Thermo-chemical Conversion of Solid Biomass

R. N. Singh and D. Asha

Abstract Due to rapid depletion of natural resources and continuous increase in energy demand, the utilization of biomass has attracted global attention. Biomass being so versatile and scattered in nature in the form of plant-derived and animal-derived. The efficient use of biomass as energy offers certain advantages in terms of energy, environment, economy, and society. In India, about 30% of energy comes from biomass. It can be used for different purposes such as cooking, process heating, electricity generation, steam generation, and mechanical and shaft power applications by using a number of the conversion process. Several technologies are available for biomass conversion such as physical, chemical, thermo-chemical, bio-conversion, etc. However, this chapter focused only on thermo-chemical conversion of solid biomass. Thermo-chemically biomass could be converted to energy by three ways named as Combustion, Gasification, and Pyrolysis. Direct combustion is the most common way of converting biomass to energy in presence of stoichiometric oxygen. Gasification is the partial oxidation process of converting solid biomass into the gaseous fuel. Pyrolysis is the thermal decomposition of biomass in the absence of oxygen. Compared to the other technologies, thermo-chemical primary conversion (gasification, pyrolysis) is the simplest and most developed technology.

Keywords Biomass · Combustion · Gasification · Pyrolysis

Biomass is a biological material derived from living or non-living organisms. In other words, biomass is a natural substance which can store energy during the process of photosynthesis in the presence of sunlight.

Chemically biomass is carbon-based and is composed of a mixture of organic molecules containing hydrogen, oxygen, nitrogen, and small quantities of other atoms. Unbalance chemical formula for biomass is: $CH_{1.44}O_{0.66}$, however, balance formula is $C_{50}H_{72}O_{33}$. It has a wide range of energy content varied from 3100 to

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Fig. 1 Solid biomass (Singh 2013)

4700 kCal/kg. This wide variation is just because of different range of ash content in biomass. For examples rice husk has ash content about 20%, db however, firewood has only about 2%, db (Fig. 1).

1 Sources of Biomass

Biomass being so versatile and scattered in nature, sufficient database, and documentation are not always available. Still, it could be grouped into two categories; plant-derived biomass and animal-derived biomass. Plant-derived biomass further could be classified as (1) Forestry Biomass (fuel wood, oil, leaves) (2) Agricultural residue such as crop waste (3) Agro-industrial residue such as ground nutshell, rice husk, seed oil cake, etc. Animal-derived biomass includes waste of slaughterhouse, poultry house, aquatic, and marine biomass.

Plant-derived biomass is being called environmental-friendly fuel (Fig. 2), which could be understood easily from Fig. 2. Through a number of the process such as hydrolysis, fermentation, gasification, etc., biomass could be converted into useful industrial products. After application of these products, it would release CO_2 to the atmosphere; however, it would be taken back by the plant with photosynthesis process. Hence, leaves no effect in the atmosphere.

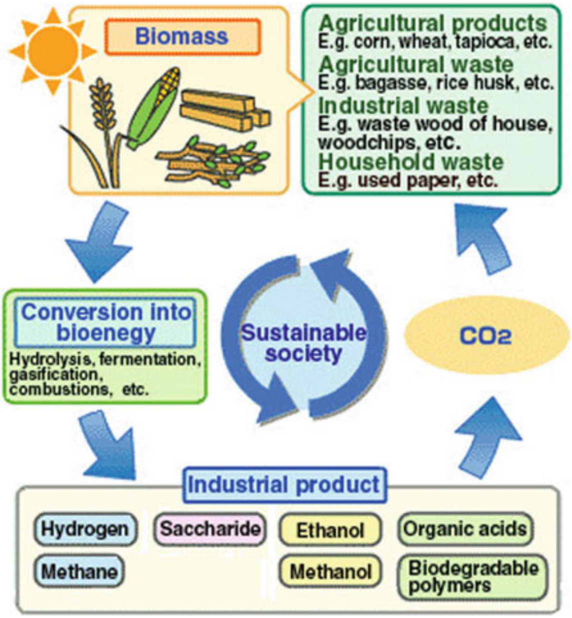


Fig. 2 Biomass-environmental friendly fuel (Singh 2014)

2 Availability of Biomass

Several estimations have been made by the different organization as well researcher. As per one of the estimate made by IISC, Bangalore (Table 1), If only half of the surplus biomass available in the country (Considering the year 2010–11) used for power generation, about 90 million Unit/year or 90000 MW/year electricity could be generated, which is about more than 66% of electrical power demand in India. The electrical power demand of India by March 2013 was 1, 35,453 MW (Energy Statistics 2013). It shows that, if all the surplus biomass used for power generation,

Table 1 Availabilities of biomass in India

Biomass availability estimates (million tons)			
Year	Ravindranath	Biomass atlas IISC, Bangalore	
		Production	Surplus
1996–97	626.5	–	–
1998–99	653.4	546.4	139.4
2004–05	741.0	619.0	157.9
2010–11	840.6	701.2	178.8
2024–25	1127.3	938.0	239.2

Source http://lab.cgpl.iisc.ernet.in/CropReport/Default.aspx. Accessed on 15 Sept 2007

Fig. 3 Burning rice straw in Punjab and Cotton sticks in Gujarat. *Source* Image taken by Author

India need not see any other sources of power generation. Now the question arises if that much potential is available with biomass then why India is not able to utilize it. One of the possible answers is that density of biomass is extremely poor and it is always in scatter nature. Resulting in worst collection economic and further processing to make it useable product. Therefore in India, it is being burnt in the field itself (Fig. 3). By burning the biomass in the field, we are inviting risk for our health apart from losing the energy content of biomass. As the ambient aerosol after burning of biomass consists of particulate matter of size normally 0.01 μm, which would never settle down on the earth and during breathing it will enter in our respiratory system and may have deposited on lungs. Therefore result in blockage of airflow in parts of lungs, a collection of fluid around the lungs or the spread of tumor throughout the lungs and causes many respiratory diseases. However, the particulates having size more than 100 μm generally do not remain suspended in the air for sufficient length of time; hence do not have sufficient impact on human health.

