliant on cultivation [3, 35]. All these factors make conditions favorable for the generation of energy from agricultural biomass to satisfy future generation needs. The energy stored in the biomass resources can be improved into useful and of higher value through thermo- chemicals conversions (i.e. gasification) into producer gas, thereafter filtration known as syngas. The aspect of this producer gas is reliant on the biomass attribute (feedstock size, the magnitude of moisture content, composition, parent biomass, ash content, bulk density, heating value). As the calorific values of biomasses gets enhanced after the gasification reaction rather than direct combustion [36]. Thus, this type of technology could be useful for the off-grid mode of power generation in rural or isolated areas [37, 38].

Table 1.2. Comprehensive Summary of raw feedstock used for gasifier

Ultimate analysis (Wt. %)				**Proximate analysis (Wt. %)**						
Biomass	**C**	**H**	**N**	**O**	**S**	**VM**	**FC**	**Ash**	**Moisture**	**Ref**
Corn straw	43.83	5.95	0.97	45.01	0.13	75.95	13.75	5.93	6.17	[40]
Dalbergia sisoo	48.6	6.2	0.33	44.87	NG	80.40	15.70	3.90	NG	[15]
Hazzlenut shell	45.9	5.7	<1	48.2	0.072	68.2	18.2	1.1	12.4	[41]
Corn stalk	47.54	6.02	0.77	43.87	0.13	69.5	12.2	5.8	12.5	[42]
Poultry litter	43.98	5.16	4.63	31.98	0.75	63.6	15.3	13.5	7.6	[43]
Eucalyptus	46.78	5.92	0.324	45.55	0.09	83.01	15.66	1.34	12.23	[44]
Oil palm fronds	44.58	4.53	0.71	48.80	0.07	83.5	15.2	1.3	16	[45]
Acacia wood	50.22	5.90	0.25	43.01	0.02	65.12	21.12	3.91	9.56	[46]
Peanut shell	44.34	6.35	0.79	45.47	0.29	65.65	17.34	5.96	11.41	[47]
Jatropha seed husk	48.5	5.7	0.67	41.8	0.01	71.04	24.99	3.97	10.75	[48]
Cashew nutshell	45.21	4.25	0.21	37.75	NIL	65.21	22.21	2.75	9.83	[49]
Black pine pellet	49.58	6.65	0.19	43.59	NIL	83.58	15.83	0.61	4.64	[50]
Peach	48.06	5.83	0.55	44.03	NG	84.80	13.90	1.53	9.8	[51]
Olive	46.43	5.63	0.55	44.91	NG	72.7	16.2	2.48	10.6	[51]
Pine	48.18	5.71	0.15	43.89	NG	84.5	15.1	2.07	9.0	[51]
Miscanthus pellet	41.51	4.85	0.4	35.08	0.04	63.9	18	6.5	11.58	[52]

Rice husk pellet	46.6	6.2	0.7	37.4	0.1	65.1	16.4	9.3	9.2	[53]
Larch sawdust	48.5	6.4	0.1	44.7	0.3	76.7	19.9	0.8	2.6	[53]

Unevenness in the biomass creates a big problem in the performance characteristics of a gasifier coupled with the engine[3]. The availability of biomass varies in a wide range both in seasonally as well as geographically. Theoretically, it is said that almost all variety of biomass with moisture content (5-30%) can be able to gasify [39]. This inequality in the biomass may also require alterations in the operating conditions of the gasifier unit. Various biomass feedstock used for gasification in the literature along with their size, proximate analysis, and ultimate analysis are summarized in table 1.2. It can be concluded from the table 1.2 that diverse nature of biomass feedstock can act as a fuel for gasifier, and the fuel possessing higher percentage of volatile mater and hydrogen content provides higher heating value, and thus can be obtained higher calorific value of syngas

Cataloging of gasifiers depends on numerous parameters like shape and size, ash content, biomass feedstock, end-user applications, and moisture content. The gasifier can be categorized into two categories: fixed bed and fluidized bed. As there is an interaction of oxygen/ steam/air and feedstock in a gasification system therefore fixed bed gasifiers are classified into three different type and fluidized bed type into two different type.

1.2 Fixed bed type gasifier

The fixed bed type gasifier integrates the reactor with a gas filtering unit and cooling unit. It has a bed consisting of solid fuels particle from which the gasifying agent like (oxygen, steam, air) and gas started to flow either up, down or cross. The designs of fixed bed type gasifiers are very simple. Materials of construction of this gasifier are generally concrete or steel made.

