

# Therochemical Conversion of Biomass: An Overview

Pragya Yadav<sup>1\*</sup>, A.K. Sarma<sup>2</sup>

## Abstract

*A viable way to utilize biomass resources for energy production is through thermochemical conversion processes. This study presents a thorough analysis of the principles, workings, benefits, and drawbacks of thermochemical conversion processes, such as pyrolysis, gasification, and combustion. We examine the various uses of thermochemical conversion in waste management, biofuel synthesis, and energy production. We also go over recent developments, technological breakthroughs, and potential future paths for biomass thermochemistry research. This review attempts to contribute to a deeper understanding of thermochemical conversion processes and their role in advancing sustainable energy solutions by synthesizing current knowledge and research findings.*

**Keywords:** Biomass, thermochemical conversion, pyrolysis, gasification, combustion, biofuels

## INTRODUCTION

Thermochemical Conversion of Biomass is the conversion of Chemical energy stored in Biomass to heat and other forms of energy to provide fuels, power and chemical to energy can be brought out by three main processes:

1. Combustion
2. Gasification
3. Pyrolysis

Thermochemical Processes is a fast process and independent of source of Biomass unlike Biochemical and Chemical Processes.

## Biomass Combustion

Thermal Conversion of Biomass using an excess of oxidant (air) is known as combustion and leads to conversion of components of Biomass into their respective oxidized forms. It is a rapid process the converts Chemical energy of fuel into heat. Combustion takes place at temperature up to 2000°C and depending upon moisture content of the fuel, produce gases between 800-1000°C that can be used for process heat or for production of steam. Stages of biomass combustion are as follows:

Drying → Pyrolysis → Combustion → Surface oxidation

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Received Date: February 24, 2024

Accepted Date: March 16, 2024

Published Date: April 15, 2024

**Citation:** Pragya Yadav, A.K. Sarma. Therochemical Conversion of Biomass: An Overview. International Journal of Energy and Thermal Applications. 2023; 1(2): 31–42p.

## BASIC PRINCIPLE OF COMBUSTION

On a micro level, molecules in the vapor phase are constantly moving and bumping into one another. When the temperature is raised, they move at higher speeds, thus, a more violent collision occur. At sufficiently high temperatures, the collisions are energetic enough to loosen the old bonds and allow formation of new bonds. During making and breaking of these bonds chemical energy is released as heat. This heats the gas further, which helps more reactions to occur, and a flame results [1].

## Biomass Cookstove

Cookstoves is an important application in thermochemical conversion. Biomass cookstove is a physical structure that contains air fuel combustion chamber for heat release and subsequently, directs the heat of combustion towards the cooking pot/pan. Besides cooking, cookstove provide useful energy for space heating, and lighting. Cookstoves are basically of two types, one is traditional coostove and other one is improved and advanced cookstoves. Traditional cookstoves have developed over thousands of years. According to the local culture and food habits these stoves are cheap and the users are familiar with their operation and hence are widely accepted in society. The main disadvantages of traditional cookstove are high fuel consumption, high CO and PM emission and low thermal efficiency. On the other hand an improved cookstove is designed using certain scientific principles, to assist better combustion and heat transfer, for improving emission and efficiency performance.

Understanding of few basic terms and concept is important before designing or testing any cookstove (Figures 1-3 and Tables 1-4).