3 Uses of Biomass

In India, about 30% of energy comes from biomass. It can be used for different purposes such as cooking, process heating, electricity generation, steam generation and mechanical and shaft power applications using Biomass Conversion Process. Such as Physical (Chopping, shredding, pulverizing & densification/briquetting); Thermo-chemical (Combustion, Pyrolysis, Gasification, Liquefaction and Ammonia production); Chemical (Acid Hydrolysis, trans-esterification); Bio-conversion (Anaerobic digestion, Ethanol fermentation and composting), etc. However, this chapter only focuses on thermo-chemical conversion of solid

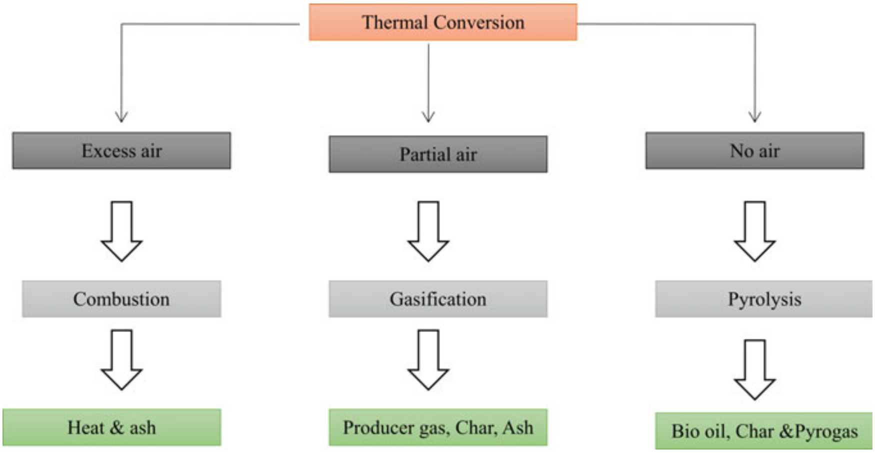


Fig. 4 Thermo-chemical conversion of biomass

biomass. Thermo-chemically biomass could be converted to energy through Combustion, Gasification, and Pyrolysis. The potential ability of thermal routes to accept a wider range of biomass feedstocks than biological/bio-conversion routes. These routes can use lingo-cellulosic (woody) feedstocks, and wastes, which cannot be converted by current biofuel production technologies. The resource availability of these feedstocks is very large. Basically, in thermal routes biomass decomposed due to heat and energy and some by-product is obtained at the end of the process. It can be done by three ways, i.e., by Combustion, Gasification, and Pyrolysis (Fig. 4).

3.1 Combustion

Technically when biomass oxidized in presence of stoichiometric oxygen (oxygen required for complete degradation of biomass) at the end of the process, hot combustion products (CO_2 and Water) are obtained. Direct combustion is the most common way of converting biomass to energy—both heat and electricity. Worldwide it already provides over 90% of the energy generated from biomass.

Compared to the other thermo-chemical primary conversion technologies (gasification, pyrolysis), it is the simplest and most developed technology. Apart from that biomass combustion systems can easily be integrated with existing infrastructure. Basically, three combustion technologies named as fixed-bed combustion systems, Fluidized bed combustion systems, and Pulverized fuel are commercially available in the markets. In fixed-bed combustion systems (Fig. 5a, b), primary air supplied below the grate, and initial combustion of solid fuel takes place on the grate and some gasification occurs. To improve the

Fig. 5 **a** Fixed-bed combustion of biomass (Singh 2014), **b** fixed-bed combustion (Singh 2008) Fig. 5, **c** metal cook stove (Singh 2017)

combustion efficiency, modern combustors have provision for the supply of primary and secondary air. Secondary air takes to care for combustion of gaseous fuel generated during combustion. For example Combustion, studies of Mahua shell and husk were carried out in the metal cook stove (Fig. 5c), which has provision for secondary air. It increases the thermal efficiency of fuel about 30% (Singh 2015). The combustible gases produced are burned after secondary air addition has taken place, usually in a combustion zone separated from the fuel bed.

However, in fluidized bed combustion system, a bed of an inert mineral such as sand or limestone is created through which air is blown from below the grate. The air is pumped through the bed in sufficient volume and at a high enough pressure to entrain the small particles of the bed material so that they behave much like a fluid.

Although combustion is very old technology, however, its efficiency is very poor (ranges from 10–35%). Apart from that its application is also limited.

3.2 Gasification

Gasification is nothing but the thermo-chemical conversion of solid biomass into a gaseous fuel usually known as producer gas (consisting of a mixture of CO, CO_2, N_2, CH_4, and H_2), which takes place under a sub-stoichiometric air supply condition. Generally, the requirement of air for gasification is one-third or less than that of stoichiometric air of biomass (Table 2). The producer gas production process is known as gasification and the equipment used to obtain this gas is known as a gasifier. Since air is used as an oxidizing medium to get the producer gas, thus energy content of producer gas is very very less 1000–1200 kCal/Nm^3. However, this gas burnt with high efficiency at about 800–900 °C temperatures if complete combustion takes place. Generally one kg biomass (10–15% moisture) produce about 2.5–3.0 Nm^3 of producer gas. The thermal conversion efficiency of the gasification process is in the range of 70–80%.

Gasification produces either producer gas or syngas, depending on the source of oxidizing media used. If air is used as a gasification agent, the products are diluted with nitrogen (as air has 79% nitrogen by volume) and gasifier generates producer gas (Table 3). However, if pure oxygen is used as a gasification agent, syngas is produced, which is rich in hydrogen and carbon monoxide. This syngas can be used as a feedstock for ethanol, methanol, naphtha, hydrogen, acetic acid, di-methyl ether, and ammonia. Syngas and producer gas can be co-fired with natural gas in conventional turbines and fuel cells or co-fired in coal-fired boilers to generate

Table 2 Requirements of air for complete combustion of biomass and its derivative

S. No.	Biomass and its derivative	Air requirement
1	Air ratio required for gasification	2.38 kg air/kg of wood
2	Air ratio required for producer gas combustion	1.15 kg air/kg of P gas
3	Air ratio required for total combustion of biomass	6.27 kg air/kg of wood

Table 3 Composition of producer gas

S. No.	Component	Percentage composition by volume
1	Carbon monoxide, CO	18–21
2	Carbon dioxide, CO_2	8–10
3	Hydrogen, H_2	14–16
4	Methane, CH_4	1–4
5	Nitrogen	50–55
6	Water vapor	4–5

electricity. Gaseous fuels can be distributed by pipeline from a gasification plant for direct use in other locations. An important advantage of gasification compared to combustion is its potential to achieve higher efficiencies (more than 75%) and lower emissions. The efficiency of a biomass-fired steam turbine system is between 20 and 25%. However, syngas-fueled engines and turbines can achieve system efficiencies in the range of 30–40%.