Generally, cylindrical shape design opts for biomass feeding unit, ash abstraction unit, etc. Fixed bed type gasifiers can sustain atmospheric pressures in the range of 20-30 atm. The gas filtering and cooling unit integrated with fixed bed gasifiers generally contain components like a cyclone, wet scrubbing, and filtration unit. As the gasification proceeds into the gasifier unit, the fuel bed started to move down gradually along the unit. Construction of this type of gasifier is simple and mostly functioned with high solid feedstock residence time, high carbon conversion, very fewer ashes carry over, and low gas velocity. However, the main limitation of this sort of gasifier is the formation of tar content which lowers the magnitude of heating values of producer gas. Despite these researchers have successfully developed a technique for tar control methods that reduces the tar content drastically. These types of gasifiers are very important for the decentralized mode of power generation and small-scale heat generation application [54] [55, 56]. The fixed bed type gasifier is further categorized into a downdraft, updraft, and cross draft gasifier according to the interaction of fuel and air, and these are discussed in this present study. Summary of installed fixed bed type gasifier along with the size, mode of decentralization, site location, and the significant analysis are depicted in Table 1.3.

1.2.1 Updraft Gasifier

The main importance of an updraft gasifier is its fuel flexibility. In this type of gasifiers, a gasifying medium such as oxygen, steam, and the air is forced to flow at the bottom of the gasifier to interact with feedstock and the combustibles gases in opposite currents direction and therefore these types of gasifier are known as counter-current gasifiers. Updraft gasifier can work on a wide range of feedstock from coal to biomass and the best advantage of this gasifier is fuel substituting does not need any amendment in the design of the reactor. The other advantage of an updraft gasifier is that it can withstand the high content of ash, a higher amount of moisture content in biomass as well as the greater variation of size in solid feedstock as compared to the co-current gasifier. In counter-current gasifiers, producer gas comes out of the reactor from the top position of the fuel bed although the gasification reactions occurred near the bottom. This type of gasifier achieves the highest thermal efficiency and it may be due to the information that hot gases pass from the fuels bed and comes out from the gasifier at a lower temperature while some portion of the heat of producer gas is used in biomass drying and generation of steam [57]. Apart from all this updraft gasifier has very little pressure drop and very little tendency of slag formation. The gas emerging out from the counter-current gasifier contains condensable volatiles. The temperature of the gas coming out from the reactor is (200-400)^{o}C and at this high temperature, approximately all the volatile hydrocarbons transformed into a vapors state which eventually adds its energy to the gas. It has been reported in the literature that an updraft gasifier is mainly used where close combined hot gas mode for continuous heating application is required. Some limitations associated with these types of gasifiers are the low production rate of syngas, poor reaction capability; the startup time of the engine is very long.

1.2.2 Downdraft Gasifier

Downdraft gasifiers are generally economical in fuel consumption. These types of gasifiers can able to operate on all types of biomass materials as well as biomass compacted into briquettes with a minimum value of bulk density 250 kg/m^3 and the magnitude of ash content must be fewer than 5%. Interaction of air with the feedstocks occurs in a downward way. These types of interactions ultimately lead to the movement of gases and waste in the same direction. These types of gasifiers are also recognized as co-current gasifiers. The gasification process that occurred in the downdraft reactors produces very little tar content. It is because of the reason that in this gasifier all the gasified products obtained from both drying and pyrolysis zone are forced to travel through the combustion zone which eventually leads to the thermal cracking of volatiles matter and thus produces gases having a minimal amount of tar content, therefore, qualities of producer gases enhance [58]. Despite this fact producer gas exhale out of the reactors also contains very little amount of ash and soot. The temperature of the producer's gas coming out of the gasifier is in the range of (260-450)°C. Gasification bed temperature is very influential parameter during combustion of wood pellet [59] Producer gas after filtering known as syngas can be castoff as a blending fuel with air in an IC engine and small-scale power generation after primary cleaning and passing it through the various cleanup arrangement. To combine gasifiers with engine producer gas must be washed to a very high level and it must be completely free from tar, soot, and ash particle.