**Table 1.** Designing or testing any cookstove.

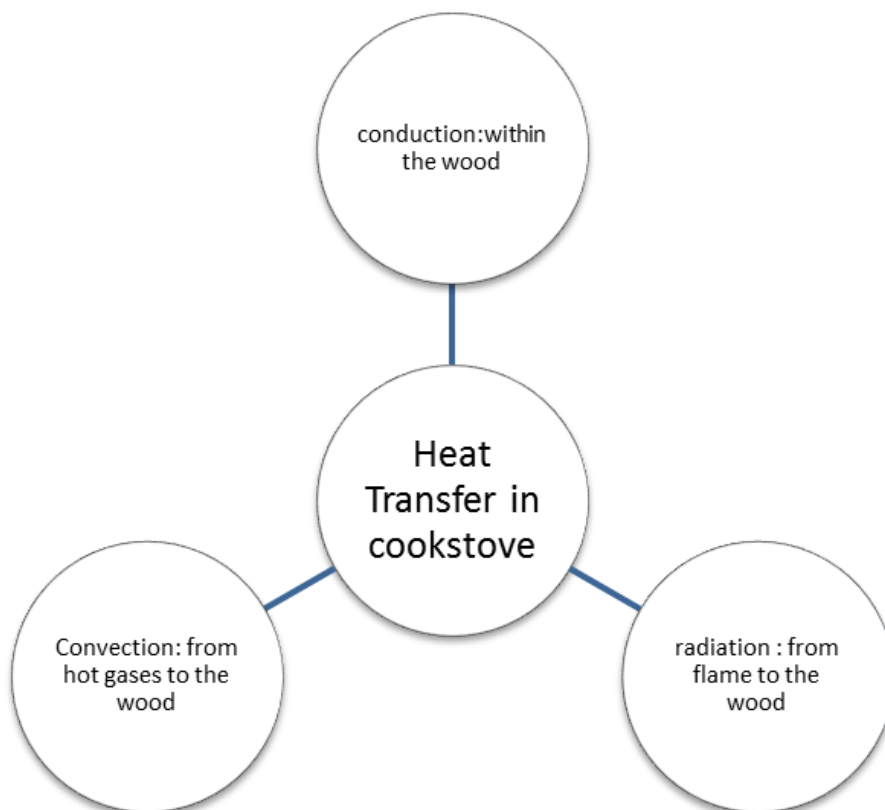
Heat Transfer	Temperature difference between any two bodies cause heat to flow from hotter to the colder body. The heat flow or transfer can take place in 3 fundamental ways: Conduction is the transfer of heat between substances that are in direct contact with each other Convection occurs when warmer areas of a liquid or gas rise to cooler areas in the liquid or gas. Cooler liquid or gas then takes the place of the warmer areas, which have risen higher. This results in a continous circulation pattern Radiation is a method of heat transfer that does not rely upon any contact between the heat source and the heated object as is the case with conduction and convection. Heat can be transmitted though empty space by thermal radiation often called infra-red.
Primary and secondary air supplies	The exact amount of air needed is not enough for better combustion. It is important to introduce it at the right point and time. The air supplied from below the grate in which it reacts with the solid biomass/char is known as primary air. While the air which is introduced from above the grate and which reacts with the volatile matter is known as secondary air. The relative amounts of primary and secondary air will depend on the proportion of fixed carbon and volatile matter in the biomass fuel, respectively.
Volume to surface area ratio of the wood	Volume to surface area ratio of the wood fuel is dependent on its size and is directly proportional to the combustion properties.
Fuel/Air Ratio	An excess air factor 1.5 to 2.0 is generally recommended for good combustion. In other words, one kg of wood requires 1.4 kg of oxygen or 6.5 kg of air at NTP. Applying the excess air factor of 2, then the total quantity of air needed becomes 13 kg.
Temperature of the flame	From the thermodynamic and heat transfer perspective, the flame temperature should be as high as possible. This depends on the calorific value and the excess air factor.

**Table 2.** Traditional cookstoves.

Types	<b>Three stone fire:</b> A pot is then balanced on three stones. The amount of heat given off by the burning wood can be increased or decreased by moving the wood further into away from the centre of the stones. <b>Chulhas:</b> This stove consists of a hollow box of mud with an opening at one end for inserting the wood, and a number of holes on top which allow cooking pots to be placed over the fire. The smoke escapes around the pot and the entrance [2]. <b>Kamado style cookstove:</b> The traditional Japanese earthenware cooker, the Kamado, made almost entirely of ceramic, the Kamado consists of an outer insulating shell that holds a removable firebox and grate. The double-walled design of firebox within shell, as well as the ceramic material itself, serves to minimize heat conduction adjusting the top damper and bottom damper to regulate the draft.
Advantages	These stoves are cheap and the users are familiar with their operation and hence are widely accepted in society.
Limitations	The main disadvantages of traditional cookstove are high fuel consumption, high CO and PM emission and low thermal efficiency