3.3 Applications of Producer Gas

Once you get producer gas, numbers of application are possible such as

- Thermal applications: Cooking, water boiling, steam generation, drying, etc.
- Motive power applications: Using producer gas as a fuel in Internal Combustion (IC) engines for applications such as water pumping
- Electricity generation: Electricity could be generated using producer gas in a dual-fuel mode in diesel engines or 100% producer gas in spark ignition engines.

4 Thermal Applications of Producer Gas

4.1 Gasifier-based dyeing unit

Dyeing industries need hot water, which could be easily mated by application of producer gas. By doing about 50% firewood consumption could be reduced. Apart from that, we can have good control of the “liquor temperature”. Biomass briquettes can also be used as fuel. It will replace petroleum fuels (kerosene, diesel) and have a low cost of CO_2 emissions.

4.2 Gasifier-based rubber drying units

India is the fourth largest producer of natural rubber after Thailand, Indonesia, and Malaysia. A 100 kg/h capacity gasifier could replace electricity/diesel based system used for drying crumb rubber in tunnel dryer and about 30 L diesel could be saved per hour.

4.3 Gasifier-based Namkeen units

Namkeen units used diesel for Namkeen making. In place of diesel, if gasifier system (40 kg/h capacity) is used, it would save diesel of the order of 11 L/h.

In terms of economic benefit, with an initial investment of Rs. 2.75 lakhs, the industry has been able to save Rs. 2400/day which translates into payback of just less than 120 days. It also reduces Green House gas (GHG) emission.

4.4 Gasifier for boiler application in bamboo mat factory

For the making of the bamboo mat, steam is required, which is generally met out from the waste bamboo fired boiler. Application of producer gas in place of waste bamboo fired boiler could a reduction in fuel consumption from 50–60 to 25–30 kg/h. Apart from that no need to continuously manage the fire. It will save time and increased daily production capacity (generally 2 h are required for initial pressure temperature build up).

In general, any thermal application where temperature requirement is up to 800–900 °C, producer gas could be used.

4.5 Types of Gasifier

Basically all the gasifier can be grouped into two categories, Fixed Bed, and Fluidized Bed. Fixed-bed gasifier could be subdivided into three categories, Downdraft, Updraft, and Cross–Draft. This downdraft and, updraft gasifier may be further subdivided as follows

(i) Downdraft as Throat Type and Throat Less
(ii) Updraft as Forced Draft and Natural Draft.

Irrespective of above-said classifications all the gasifier have four zones, names as drying zone (temperature varied from room temperature—160 °C); Pyrolysis zone (temperature varied from 200 to 800 °C); Oxidation zone (temperature varied from 850 to 1200 °C) and finally Reduction zone (temperature varied 900–400 °C). The sequence of these zones may change based upon design as well as operational conditions of the gasifier. Although all the gasifier has four zones, however, their positions are not fixed. It changes based upon the temperature of the reactor. For example, if any gasifier reactor length is 100 cm, then it does not mean that first 25 cm from the top would be drying zone, next 25 cm would be pyrolysis zone; further next 25 cm would be oxidation zone and finally, next 25 cm would be reduction zone. No doubt all four zones would be there, but length/size of the zone would be based upon temperature. Hence different parameter is responsible for sequences of the zone.

5 Downdraft Gasifier

In downdraft gasification process, solid biomass is fed from the top (Fig. 6a, b) and the air/oxygen from the sides, hence the biomass and gases move in the same direction and the gas is collected below the grate. At hearth zone/combustion zone, air is supplied with the help of a blower. The supply of air for gasification is controlled with valve fitted at air entry to the blower (Fig. 6b). At controlled air supply solid biomass, broken down to a combustible gas by the use of heat in an oxygen-starved environment. Heat for gasification is generated through partial combustion of the feed material. The resulting chemical breakdown of the fuel and internal reactions result in a combustible gas usually called "producer gas" (Kaupp and Goss 1984). The main combustible gases are H_2, CO, and CH_4. Overall gasification efficiency of the gasifier depends on a number of parameters such as the design of gasifier, biomass characteristics, size and shape of the biomass and operating parameters. Producer gas obtained using air as an oxidizing medium has a low calorific value about 1000–1200 kCal/Nm^3. However, the calorific value of the gas could be increased using oxygen in place of air as an oxidizing medium. In that case, gas obtained from the gasifier is called as syngas. Downdraft gasifier is more suitable for IC engine application. As here, generated gas from the gasifier has to pass through combustion zone, which has a very high temperature (850–1200 °C). At this high temperature all the impurity present in the gas cracked down and clean gas could be obtained. Typically less than 1% volatile tar-oils are produced in a throat-type downdraft gasifier. However, due to narrow size of the throat (Throat-type downdraft gasifier), smaller and wood biomass is required. Generally, one-sixth size of the throat, biomass size is required. For example, if throat diameter of the gasifier is 60 mm, then only 6 mm size biomass is needed, which makes the processing cost of the biomass very high. To overcome the above-said problems, Throat Less or Open Core downdraft gasifier has been designing and developed (Fig. 6b). The working principle of throat less downdraft gasifier is same as throat-types downdraft gasifier only difference in diameter of the gasifier reactor which, is uniform throughout the reactor. This gives the space for accepting the multi-size of biomass. However, at the same time, we have to compromise with the quality of gas. Gases obtained from throat less or Open Core downdraft gasifier is inferior in quality as compared to throat-type downdraft gasifier.