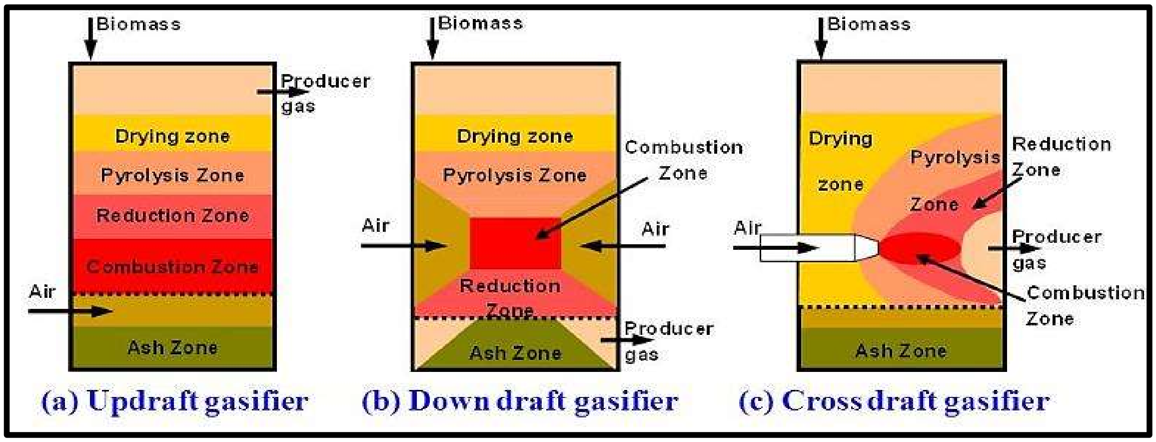
Table. 1.3. Summary of installed decentralized biomass-based gasifier in India

Ref	Mode of decentralization	Fuel	Size	Research findings
[56]	Biomass-based gasifier plant	Woody biomass with dual fuel mode	20 kW	• Caters the need of 143 households • The generated electricity is used for running water pump, street lighting, and general household purpose
[56]	Biomass centered gasifier unit	Woody biomass with dual fuel mode	10 kW	• Caters the need of 85 households • The generated electricity is used for running water pump, street lighting, and woodcutter
[60]	Biomasses centered gasifiers unit	Woody biomass with DF mode	20 kW	• 35 households were benefitted by the generation of power • The generated power is utilized for running water pump for households, lightning, and running a flour mill
[61]	Biomass-based gasifier coupled with Gujrat	Woody biomass with fully Producer gas mode	500 kW	• Biomass drying is done by generated waste heat • Residues of crops like Mango seeds, corncobs, cotton, astur stacks, and tur were used as feedstock for gasifier
[60]	Biomasses centered gasifiers plant	Woody biomass with DF mode	20 kW	• Caters the need of 58 households • The generated power is utilized in irrigation water supply and household purpose

[62]	Biogas centered plant	DF mode	20 kW	• 98% pure biogas was generated • Compressed biogas is utilized for industrial fuel and cooking purpose
[63]	Biomass centered gasifier	DF mode	10 kW	• 55 households were benefitted by the generation of power • The cost per unit of electricity was Rs. 3.79
[64]	Biomass centered gasifier	DF mode	120 kW	• Approximately 100 farmers were benefitted from the gasifier unit. • The feedstock used for gasification is mainly dhaincha.
[65]	Biomasses centered gasifiers	DF mode	500 kW	• Caters the need of 1113 households • The power generated was in the range of 10 kW to 2200 kW
[64]	Biomass-based gasifier	Fully producer gas mode	500 kW	• Caters the need for 4-gram panchayat across approximately 28 villages • CO_2 sequestration reached up to 26,580t annually
[66]	Biomasses centered gasifiers unit	DF mode	500 kW	• 225 households were benefitted from the plant • The generated power is utilized for commercial, industrial, and household use.
[68]	Pine biomass-based gasifier	DF mode	9 kW	• Fulfills the demand of 2 villages • Generated electricity improves the overall quality of life.
[68]	Biomass centered gasifier unit	DF mode	250 kW	• 15 micro-enterprises were benefitted from this gasifier • 125 kW is connected to load capacity
[68]	Biomass gasifier	DF mode	61 kW	• 60 kW is the connected load capacity • The generated electricity is utilized for running a rice mill, wheat mill, and water pump.

