READING MATERIAL

TECHNOLOGIES FOR CONVERTING WASTE AGRICULTURAL BIOMASS TO ENERGY
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Technologies for Converting Waste Agricultural Biomass to Energy

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PREFACE

Energy has become a prime requirement for the development of human society. With the industrialization, considerable economic development has taken place in many countries. However, extensive use of fossil fuels for energy has resulted in a daunting array of energy related challenges, both related to quantity and quality of fuels. Fossil fuels, mainly oil, coal and natural gas that contribute to about 80% of the global primary energy supply today, are depleting resources. At the rate of present consumption, the world proved fossil reserves at the end of 2011 are sufficient for only about 54 years for oil, 64 year for natural gas and 112 year for coal. For under developed countries, this situation is further exacerbate by several other aspects including use of technologies with low energy conversion efficiencies resulting excessive losses, lack of development in alternative indigenous resources and local technologies resulting excessive external dependency, escalation of cost of energy leading to heavy drain of foreign exchange and wide disparity in access to energy services leading to inequity, ultimately challenging the sustainable development.

The prevailing unsustainable economic growth signals the urgent need to make a paradigm shift from the way the human development is determined today. In fact, many Asian countries had traditional agrarian economies and social formations, which were nurtured by the natural resources and biodiversity adding immense value to the society. The harmonious practices adopted by the people brought about not only environment and economic sustainability, but also social and political stability, signifying the true long-term sustainability. These traditional and cultural backgrounds of sustainable livelihood still hold the key to the future as well.

One of the essential facets of a green economic development model of a country is the development of indigenous resources and local expertise together with utilization of environmentally sustainable technologies for energy services needed for development activities. In this context, it is apparent that there exists a huge potential of waste agricultural biomass, and programmes for well-managed exploitation and utilization of them for appropriate energy services could contribute significantly not only to achieve rural development and less dependency on external resources but also for the diversification of energy sources and thereby improving energy security of the country.
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CHAPTER 01: BIOMASS AS A SOURCE OF ENERGY

1.1. INTRODUCTION
The term biomass refers to all materials derived from living organisms, or recently living organisms (plants and animals). Biomass can be used as a material (such as food, timber products, fiber, fertilizer, chemicals, etc.) or energy. In the context energy, biomass is often used to mean plant based material, but biomass can equally apply to both animal and vegetable derived material and waste. Biomass is carbon based complex polymers and is composed of a mixture of organic molecules containing hydrogen, oxygen, and also small quantities of other atoms, including nitrogen, alkali, alkaline earth and heavy metals. Fossil fuels such as coal, oil and natural gas are also derived from biological material, however material that absorbed carbon dioxide (CO₂) from the atmosphere many millions of years ago. Therefore the vital difference between biomass and fossil fuels as energy sources is the time scale. If it is managed on a sustainable basis, biomass is harvested as part of constantly replenished plants or crops in which the new growth in the re-plantation takes up CO₂ from the atmosphere at the same time as it is released by an energy conversion process (e.g. combustion) of the previous harvest. This maintains a closed carbon cycle with no net increase in atmospheric CO₂ levels, in contrast to that of fossil fuels, and therefore biomass is considered as a renewable energy resource.

The primary source which supplies the energy to biomass is the sun, as solar energy is used indirectly to grow plants by photosynthesis. The Photosynthesis captures approximately 3,000 EJ from the total solar energy absorbed by Earth of about 3,850,000 EJ per year and produces more than 100 billion tons of dry biomass annually [1].

Radiant energy of sun is absorbed by the green pigment chlorophyll in the plant leaves and is stored within the plant in the form of chemical bond energy. Less than five percent of solar energy incident on a leaf is absorbed while the rest is reflected and transmitted. The process of photosynthesis is extremely complex and consists of a series of reactions catalyzed by certain enzymes. Only some of these reactions require light while others do not. In all, water
and CO₂ molecules broken down, and a carbohydrate is formed with the release of pure oxygen. A simple chemical equation for photosynthesis, neglecting the intermediate steps, can be written as follows:

\[
6\text{CO}_2 + 6\text{H}_2\text{O} + \text{Light} \xrightarrow{(\text{Chlorophyll})} \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2
\]

This stored energy is recycled naturally through a series of chemical and physical conversions processes in the plant, the soil, the surrounding atmosphere and other living matter. Most of this energy is eventually radiated away from the earth as low-temperature heat. A small fraction of energy may remain in peat and a tiny proportion may slowly become fossil fuel energy.