6 Updraft Gasifier

In Updraft gasifier biomass is fed from the top or side (Fig. 7a, b) while air enters the combustion zone through the grate and flows upward through the bed. The grate is mounted at the base of the gasifier, air reacts with charcoal from biomass to produce very hot CO_2 and H_2O. This CO_2 and H_2O react endothermically with char to form CO and H_2. The ascending, hot, reducing gases pyrolyze the incoming

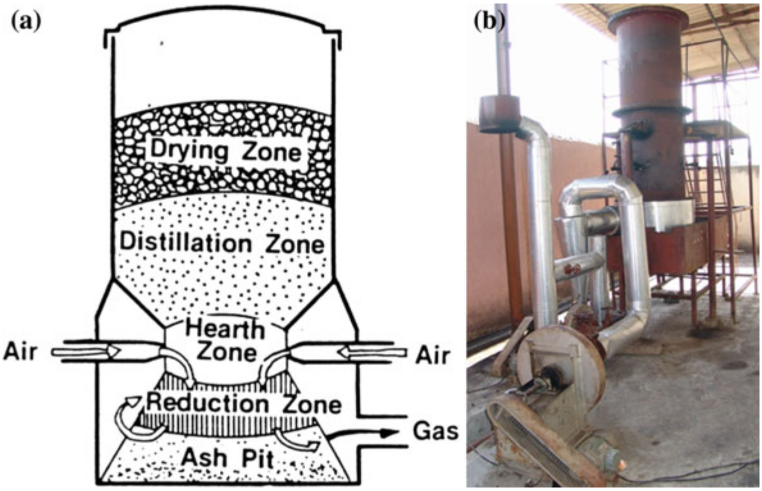


Fig. 6 **a** Throat type (Reed and Das 1988), **b** throat less or open core (Bhoi 2006)

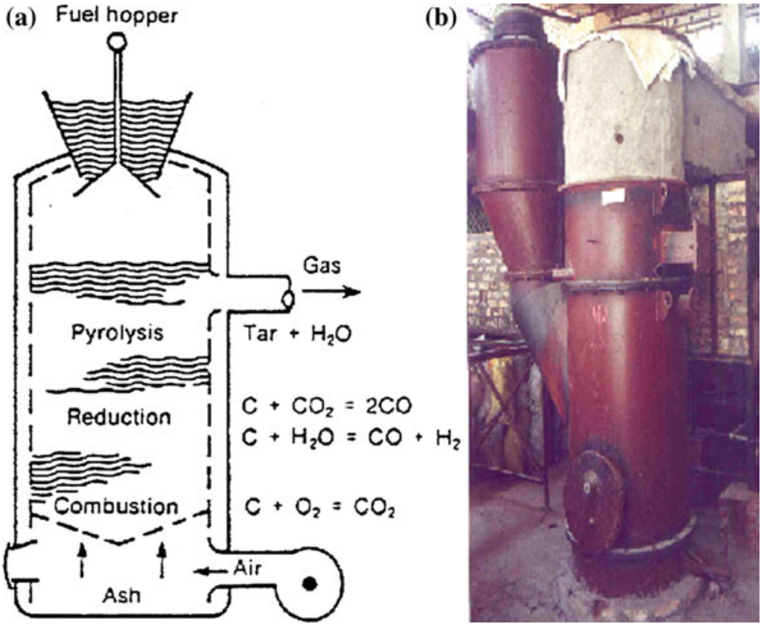


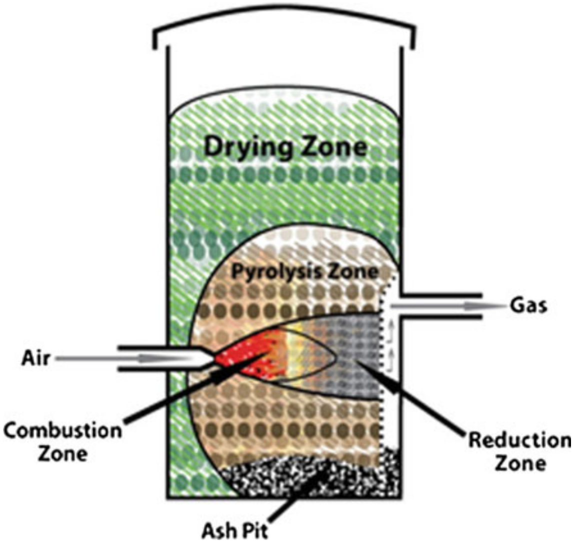
Fig. 7 **a** Forced draft (Reed and Das 1988), **b** natural draft (Patil et al. 2002)

biomass (Shrivastava 2012). Although producer gas has no ash, however, contains a higher quantity of tar and water vapor because of the passing of gas through unburnt biomass. Usually, 5–20% volatile tar-oils are produced in Updraft gasifier. The remaining heat dries the wet biomass so that none of the energy is lost as sensible heat in the gas. The advantage of updraft gasifier over other gasifier is its high conversion efficiency up to 80%. The working principle of the Natural draft gasifier is same as forced draft gasifier only difference is that it operates on chimney effect without electrical input.

7 Cross–Draft Gasifier

This type of gasifier is not so common like Downdraft and Updraft gasifier, because this type of gasifier cannot accept high volatile biomass. Although design of this type of gasifier is very simple, however, it is more suited for charcoal. In this type of gasifier biomass is filled from the top, however supply of air to the gasifier and outlet of gas is almost opposite to each other (Fig. 8). The gas is produced in the horizontal direction in front of the air nozzle and passes through a vertical grate and collected from the opposite side of air supply. Since the combustion zone and gas outlet are closer to each other, thus produced gas have very very less Tar and highly suitable for variable load gas engine (Shrivastava 2012).

Fig. 8 Cross draft (Shrivastava 2012)



8 Other Gasifier (Modular Gasifier)

The presently used downdraft gasifiers have circular throats, which have to be dimensioned separately for each capacity of design. In addition, these gasifiers have not performed satisfactorily in the size range of more than 250 kg/h. This happens because air cannot travel up to the center of the gasifier system and between the air tuyeres, which creates hot and cold spots inside the gasifier during operation, resulting in incomplete tar cracking and high tar content in the gas. To overcome the above-mentioned problem, a modular throat-type downdraft gasifier having a rectangular throat, with suitably rounded corners to ensure uniform gas flow across the reactor section has been designed (Pathak et al. 2008). In this design, the throat of the gasifier has a square shape (module of 260–260 mm). A larger capacity gasifier can be designed by adding modules in series (Fig. 9), thus yielding the throat of a larger gasifier with a rectangular shape (260–780 mm).