1.2.3 Crossdraft Gasifier

The working principle of Crossdraft gasifiers is theoretical. It has some advantages as well as disadvantages. This type of gasifier is simple where biomass enters into the reactor from the top position and ultimately thermo-chemicals reactions take place gradually as the solid feedstock goes down in the gasification reactor. The main difference between the Crossdraft gasifier and downdraft or updraft is that in this case air will force to move into the gasifier from the side's position rather than the top or bottom position, which is depicted in fig 1.4. One of the best benefits of a Crossdraft gasifier is its rapid response behavior against the load. Other advantages of these types of gasifiers include requires less time for a startup, production of gas is flexible, highly compatible with an arid air blast and the height of the reactor is shorter than the other two types of gasifiers. However, unlike co-current and counter-current gasifiers, this type of gasifier has distinct fire, reduction zone, and ash bin, and therefore use of a wide variety of fuel with less ash content in producer gas is limited. These types of gasifiers have also some limitations as this gasifier cannot able to operate with high tar content and small-size fuel particles. The temperature of the gases coming out of the reactor is very high and therefore reduction of CO_2 is poor. Due to the manifestation of the good quality of the permeable bed, these gasifiers have little application. Hence very less work has been disclosed in the literature [69]. A schematic diagram of downdraft, updraft, and the Crossdraft gasifier is shown in Fig.1.4. It has been evident from table 1.3 that the downdraft gasifier is the most optimized gasifier for the process of gasification as it can generate producer gas having the highest calorific value due to the high concentration of volatile matter and least tar content due to thermal cracking among all the different type of gasifier. Therefore it is recommended to use a downdraft gasifier for gasification.



(a) Updraft gasifier (b) Down draft gasifier (c) Cross draft gasifier

Fig. 1.4. Line diagram of (a) Updraft (b) Downdraft and (c) Crossdraft gasifier [70]

1.3. Fluidized Bed Gasifier

In this category of the gasifier, the biomass feedstocks get fluidized into dissimilar gases like oxygen, hot gases, steam, or hot air, and the remaining ashes used to be eliminated as fluidizing torrid ashes or as substantial agglomerates. The temperature of gasification is very low in the case of dry ash gasifiers. These types of gasifiers mainly opt when the biomass material is of low-grade quality in respect of calorific value whereas the temperature of gasification is relatively higher in the case of agglomerating type fluidizing bed gasifiers. Agglomerating fluidized bed types of gasifiers mainly opt when the biomass material is of high-grade quality. The main advantage of a fluidized bed gasifier is its larger capacity than a fixed bed but lower than entrained flow gasifiers. The conversion efficiencies of these types of gasifiers are relatively lower and it is mainly due to the intermixing of carbonaceous materials into the gases. To enhance conversion rate entrained solids should be recycled back to bed. Highly fluctuating characteristics of ash are also challenging in fluidized beds, to overcome this, coal feed must be mixed well so that the same type of characteristics can be maintained [71]. The application of these types of gasifiers is very useful where the feeding materials produce corrosive ashes. Generally, fluidized biomass fuels have an immense concentration of corrosive ashes, therefore, biomass material gasification generally opts for fluidized bed gasifiers. Mainly, there are 2 categories of fluidized bed gasifiers and they are bubbling and circulating bed gasifiers, and are discussed below, the Schematic diagram of both types of fluidized bed gasifiers is depicted in fig 1.5.

1.3.1 Bubbling Bed Gasifier

The design of construction and operation is very simple in bubbling bed gasifiers. In this type of gasifier, gasification of a wide range of biomass can take place with an operating condition of very high pressure. Usually, a highly pressurized fluidized medium such as O_2, steam, and the air is forced to move through the reactors bed which is having inert bed materials like dolomite, sands, etc. these types of gasifiers are generally designed to engage at a very low velocity of gas even less than 1 m/s. Unwanted particles like solids get segregated from the gases flow in a cyclone and eventually get poised at the bottommost portion of fluidized bed reactors. Tar conversion is very scant in these gasifiers as a major process of transformation supervenes within the bubbling bed section. In the literature [71], it has been stated that the thermal decomposition of biomass is higher in this gasifier. It may be due to the information that these gasifiers operate at a very high temperature approximately 850^{o}C. Though carbon conversion efficiencies of these types of gasifiers are less than circulating fluidized bed gasifiers and it may be due to the sticking behavior of feed particles which eventually leads to a decline in contact surface [72].