**Table 3.** Accordingly, ICSs can be classified into various categories.

Function	<p><b>Mono-function stoves:</b> An ICS that performs mainly one function, such as cooking.</p> <p><b>Multi-function stoves:</b> Apart from cooking, an ICS can also be used for other purposes or in combination, such as for water heating, room heating etc.</p>
Construction Material	ICS are mainly made of single materials: metal, clay, fired-clay or ceramics and bricks or are hybrids in which more than one material is used for different important components.
Portability	Metal and Ceramic ICS are normally portable in nature and can be moved indoors or outdoors while clay/brick, clay/stone ICSs are generally high mass and thus are fixed.
Fuel Types	<p>Stove designed for one fuel may not be compatible for use of different one. Commonly used fuel types are:</p> <ul style="list-style-type: none"> <li>• Charcoal ICS</li> <li>• Fuel wood ICS</li> <li>• Granular/loose agri-residue ICSs</li> <li>• Stick – form agri residue ICSs</li> <li>• Cow dung cake ICSs</li> <li>• Briquetted biomass-fuel ICSs</li> </ul>
Fuel Feeding	The feeding of fuel is also varying in the ICSs. Same function and efficiency of ICSs may be vary with the fuel type and feeding. Fuel feeding type is decided by manufacturer. Most of the ICSs come under continuous type fuel feeding only.
Air supply	<p>The amount of air needed is important consideration in combustion. Excess air will lead to efficient combustion. Recently, in most of the ICS are trying with excess air by experts. It can be classified as follows:</p> <p>Natural draft ICSs</p> <p>Forced draft ICSs</p>
Design	<p>According to the design of ICS it can be divide as follows. It give the importance to the cookstove accessories like grate, holes of primary and secondary air with possibility of their preheating.</p> <ul style="list-style-type: none"> <li>• Metal cookstoves</li> <li>• Rocket cookstoves</li> <li>• Heavy mud/Ceramic coostoves</li> </ul>