9 Other Gasifier

9.1 Horizontal Gasifier

Horizontal gasifier consists of the horizontally oriented reactor (Fig. 10), grate, producer gas flaring burner as a major component. The gasifier is configured horizontally to increase the particles residence time as opposed to a vertical

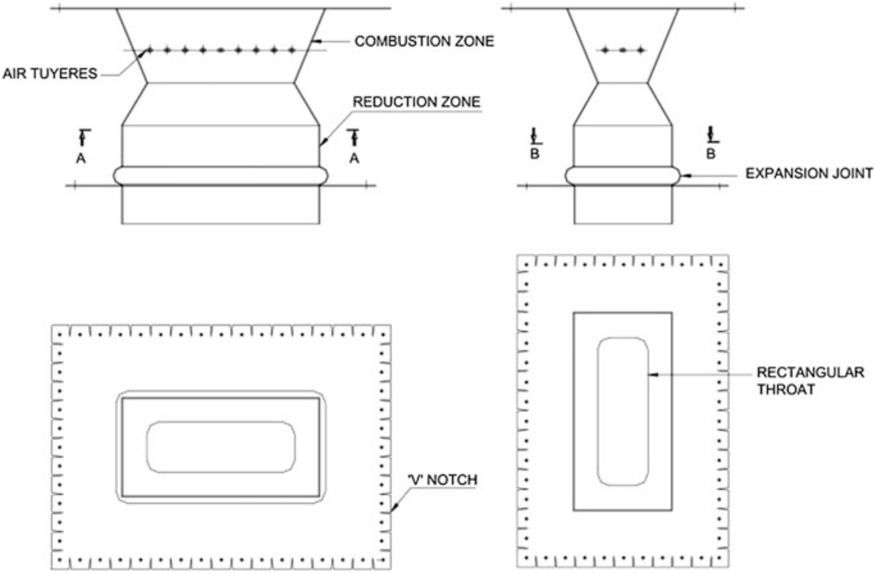


Fig. 9 Modular gasifier (Pathak et al. 2008)

Fig. 10 Horizontal gasifier (Singh et al. 2016)

fixed-bed system, where gravity forces result in lower residence time. Additionally, the enhanced particle to metal surface contact promotes heat transfer to the particle, thus increasing fuel conversion efficiency. Horizontal gasifier producer less tar and particulates matter compared to vertical updraft gasifier.

Basically, in the vertically fixed draft gasifier, biomass moves from upward to downward due to gravity which, sometimes create a problem in proper flow and attract for proper sizing of biomass. Moreover in the existing gasifier thermal zones are fixed, i.e., the residence time in a vertical gasifier is fixed (based on the travel time driven by gravity as the fuel "falls" through the unit), which may sometimes create clinker formation for biomass having higher ash content and again responsible for discontinuation of gasification process. However, vertical gasifier design is simple, requiring few moving parts, and provides ease of control. This design results in high online availability, with the exception of the time required to "clean out" the ash system.

In horizontal gasifier instead of moving the biomass, temperature zone moves (All the gasifier has four-zone named as drying, pyrolysis, reduction, and combustion). Their positions are changing as per the temperature of the gasifier rather than moving the biomass, which overcomes the limitation of vertical updraft gasifier, mainly for bridging of biomass (Singh et al. 2016).

9.2 Two-Stage gasification

All gasification design basically has four zones, namely drying, pyrolysis, combustion, and reduction. In two-stage gasification process, theses four zones are grouped in two stages. In first stage drying and pyrolysis zone reaction is taking place in one reactor; however combustion and reduction takes place in another reactor. Here producer gas produced in one reactor is partially oxidized in another reactor. As a result, due to thermal cracking, most of the tar cracked and increase the energy content of the gas. To enhance the high energy efficiency, the thermal energy present in the producer gas and the exhaust gas is being used for drying, preheating of air and for pyrolysis. The two stage gasification process offers low tar (less than 20 mg/Nm^3) and particulate matter (less than 5 mg/Nm^3).

9.3 Critical Parameters Influencing the Gasifier Performance

Performance of the gasifier depends upon the following parameters named as

- Energy content of fuel
- Fuel moisture content
- Size and shape of fuel
- Size distribution of the fuel
- Bulk density of the fuel
- Volatile matter content of the fuel
- Ash content and chemical composition
- Ultimate analysis of the fuel
- Operating conditions of the gasifier.

9.4 Performance of Gasifier

Generally, the performance of the gasifier is defined in terms of Fuel consumption rate, Specific gasification rate, Specific gas production rate, Equivalence Ratio, Gasification Efficiency, the temperature profile of gasification reactor, Flame temperature, Quantity of gas flow and Calorific value of gas. These parameters should be measured after the stable operation of the system and can be defined as:

Fuel consumption rate (FCR) This is the amount of biomass used in operating the Gasifier divided by the operating time. It could be measured by topping the gasifier after one hour of Continuous operation. Mathematically can be represented as,

$$\text{Fuel consumption rate (FCR), kg/h} = \frac{\text{Weight of biomass used in kg}}{\text{Operating time in hour}}$$

Specific gasification rate (SGR) Specific gasification rate (kg/h-m^2) could be calculated using the weight of biomass for a run, net operating period and the cross-sectional area of the reactor. As per the Kaupp and Goss (1984) for agriculture residues, the specific gasification rate varied in the range of 100–250 kg/h-m^2

$$\text{Specific gasification rate (SGR)} = \frac{\text{Weight of feed material in kg/h}}{\text{Cross-sectional area of the reactor in m}^2}$$

Specific gas production rate: (SGPR) Specific gas production rate (m^3/h-m^2) is the rate of gas production at standard temperature and pressure per unit cross-sectional area of the gasifier. $\text{SGPR} = \frac{\text{Rate of gas production in cum per hour}}{\text{Cross-sectional area of the gasifier in m}^2}$

Gasification Efficiency (*η*) Gasification efficiency is the percentage energy from biomass converted into cold producer gas (free from tar).

$$\text{Gasification efficiency } (\eta) = \frac{\text{Heating value of gas} \times \text{Volume flow rate of gas}}{\text{Heating value of gasifier fuel (Biomass)} \times \text{Fuel consumption rate}} \times 100$$

Temperature profile Temperature profile of gasifier reactor could be measured by using chromel-alumel “K” type and a Platinum rhodium “R” type thermocouple connected with Datalogger/digital temperature indicator. Since the temperature at combustion zones is generally higher, thus here “R” type thermocouple and at other places of the reactor “K” type thermocouple could be used. These thermocouples can be inserted through the probe at a different location above the grate.

Flame temperature The flame temperature could be measured by holding the “K” type thermocouple with digital temperature indicator, temperature attained at burner of different heights in the flame.

The quantity of gas flow (Q_g) Quantity of gas flow could be obtained by multiplying the area of pipe (m^2) through which gas flow with a velocity of gas flow (m/s). Mathematically can be written as $Q_g = A \times Vg$ Where, A is the area of pipe through which gas flow and, Vg is the velocity of gas flow.