1.3.2 Circulating Bed Gasifier

The main limitation of bubbling bed type gasifier can be curbed out in circulating bed gasifier and that is carbon conversion efficiency. Due to the high gases velocity majorly in the range of 3 to 10 m/s carbon conversion efficiencies of circulating fluidized bed gasifier (CFBG) is much higher than bubbling bed gasifier. Energy input per unit reactor body cross-sectional area is generally higher than the bubbling bed gasifier. The core limitation of circulating bed gasifiers is higher tar conversion and dust-related problems. These types of gasifiers emit lower emission of pollutants. The major advantages of circulating bed-type gasifiers are a faster rate of fluidization which increases the heat and mass transfer and ultimately pace up the gasification processes, dissemination of char enhances the residence time and eventually leads to a decline in char loss. CFBG finds its application majorly in the paper industry, boiler, and cement kiln. The difference between BFB and CFB are detailed in table 1.4.

Table. 1.4. Summary of the basic differences between a bubbling and a circulating fluidized bed gasifier.

Properties	**BFB**	**CFB**	**References**
Fluidizations regimes	Bubbling beds	Fast beds	[73]
Capability of mixing	Good	Excellent	[73]
Resilient in solids feed (size)	Fine material not wanted	Fine & coarse material	[73]
Tar yield (gm/n^3)	The moderate average is 12	Less than Moderate average is 8	[73, 74]
Conversion of carbon (%)	Less than CFB	Generally, in the range of (88–96)	[75]
Loss of carbon by entrainment	Substantial	Trivial	[76]
Particle concentration in the gas (gm/n^3)	Average: 4	Average: 20	[74]

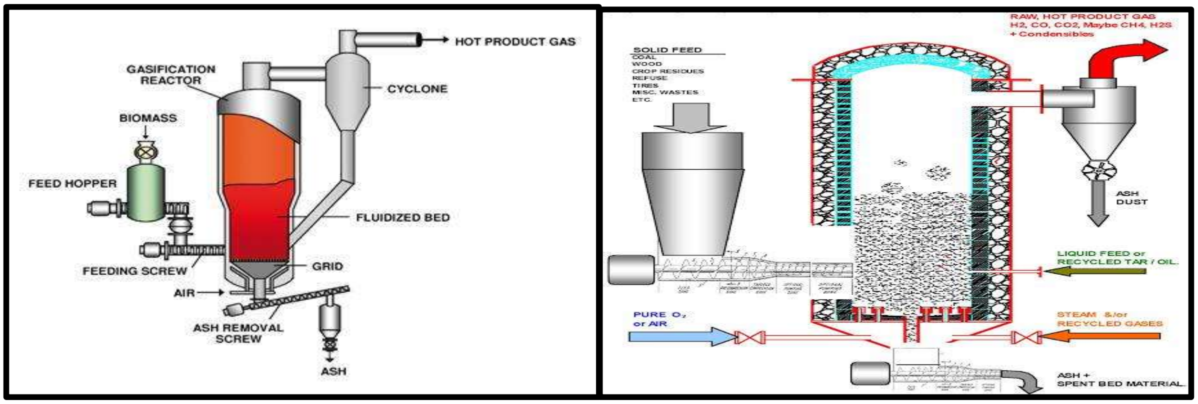


Fig. 1.5. Schematic of Bubbling fluidized bed (Left) [77] and Circulating fluidized bed. (Right) [78]

In regard to the previous work, mostly the research work has been conducted in the area of biomass gasification with limited operating conditions. Moreover, there is very little work has been attempted in the literature where specially studied on the gasification of waste Biomass and low-grade Coal to generate producer gas (PG) from down draft air-Gasifier and integration with diesel-fuelled CI engine, and subsequently analysis of engine performance and exhaust emission characteristics through experimental as well as numerical approach. Also, there is lack of study for the assessment of cumulative effect of gasifier operating variable and engine input variable to optimise between the maximise engine power and minimum exhaust emission and fuel consumption. Hence, there is essential to study low-grade coal and biomass gasified PG coupled with an internal combustion engine and provide the optimum engine input parameters for improved engine performance and operation. Because, if the blended form of chemical energy is available for power generation in an engine and its operating variables are not optimized, there will be a reduction in power and increment in fuel consumption and emission. Concerning these aspects, in the present study, we have attempted to resolve this obvious gap.