**Figure 1.** Heat transfer in a cookstove.



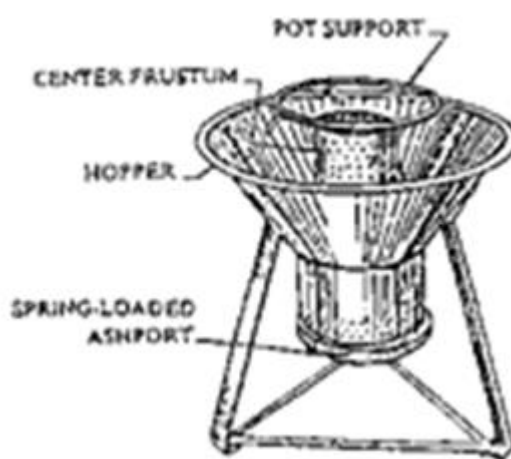
Three stone cookstove



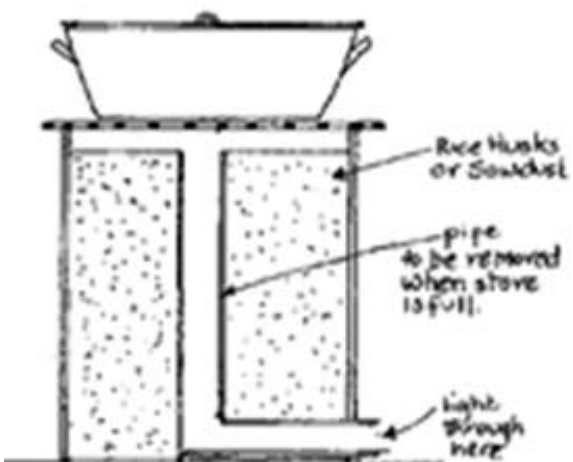
Improved mud chulha



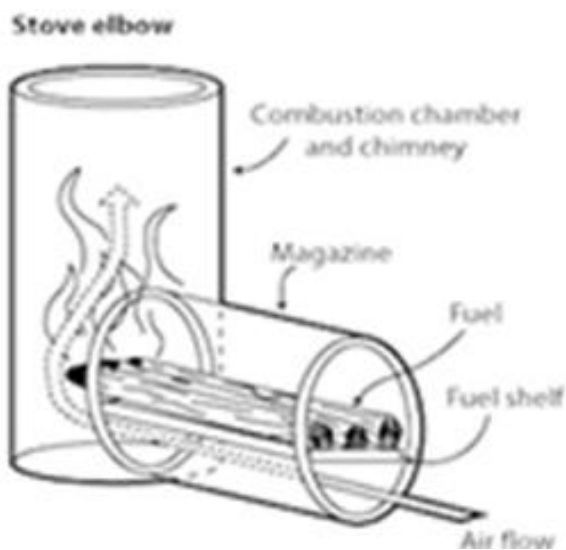
Kamado cookstove



Rice Hull stove



Sawdust cookstove



Rocket cookstove

**Figure 2.** Variety of cookstoves.



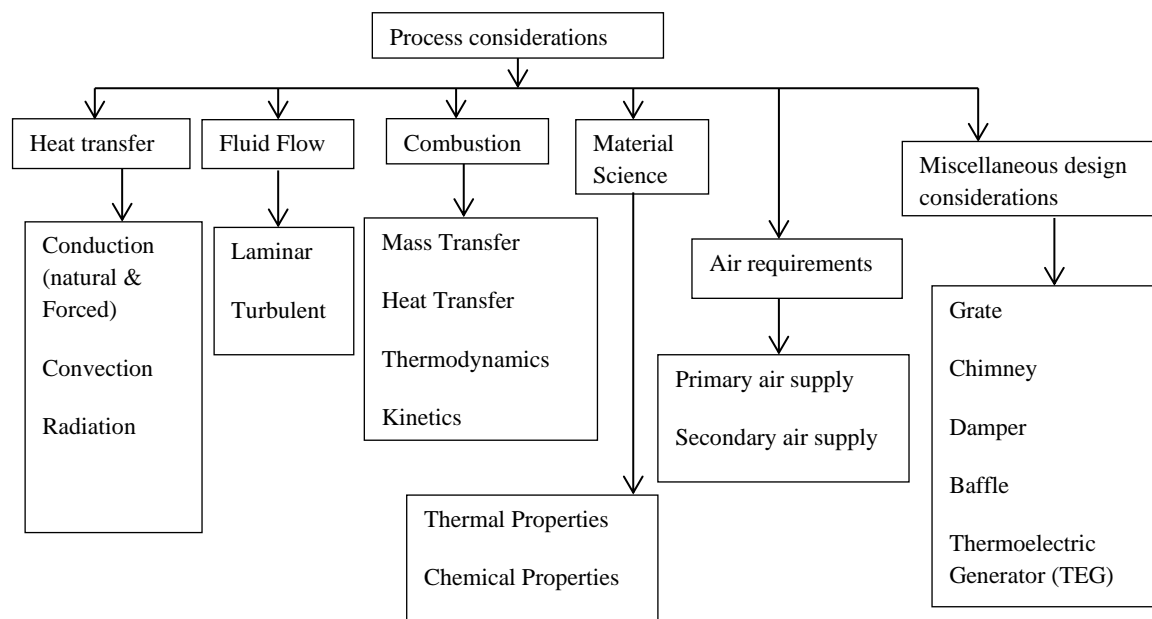
**Figure 3.** An ICS designed by SSS-NIRE.

**Table 4.** Design principles.

Design Goals	<p>Complete combustion of fuel</p> <p>Maximum transfer of the heat of combustion from the flame to the cooking pan</p> <p>Minimum loss of heat from cookstove/pot to the environment</p>	
Design Features	Grate	The use of a grate generally improves the combustion quality and rate of combustion significantly, due to improved supply of primary air under the bed and better contact of this air with the fuel. Use of grate will increase the efficiency of cookstove 3 to 5 %.
	Chimney	A chimney provides draft for suction of air into the cookstove and to remove flue gases from kitchen. While draft directly depends on chimney height, a larger diameter results in greater mass inflow of air due to larger area and a reduced frictional pressure drop through the chimney. The flow rate of air induced through the chimney depends more on its diameter than its height. For every cookstove configuration the height and diameter of the chimney must be so chosen as to balance the chimney draft with the air required for combustion and the frictional pressure drop, resulting in its best performance.
	Damper	A damper is used to regulate chimney draft and hence the air flow rate through the cookstove and thus can substantially reduce the fuel consumption. The damper design in cookstoves has been kept simple in order to keep the cost low and enable easy maintenance.
	Baffle	A baffle is a constructional element generally provided in a multipoint cookstove restricts the passage and direct the air flow so as to improve convective heat transfer between the combustion gases and all the pots. It can also improve combustion in such cookstoves by restricting the combustion volume. Since the baffle itself can get very hot, it also provides for increased radiant heat transfer to the pots.
	TEG	Forced draft cookstoves require electrical energy to operate the fan. Besides using a battery, some stoves use ThermoElectric Generator (TEG), which produces electric power using the temperature difference between the hot combustion chamber and the surroundings. The electric energy so generated can also be used to charge battery.
Parameters affecting Efficiency	Fuel (size, shape, density, moisture content, fixed carbon content, Volatile matter its calorific value and chemical composition)	
	Quantity and mode of air supply (primary and secondary air)	
	Conditions of the surroundings (temperature, wind, humidity etc.)	
	Stove components (fire-box, grate, baffles, dampers, chimney, stove geometry, thermal mass of the stove)	
	Cooking pot materials (shape and size)	
	Thermal properties of ingredients cooked	
	Sequence of cooking, etc.	
	Requirements of opening the lid (stirring, checking etc.)	

### Considerations Before Designing a Cookstove

Bureau of Indian Standards has recommended standards for designing of a cookstove (Indian Standard Potable Solid Biomass-Cookstove, IS13152: Part 1:2013). Therefore, before designing the cook stove such parameters should be strictly followed. The Figure 4 tries to club all points worth considering for the designing purpose and according the students must refer the above mentioned document [3].