Equivalence Ratio (ER) Equivalence ratio is defined as the ratio of oxygen supplied per kg biomass to the stoichiometric requirement. Equivalence ratio fixes the amount of air supplied for gasification. A value of 0.3 ER is the theoretical optimum, however, it may vary from biomass to biomass. As the ER value approaches 1.0 combustion reaction is predominant and as it tends to zero, pyrolysis is the major process.

Total Mass Flow Rate The amount of gas generated through the known amount of biomass was calculated with the help of total mass flow rate equation ($Q = \rho \times A \times V$, whereas ρ (kg/m^3) density, A (m^2) area, V (m/s) velocity).

10 Calorific Value of Gas

The calorific value of gas can be determined by using either Gas chromatograph (GC), or Junkers Gas Calorimeter. Gas chromatography is a technique that is used to separate the components of a substance. The separated material of an amount converts electric signal in the detector in the form of pick (Fig. 11a). The gaseous compounds being analyzed interact with the walls of the column, which is coated with different stationary phases. This causes each compound to pass at a different time, known as the retention time of the compound. The comparison of retention times is what gives GC its analytical usefulness and in terms of pick on the recorder (Fig. 11a). Based on pick area of different gasses, their percentage compositions in unknown calorific value gas are assigned. Caloric values of standard gases such as CO, H_2, CH_4 can be taken as 13.1, 13.2, and 41.2 MJ/m^3 respectively (1 MJ/m^3 $\approx$ 238.8459 kcal/m^3, Reed and Das 1998). Finally multiplying the percentage composition of standard gases with Caloric values and adding them will give the Caloric value of unknown gas.

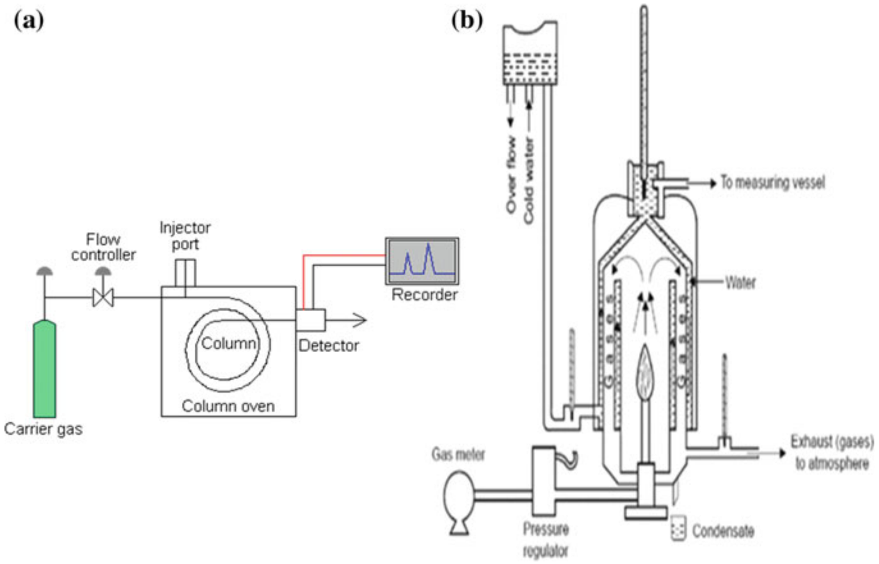


Fig. 11 **a** Gas chromatograph, **b** junkers gas calorimeter

11 Junkers Gas Calorimeter

Junker's gas calorimeter works on the Junker's principle of burning of a known volume of gas and imparting the heat with maximum efficiency to steadily flowing water and finding out of the rise in temperature of a measured volume of water (Fig. 11b). The Calorific Value of Gas = (Volume of water × Rise in Temperature)/Volume of Gas (assuming that heat capacity of water is unity). Mathematically it can be written as $CG_g = (V_w \times \rho_w \times CP_w \times \Delta T)/(V_g \times \rho_g)$.

Where, CG_g is the calorific value of gas, V_w is Volume of water collected in liters, ρ_w is density of water, CP_w is the specific heat of water, ΔT is the change in temperature of water, V_g is the volume of the burnt gas in liters, ρ_g is the density of gas burnt.

12 Properties of Producer Gas for Engine Application

Gas produced from a gasifier has a high temperature (300–450 °C) and contain impurities such as Soot, Ash, Water vapor, and Tar. The range of these impurities present in producer gas varied from the type of gasifier (Table 4). These impurities are present in sub-micron size and must be removed to acceptable levels. Acceptable levels of these impurities depend upon applications. For IC engine particulates matter should be <50 mg/N m^3 and Tar < 100 mg/N m^3. However for turbine application, Tar content in the producer gas should be <5 mg/Nm^3. Failure to remove these impurities may cause excessive wear in the engine component, carbon deposition, the filing of valve and seats and sticky of valves and rings, etc. Apart from above calorific value of producer gas should be more than 1000 $kCal/Nm^3$. However, it is possible to achieve the acceptable level by using suitable gas cleaning device. Particulates matter could be removed using Cyclone separators, which utilize a centrifugal force generated by a spinning gas stream to separate the particle from the raw gas. A well-designed cyclone can remove more than 95% carbonaceous fly ash particles greater than 10 microns in size.

Table 4 Tar content in different design of gasifier

S. No.	Tar	Fixed bed		Fluidized bed	
		Counter current (updraft)	Co current (downdraft)	Bubbling	Circulating
1	Mean tar content (g/Nm^3)	50	0.5	12	8
2	Tar range (g/Nm^3)	10–150	0.01–6	1–23	1–30

Sources Reed and Das (1998)

Fig. 12 Organic filter (Singh 2007)

However for removal of Tar any wet scrubbing device (such as spray tower, Centrifugal/Cyclone scrubber, Impingement scrubber, packed bed scrubber, Venture scrubber, etc.), thermal cracking or Organic filter could be used.

Organic Filter The main features of the organic filter are: It is a low-cost technology and environmentally friendly, as no waste is generated. The saturated biomass with tar could be reused as a feed to the gasifier. Fresh biomass saturated in 6–7 h. The unit (Fig. 12) consisted of a cylinder having three compartments, one for graded organic biomass like wood scrap, a second compartment for graded sawdust and a third compartment for cotton waste.