In light of the above concerned, the present thesis work comprises with two parts, first is conduction of experiment and thereafter optimization of the operating parameters of diesel engines fuelled by biomass or coal-based producer gas blended with diesel fuel in terms of optimal performance and exhaust emissions by integrating advanced multi-objective optimization technique Response surface Methodology (RSM). In the experiment, a total of 48 number of the experimental matrix wherein downdraft gasifier integrated with dual fuel diesel engine fuelled with diesel and producer gas derived from low grade coal and biomass like Mahua, Coconut and Jarmoon feed material. Thereafter, performance and emission optimization were executed to using RSM optimization and ANOVA sensitivity test with the Gasifier-Engine operating variables of gasifier equivalence ratio, PG-Diesel blend, engine compression ratio and load. The second part of the thesis comprise of comprehensive thermochemical equilibrium-based model of downdraft gasifier was developed by minimizing Gibbs free energy using Aspen Plus software. The producer gas (PG) quality as gas composition (CO, H_2, CO_2, H_2O, N_2 and Tar), and calorific value has been simulated of feed material as plastic waste, jamun tree waste, poultry litter pallet, hardwood chip, and medical waste by ASPEN PLUS software. Also, the PG fuel quality has been analysed and optimized with operating variable like temperature, equivalence ratio, moisture content, and steam-biomass ratio.

Thus, the present work , comprising five chapters, which comprise the motivation to emphasize and resolve various issues related to the possibilities , problems, and prospects of utilizing gasification technique in better way so that the renewable energy can be promoted and subsequently problems of fuel oil scarcity and environment degradation could be squarely met

1.4 Research gap

After performing extensive literature survey, it has been found that there is no author who has concluded with the cumulative effect of engine input variable for an optimum response of performance and emission together. Hence, there is essential to study biomass and low-grade coal-gasified PG coupled with an internal combustion engine and provide the optimum engine input parameters for improved engine performance and operation. Because, if the blended form of chemical energy is available for power generation in an engine and its operating variables are not optimized, there will be a reduction in power and increment in fuel consumption and emission. Concerning these aspects, in the present study, following research gap has been concluded.

- From the extensive literature review It has been observed that very few experimental analysis was performed which integrates the gasifier with VCR IC engine.

- It can be also be inferred from the literature survey that most of the previous studies only investigated the conventional operating parametric impact of gasifier on the gasification performance.
- There is an utmost need for the optimal range of operating parameters wherein the gasifier should operate and delivers the most optimum response in terms of high quality of syngas.
- Very few experimental investigations integrated with simulation work have been reported on the influence of variable gasifier equivalence ratios on the gasifier performances, and the subsequent effect on fuel consumption at different load and compression ratio on VCR CI engine.
- The latest design of gasifiers which include the integration of gasification process and gas conditioning in one reactor, plasma gasifier are very captivating and can act as a promising opportunity in the future perspective of nonconventional energy generation

1.5 Research objective

Based on the problem formulation and research gap on the probable technique for the proper valorisation of waste biomass to generate energy. It has been that there is little work has been attempted in the literature that specially studied the biomass and low-grade coal gasified producer gas (PG) and integration with diesel-fuelled CI engine, and to analyze engine performance and emission. Concerning these aspects, this present thesis work have attempted to resolve this obvious gap. Following research objective have been formulated for the present Ph.D. work.

- Development of highly efficient modified downdraft gasifier that can able to producer enhanced heating value of producer gas.
- Numerical modelling of biomass air gasification and steam gasification in the ASPEN PLUS MODEL
- Process modelling and sensitivity analysis of steam injected plasma gasifier fuelled with hazardous plastic waste.
- Optimization of gasification and engine operating parameter using multiobjective Response surface methodology technique
- Experimental work on the downdraft gasifier using different blend of biomass under variable operating condition integrated with dual fuel IC engine
- Facilitation to investigate the performance and emission characteristics of engine under different operating condition for achieving optimal range of power generation and emission produced from an engine.

This thesis work will provide a base for the end-users and researchers to adopt a Gasifier-IC engine integration system as a feasible approach toward utilizing Biomass and low-grade hard coke coal in air gasification through a downdraft gasifier. In addition to this, the present thesis work will also appeal to the technicians, and stakeholders investigating the design and development of predictive process modelling for complete gasifier to constitute an understanding of optimal use of gasifiers and syngas for extracting energy from biomass, Plastic waste and objectify the possibility of improvement in this domain.