**Figure 4.** Various aspects of cook stove designing.

### Biomass Gasification

Biomass gasification is a process that involves incomplete combustion of biomass in the presence of limited supply of air/oxygen at high temperature resulting in production of gaseous fuel i.e. mixture of hydrogen ( $H_2$ ), Carbon monoxide (CO) and methane ( $CH_4$ ) called producer gas. This producer can be used for power generation using internal combustion engines, direct heat applications and further fuel production like methanol [4].

### Principle of Gasification

Every fuel requires some amount of oxygen to carry out the process of combustion. The stoichiometric air to fuel ratio required for the complete combustion of biomass fuel varies from 6:1 to 6.5:1 with  $CO_2$  and  $H_2O$  as the end products (Figure 5 and Tables 5 and 6).

However, gasification process requires less amount of oxygen which resulting incomplete combustion of biomass. In gasification process, the biomass combustion occurs at sub stoichiometric conditions with air to fuel ratio varying from 1.5:1 to 1.8:1. Thus the key to gasifier design is to create conditions such that a) biomass is reduced to charcoal and, b) charcoal is converted at suitable temperature to produce CO and  $H_2$  [5-7].

### Types of Gasifiers

Since there is an interaction of air or oxygen and biomass in the gasifier, they are classified according to the way air or oxygen is introduced in it [9].

There are three fundamental types of gasifiers Downdraft, Updraft and Crossdraft. With slight variation almost all the gasifiers fall in the above categories (Table 7).

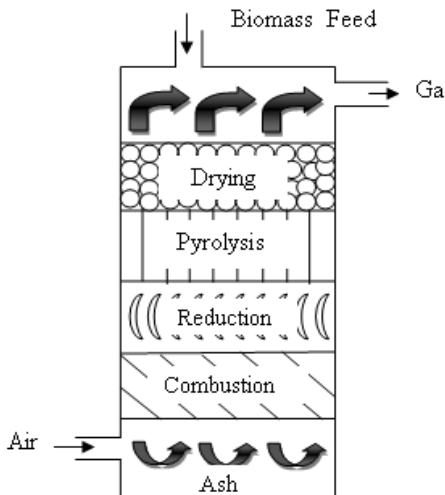
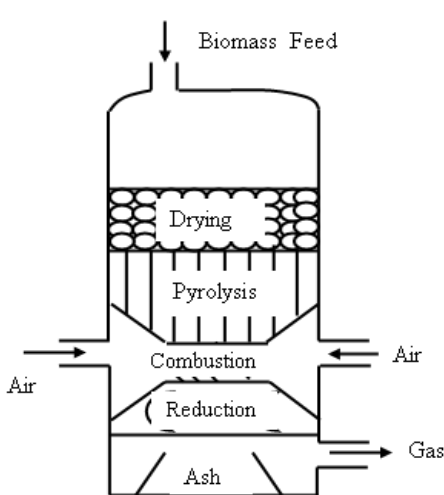
**Table 5. Stages in gasification.**

Drying	The biomass fuel contains moisture ranging from 5% to 35% depending on the nature of biomass. This moisture of biomass get converted into the steam at a temperature around 373 K.
Pyrolysis	Pyrolysis is a process of thermal decomposition of biomass fuels in the absence of oxygen/air. Pyrolysis takes place in a low temperature zone and condenses the hydrocarbons in the form of tars
Partial Oxidation	Partial Oxidation: Oxidation process oxides the volatile materials from biomass under exothermic chemical reactions and generate the heat with peak temperature of 1400 K to 1500 K with gaseous fuels like CO, H <sub>2</sub> , CO <sub>2</sub> and H <sub>2</sub> O. In this zone, a heterogeneous reaction takes place between solid carbonized fuel and the oxygen present in the air which produces carbon dioxide and substantial amount of heat. $C + O_2 \rightarrow CO_2 + 406 \text{ kJ/g. mole}$ $H_2 + \frac{1}{2} O_2 \rightarrow H_2O + 242 \text{ kJ/g.mole}$
Reduction	In this zone, a number of high temperature chemical reactions take place under a reducing atmosphere. The reduction process occurs while executing endothermic reaction to generate combustible products such as CO, H <sub>2</sub> , and CH <sub>4</sub> as shown below. $C + CO_2 \rightarrow 2 CO - 172.6 \text{ kJ/g.mole}$ $C + H_2O \rightarrow CO + H_2 - 131.4 \text{ kJ/g.mole}$ $C + 2 H_2 \rightarrow CH_4 + 75 \text{ kJ/g.mole}$