Cool gas is passed to the first compartments of the organic filter where moisture and tar were absorbed. From the first compartment, gas passed to the second compartment having sawdust where micron size particle matters were removed. If further any tar and dust are left in the producer gas passed out from first two compartments, are removed in the third compartment, which acted as a security filter.

12.1 Power Generation Using Producer Gas

Using IC engine producer gas could be used for power generation either in Dual—Fuel mode (75–80% producer gas & 20–25% diesel/bio-diesel) or 100% gas mode.

12.2 Working Principle of Dual—Fuel Based CI Engine for Power Generation

Dual-fuel operation combines the possibility of operating a diesel engine on liquid fuels such as diesel/bio-diesel and on gaseous fuels (natural gas, biogas, producer

Fig. 13 Gasifier based CI engine for dual-fuel operation (Singh 2007)

gas, etc.). It works on diesel cycle. Here gaseous fuel (primary fuel) is added to air into the engine or supplied by a supercharger (Fig. 13). The mixture of air and gaseous fuel gets compressed in the cylinder. Liquid fuel called pilot fuel injector near the Top Dead center (TDC) as a source of ignition. Gas–air mixture ignites establishing a number of flames–fronts. Basically in dual-fuel engine combustion also starts similar to Compression Ignition (CI) engine, but it is propagated by flame–fronts as in Spark Ignition (SI) engine.

12.3 Performance of Dual-fuel Engines

Duel fuel engine, produced equal power when operating on liquid fuels as with gaseous fuel. Duel fuel engine is slightly more efficient to conventional diesel engine at full load. However, the maximum output is almost same. The efficiency of dual-fuel engine in part load is slightly poor. Typical diesel engine efficiency is 41% and dual-fuel engine 38.5%.

12.4 Merits and De-Merits of Dual—Fuel Mode Power Generation

Merits

- Efficient utilization of cheap gas available from various sources and gas burns without leaving any residue (no pollution).

- Clean combustion results in reduced wear of engine parts and reduced combustion of lubrication oil.
- Easy for retrofitting with existing diesel engine without any modifications
- Plant availability higher—utility will not suffer due to nonavailability of gasifier
- Economical compared to fossil fuel—diesel.

Demerits

- Duel fuel engine has a tendency of vapor locks while using lighter fuels.
- It has a tendency of increase wear-tear due to the poor quality of gaseous fuel.
- It requires for injecting different volumes of gaseous fuel depending on their heating values and compressibility.
- Expensive cannot compete with State grid electricity.

13 Producer Gas Based Engine

The engine runs through producer gas is mainly sparked ignition engine, however operating conditions mostly based on gas derived from biomass at lower compression ratio (CR) range. Producer gas based engine gives better performance under suitable operating conditions. However due to low energy content (1000–1200 kCal/Nm^3) during operation it is derated about 40–50% and resulting loss of power about 30%. Producer gas has low flame speed as compared to gasoline, therefore improvement need to be made in ignition timing for about 30–40°, which depends on rpm and compression ratio of the engine. In the case of natural gas engine, the mixture of gasoline-air is automatically adjusted through the carburetor as well as controlled by the accelerator. But in case of producer gas based engine it is difficult to maintain as the composition of gas changes drastically over a run of gasifier. At low-speed engine, the producer gas could be used more efficiently.

A spark ignition engine requires very little/no modification to run on P gas. The cold gas efficiency of producer gas in favorable condition can be 70%. In the gasifier-engine system, losses also occur at different stages. Engine performance is expressed in terms of brake thermal efficiency. The overall efficiency of the system is the product of gasifier efficiency and brake thermal efficiency. The actual efficiency of the engine varies with design, size, and running condition. The efficiency of diesel and gasoline engines under the good condition is considered to be 30 and 20% respectively (Fig. 14). The efficiency of engine run with producer gas goes down owing to the lower density of gas–air mixture and other power losses associated with the suction of mixture in engines. Theoretically, gasoline and diesel engine operated on producer gas suffer a power loss of 30 and 20% respectively. In practice, considering a wide range of producer gas quality, a power drop ranging from 25 to 60% can be expected when diesel or gasoline engine is run with producer gas (http://cturare.tripod.com/bio.htm).

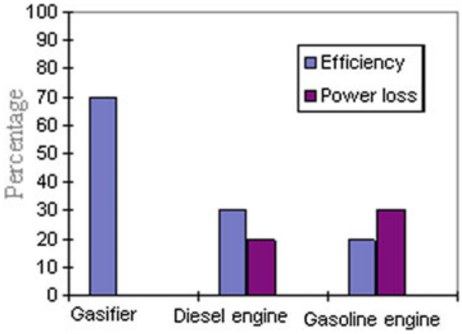


Fig. 14 Theoretical efficiency and power loss in different units of gasifier-engine system. *Source* http://cturare.tripod.com/bio.htm

14 Operational Difference Between Diesel and Gasoline Engine

There is a significant difference between diesel and spark ignition engine system with respect to its suitability for producer gas. In a diesel engine, diesel is injected at the end of the compression stroke and gets ignited immediately without any spark ignition. These will not the case with producer gas–air mixture. In fact, the diesel engine cannot operate alone on producer gas as temperature and pressure are not sufficient to ignite the gas–air mixture. Hence, during the injection of the producer gas mixture, some quantity of diesel is also injected into the combustion chamber.

15 How Producer Gas Engine Different from Natural Gas Engine

The air-to-fuel ratio of Producer gas is 1.1–1.2:1 while in Natural Gas it is 17:1, this identified for a different carburettor. Producer gas can be used in engines with higher compression ratio due to its higher octane rating. Flame speed of producer gas is higher (~20%), identified the setting ignition timing. Derating of the engine power is also observed which is due lower energy density of producer gas (~20%). Producer gas engine need different conditions in the engine cylinder and turbocharger due to lower flame temperature (about 300 K).

16 Merits and Demerits of Producer Gas Based Power Generation System

Merits

- Economically viable and can compete with State grid electricity

- Plant availability reasonably high—provided correct operation practice is adhered to
- Eco-friendly—emission from gasifier meets pollution norms and regulations.

Demerits

- Power Start-up is required were as grid is not available
- Not suitable for application if gas quality is poor (for example: low energy content and high contaminants).