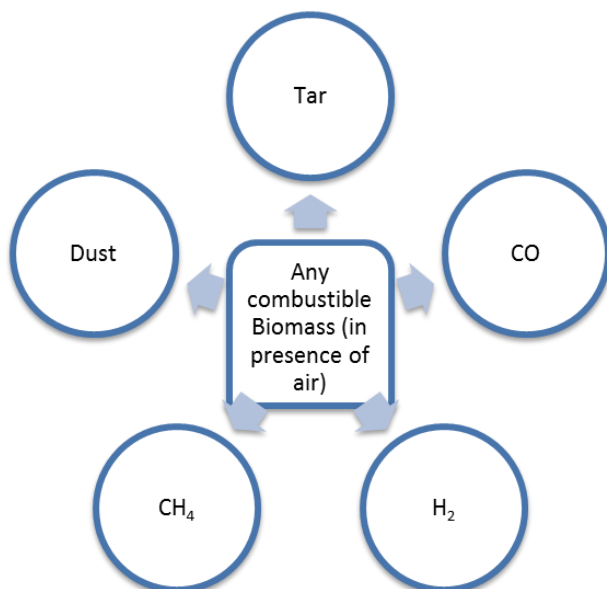
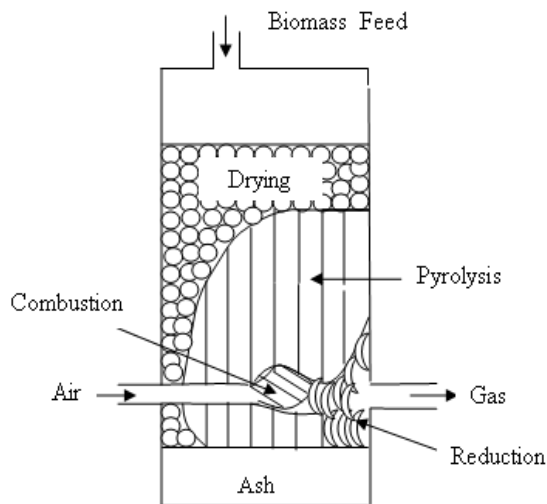
**Table 6. Parts of a gasifier.**

Hopper	It performs three functions of gasification viz. drying, pyrolysis and combustion. It has Air nozzles for induction of Air into combustion cone. There's a vibrator motor for uniform flow of biomass. A pressure point, i.e. for reading of pressure drop across nozzles ( $\Delta P_N$ ) to determine air flow.
Reactor	It performs the reduction function and thus, production of producer gas. The reactor table with comb rotor holds the charcoal bed and the comb rotor helps in maintaining the charcoal bed by removing ash from it. Pressure point, i.e. for reading of pressure drop across the charcoal bed ( $\Delta P_G$ ) to determine the charcoal bed condition. A water column manometer is connected to measure the charcoal bed pressure drop, known as $\Delta P_G$ . The hot gas line carries the hot producer gas having temp. of 400 0C to 500 0C from the gasifier outlet to the Venturi scrubber inlet [8].
Dry Ash Collection Box	It acts like storage for ash collection produced by biomass gasification. The Reactor holds charcoal for reduction of partial combustion products while allowing the ash to escape through perforated sheet provided in reactor which in turn taken out in the reactor dry ash collection box. When the system is in operation, ash can be removed from the ash collection box by closing the flap valve and opening the flange provided at the bottom of the box. The flap valve and the bottom flange should not be opened simultaneously when the system is in operation.
Venturi Scrubber	Performs cooling and cleaning of hot gas by spraying pressurized water jet on it and reducing the gas temp. to 40 0C. Water drains down and the cold gas is sucked from drain box gas outlet. A cleaning port is provided at the bottom of the drain box for cleaning of the drain tub. A cleaning port is provided on the hot gas outlet.
Fine Filter and Safety Filter	They perform the cleaning of gas. The fine filter is filled with graded saw dust as the filtering media. Fine particles from the gas get trapped in the filter media. All the filters are provided with pressure points to measure pressure drop across the filter media. Safety filter performs the ultra cleaning of the producer gas. It has a fabric filter bag fixed inside. Safety filter is provided with a pressure point to measure the pressure drop across the filter bag
Flare	It is provided for checking the quality of the producer gas. When the system is used for any purpose say power or thermal application, the producer gas is first tested on the flare by igniting the gas to check whether the producer gas burns colorless (blue flame will be visible during night time) and continuously i.e. ultra clean gas. Then only it can be introduced into the engine. Before starting the gasifier, always ensure that the flare valve is fully opened and the gas control valve is fully closed. When the gas is ready to be introduced into the engine, the gas control valve should be opened slowly and gradually and simultaneously the flare valve should be closed to about half position. When any failure or erratic operation of the engine takes place, flare acts like a safety by opening the flare valve and simultaneously closing the gas control valve.