17 Biomass Pyrolysis

Pyrolysis is nothing but the thermal decomposition of biomass occurring in the absence of oxygen. It is the basic chemical reaction which is happen before the combustion and gasification processes and occurs naturally. Pyrolysis of biomass generates three different energy products such as charcoal, bio-oils, and uncondensed pyro-gases in different quantities. The quantity of these products depends upon heating rate and heating temperature of reactor. Several kinds of biomass such as agricultural residues, forest residues, municipal waste, etc., could be used for Pyrolysis. The efficiency of pyrolysis process depends upon particle size of biomass. In the pyrolysis process heat transfer take place from one particle to another particle of biomass thus size of the biomass particle is very important. Pyrolysis may be either fixed-bed pyrolysis or fluidized bed pyrolysis. In fixed-bed pyrolysis, the feed material is fixed, heated at higher temperature (Fig. 15). Generally inert gas such as helium, argon, nitrogen est. is passed in the pyrolysis reactor which helps to disposal of gaseous mixture into the condenser (Asadullah 2014).

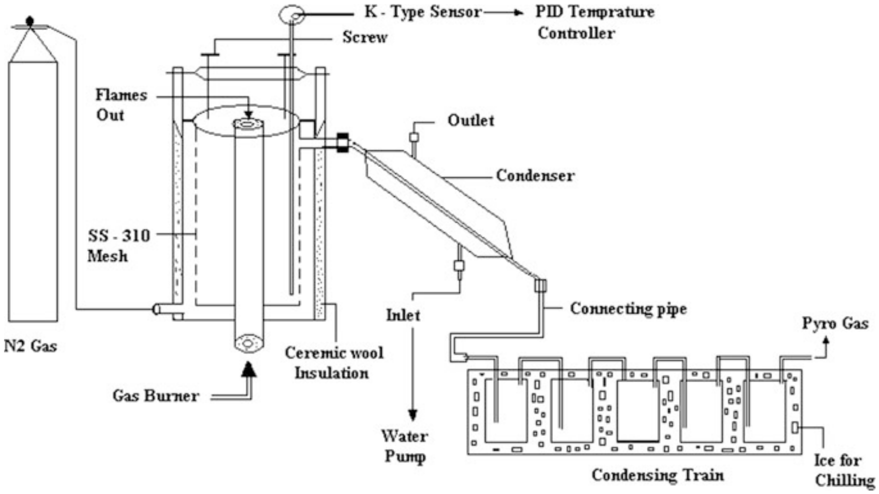


Fig. 15 Schematic of thermally heated Pyrolysis reactor (Chouhan 2010)

17.1 Pyrolysis Classification

Pyrolysis processes can be classified into Slow Pyrolysis, Fast Pyrolysis, and Flash Fast Pyrolysis. The complete thermal decomposition of the feed materials for all categories is based on heating time and heating temperature.

17.2 Slow Pyrolysis

Slow pyrolysis is being used for production of charcoal from a long time. Generally it is done at low temperatures (less than 450 °C) and low heating rates (4–8 °C/min) in the absence of air/oxygen. In this process, the residence time of vapor in the reactor is too long (5–30 min) which helps in continue to react the generated gas with each other for longer duration. As a result, formation of solid char is more compared to other component (liquids and gases). Due to low temperature and heating rate the slow pyrolysis process is not used for bio-oil production (Asadullah et al. 2013).

17.3 Fast Pyrolysis

In the fast pyrolysis process, heating rate (5–10 °C/min) and heating temperature (600–700 °C) is quite high as compared to the slow pyrolysis. Higher temperature and heating rate resulted higher formation of pyrogas which could be condensed and converted into bio-oil. Presently, in all the pyrolysis system, fast pyrolysis is the most widely used. It yields 60% wt bio-oil and takes few seconds for complete pyrolysis as well as in addition it gives 20% biochar and 20% syngas. The basic characteristics of the fast pyrolysis process are high rate of heat transfer, very short vapor residence time, rapid cooling of vapors and aerosol for high bio-oil yield and precision control of reaction temperature. The liquid product (Bio-oil) can be economically transported and easily stored (Asadullah et al. 2013). It also has potential to supply a number of valuable chemicals that offer the attraction of much higher added value than fuels.

17.4 Flash Fast Pyrolysis

The flash pyrolysis process is further advance stage of fast pyrolysis. In the case of flash fast pyrolysis heating rate and heating temperature are very high (10–15 °C/s, 800–1000 °C) and biomass residence time is very low, resulting large quantity of bio-oil production (more than 75% bio-oil). However, due to very high temperature

Table 5 Typical product yields (dry wood basis) obtained by different modes of thermo-chemical conversion of wood

Process	Conditions	Liquid, %	Char, %	Gas, %
Fast pyrolysis	Moderate temperature, short residence time particularly vapor	75	12	13
Carbonisation	Low temperature, very long residence time	30	35	35
Gasification	High temperature, long residence times	5	10	85

Source Crocker (2010)

and heating rate requires very small particle size of biomass and gas gets very short residence time (less than 1 s). This calls for long condensing trains. Flash fast pyrolysis process also has some technical limitations; thermal stability is poor as well as corrosiveness of the oil. The solids in the oil increases the viscosity over a time by catalytic action of char whereas alkali concentrated in the char dissolves in the oil which produces pyrolytic water. Typical yields obtained through different modes of thermo-chemical conversion are tabulated in Table 5.

18 Parameter Affecting the Pyrolysis Process

18.1 Moisture Content

Moisture content of the biomass is one of the important parameter for pyrlysis process. It should be maintained about 10–20% wb. High moisture in the biomass may produce low energy content of bio-oil; however less moisture in the biomass may produce only dust.

18.2 Particle Size of Feedstocks

In pyrolysis process size of the biomass particles has very important role as inside the pyrolysis reactor hear transfer take place from particle to particle. Smaller biomass particle offer more surface area compared to bigger size particles and hence help in more and uniform generation of pyrogas. Considering above 2 mm or less biomass particle found better for rapid heat transfer.

19 Conclusion

The conversion of biomass into the useful energy is the greatest contribution to the environment and society which fulfill the basic need of energy for day-to-day activities. Numbers of technologies are available to convert biomass into the energy. In this chapter, thermo-chemical conversion of biomass is discussed. Thermo-chemically biomass could be converted to energy by three ways named as Combustion, Gasification, and Pyrolysis. Combustion occurs in presence of stoichiometric oxygen, Pyrolysis in the absence of oxygen and Gasification requires partial oxidation. Compared to other available technologies, the route of thermo-chemical conversion is the simplest and most developed technology.

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