**Table 7.** Types of gasifiers.

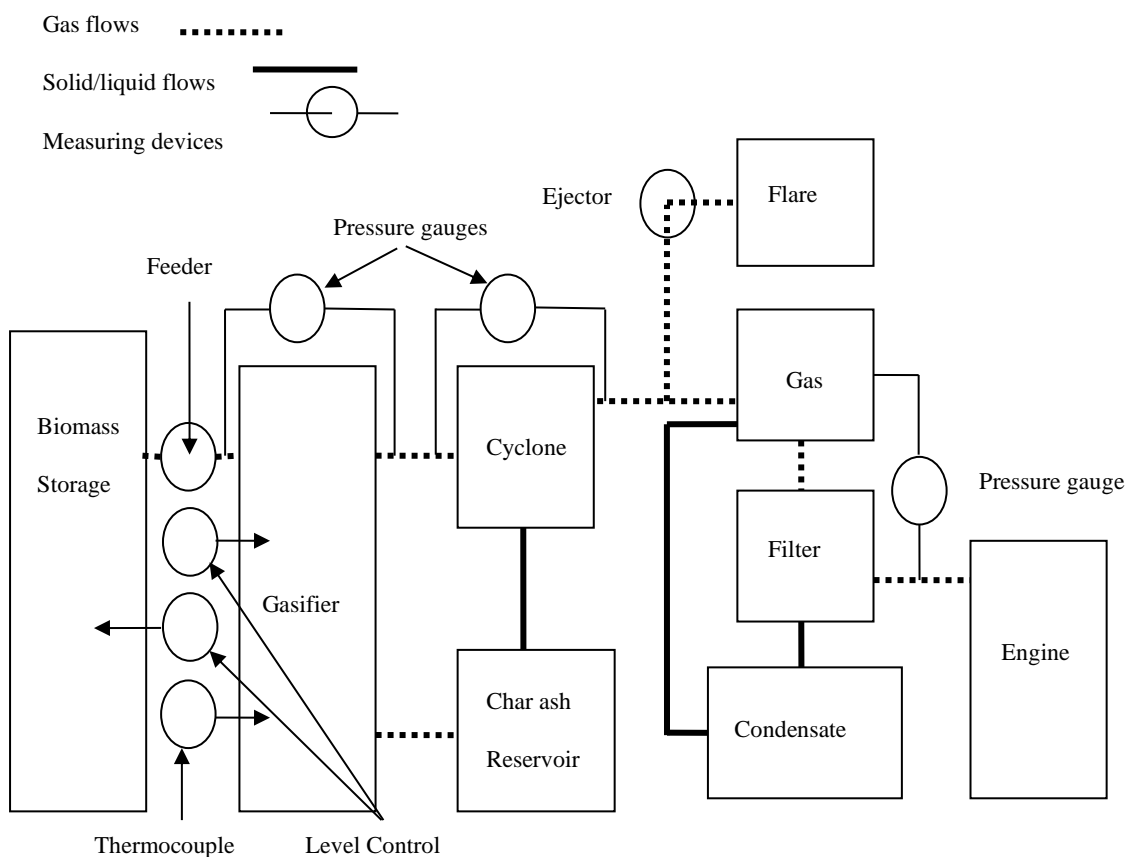
<p>Up draft gasifier</p>	<p>In updraft gasifier, the air/oxygen is introduced at the bottom to interact with biomass and the combustible gases come out form the top of the gasifier unit. These gasifiers are also called counter current gasifier. The gas produced in the reduction zone leaves the reactor along with pyrolysis products and steam from drying zone. This gas is rich in hydrocarbon and hence has higher calorific value.</p> <p><b>Advantages:</b>                  Small pressure drop                  good thermal efficiency                  little tendency towards slag formation</p> <p><b>Limitations:</b>                  Great sensitivity to tar and moisture content of fuel                  relatively long time required for start up of IC engine                  poor reaction capability with heavy gas load</p> 
<p>Downdraft gasifier</p>	<p>In downdraft gasifier, the air interacts with the solid biomass fuel or downward flowing packed bed and gas is drawn off at the bottom. On other way we can say that, the waste is fed in at the top of the gasifier while the oxidant from the top or the sides. The waste and gases move in the same downward direction. So these gasifiers are also called as co-current gasifiers.</p> <p><b>Advantages</b>                  Flexible adaptation of gas production to load                  low sensitivity to charcoal dust and tar content of fuel</p> <p><b>Limitations</b>                  Design tends to be tall                  not feasible for very small particle size of fuel</p> 

<p>Crossdraft Gasifiers</p>	<p>Crossdraft gasifier is one of the simplest types of gasifier in which the fuel will get entered from the top and the thermochemical reactions will occur progressively as the fuel descends in the reactor. Here, the air will enter into the reactor from the side, rather than from the top or the bottom as shown in Figure 4. Unlike upward and downdraft gasifier, crossdraft gasifier has separate ash bin, fire and reduction zone and hence limit the fuel used for operation with less ash content in the producer gas.</p> <p><b>Advantages</b>                  Short design height                  very fast response time to load                  flexible gas production</p> <p><b>Limitations:</b>                  Very high sensitivity to slag formation                  high pressure drop</p>
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**Figure 5.** Products of gasification.

Downdraft gasifiers are best suited for the applications where clean gas with control temperature is required. The main applications of these gasifiers are in IC engines, backing ovens, boilers, dryers, direct fired rotary kilns etc. The main advantages of these gasifiers are good fuel gas quality, short start time for engine, flexible in gas production and possess low sensitivity towards tar, moisture content of fuel [10]. A lower overall efficiency and difficulties in handling higher moisture content of fuel is the limitations in downdraft gasifier yet they are most widely used types of gasifier (Figures 6 and 7).



**Figure 6.** Schematic representation of biomass gasifier system.



**Figure 7.** Downdraft gasifier.

### Maintenance of a Gasifier

- Always use recommended size wood chips, not more than 25 X 25 X 10 mm (Thk). Wood must be naturally dried with moisture content less than 20%.
- Always use recommended charcoal size (15 to 20 mm) for preparing reduction bed in reactor.
- Clean ash from dry ash collection box everyday specially before starting the gasifier. The ash collection box capacity is 8 hrs of ash holding on continuous engine running basis.

- Always before putting back the flange of the dry ash cleaning port, clean the surface of the flange properly and tighten the nut-bolts firmly so that there is no air leak. Replace the gasket, if found damaged.
- The **water tank** should be filled with water and the filtering tank should be filled with charcoal upto 5 inch height. Always make-up water level in the tank before starting the gasifier up to correct level. (Just below the skirting). The tank should be kept clean of fallen leaves, wood pieces etc. and cleaned completely once in 1 to 2 months removing settled particulates, soil etc.
- Scrubber water pump as well as cooling spray pump should be kept clean without any obstruction in suction valve or casing or water nozzle. When everything is clean, the Scrubber pump can be checked along with water nozzle to give a discharge of not less 1600 litres/hr. Check once a week. This is important as not only the gasifier start-up depends on correct working of the scrubber pump, but also the gas cooling and cleaning
- Check feed door, ash door rubber seal and tightness of hopper-reactor, asbestos rope seal periodically approximately once in a month. Also check the water seal in the drain tub is always 25 to 50 mm. This may get disturbed due to inadvertent shifting of drain tub below the drainpipe.
- Clean-up nozzle area in the venturi scrubber with a 250 mm long, 3 or 5 mm dia straight wire through on opening (normally kept closed by a plug) on top of nozzle-end of venturi. This can be done twice a week. The opening must be plugged after use. An unclean area will obstruct gas flow thereby reducing output of engine generator.
- All doors of fine filter, top and bottom, safety fabric filter, feed doors and water condensate plugs should be checked for good sealing rubber etc. and should be tight in operation
- In initial stages up to a year or so, it is advisable to lift the hopper by taking out the fixing bolts and nuts with reactor every three months. Observe the reduction bed for pieces of stone, clinkers formed if soil is mixed in the feed. Remove the bed and clean it of all such unwanted materials. Clean the punched sheet gas outlet holes; see that the comb rotor is not distorted. Fill the reduction bed with clean charcoal again as explained under erection procedure. Refit the hopper on top and tighten bolts. The above maintenance will ensure that biomass feed discipline is maintained and the gas engine runs trouble-free.

## CONCLUSION

In conclusion up, thermochemical conversion processes present viable avenues for releasing biomass resources' energy potential and facilitating the shift to a future reliant on renewable and sustainable energy sources. We have looked at the fundamentals, innovations, uses, benefits, and difficulties of thermochemical conversion processes, such as pyrolysis, gasification, and combustion, in this thorough review. One of the keystones of the global shift towards cleaner, more sustainable energy systems is the thermochemical conversion of biomass. By utilizing cutting-edge thermochemical processes to unlock the energy potential of biomass resources, we can lessen our dependency on fossil fuels, mitigate greenhouse gas emissions, and build a more resilient and sustainable energy future for future generations.

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