Biomass has always been a major source of energy for mankind. In 2010, biomass accounted for about 12.2% of global primary energy consumption, which makes up 73.1% of the world’s renewable energy [2] and is the fourth largest source of energy following oil, coal, and natural gas (see Figure 1.1). In developing countries, biomass plays even more significant role in the energy sector, especially as the main source of energy for cooking in the domestic sector and thermal energy for many small and medium industries and commercial establishments.

![Figure 1.1: Global primary energy consumption by source in 2010 (Total consumption = 8823 Mtoe = 369 EJ).](image)

In the recent past, there has been renewed interest in biomass energy resources and technologies, especially as an alternative for fossil fuel systems. Main reasons for this include the following:
• Significant potential, as well as the social, economic and environmental benefits of the utilization of biomass as a sustainable source of energy, especially in the context of present energy and environment crises arisen from extensive use of fossil fuels;

• Progressively increase in fossil fuel prices leads to high cost of energy in many applications and biomass is the main alternative source of energy that could potentially replace almost all categories of fossil fuel based technologies/applications;

• Technological developments related to energy conversion as well as resource management promise the application of biomass at lower cost and with higher conversion efficiency than was possible previously;

• Some biomass resources are presently considered to be waste materials and conversion to energy is one of the effective ways of managing them, while satisfying a variety of local energy needs productively.

But these main issues are not the only stimuli. Biomass is also an indigenous energy source available in most countries in variety of forms such as fuel wood, wood residues, agricultural residues, animal waste, significant portion in municipal solid waste (MSW) and market waste, and its utilization may diversify the fuel supply in many situations which in turn will contribute to achieve much needed energy security. Biomass can generate employment, and its use will contribute to additional income for the local people. Development of biomass resources creates wide opportunities for the application of indigenous knowledge, inventions and innovations, thus contributing to the establishment of a knowledge society, a much needed prerequisite for sustainable development.

1.2. SOURCES OF BIOMASS

1.2.1 Main Categories

Raw materials that can be used to produce biomass fuels are widely available in many countries and come from a large number of different sources, and in a wide variety of forms. Fuel wood is still the largest biomass energy resource today, but other sources of biomass can also be used. These include food crops, energy crops, herbaceous plants/grasses and woody plants, and residues from timber processing, agriculture or forestry. The supply of these biomass resources mainly comes from traditional plantation, natural forests, forest plantation, home gardens, and other agricultural lands. Further, oil-rich algae, animal wastes and the organic component of municipal and industrial wastes are also important forms of biomass resources. A general classification of biomass according to the origin is presented in Table 1.1 [3].
Table 1.1: General classification of biomass according to the origin

<table>
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<th>Biomass Group</th>
<th>Biomass Sub-Group, Varieties and Species</th>
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<tr>
<td>Wood and woody biomass</td>
<td>Coniferous or deciduous; Soft or hard; Stems, branches, foliage, bark, chips, lumps, pellets, briquettes, sawdust, sawmill and others from various wood species</td>
</tr>
<tr>
<td>Herbaceous and agricultural biomass</td>
<td>Annual or perennial and field-based or processed-based such as:</td>
</tr>
<tr>
<td></td>
<td>- Grasses and flowers (alfalfa, arundo, bamboo, bana, brassica, cane, miscanthus, switchgrass, timothy, etc.)</td>
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<tr>
<td></td>
<td>- Straws (barley, rice, wheat, sunflower, oat, rape, rye, bean, etc.)</td>
</tr>
<tr>
<td></td>
<td>- Other residues (fruits, shells, husks, hulls, pits, grains, seeds, coir, stalks, cobs, kernels, bagasse, food, fodder, pulps, etc.)</td>
</tr>
<tr>
<td>Aquatic biomass</td>
<td>Marine or freshwater algae; macroalgae or microalgae; blue, green, blue-green, brown, red, seaweed, kelp, lake weed, water hyacinth.</td>
</tr>
<tr>
<td>Animal and human biomass wastes</td>
<td>Various manures, bones, meat-bone meal, chicken litter, …</td>
</tr>
<tr>
<td>Contaminated biomass and industrial biomass wastes (semi-biomass)</td>
<td>MSW, demolition wood, refuse-derived fuel (RDF), sewage sludge, hospital waste, paper-pulp sludge and liquors, waste paper, paperboard waste, tannery waste, …</td>
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<td>Biomass mixtures</td>
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1.2.2 Wood and Wood Processing Residues

Wood remains a major energy source in the developing countries. Wood is often the main household fuel and also contributes significantly to industrial energy consumption. It is estimated that about 55% of global wood harvest is burnt as fuel, and the remaining 45% is used as industrial raw material, a considerable portion of which is also ended up as primary or secondary process residues, suitable for energy production [4]. Wood fuels consists of woody biomass, i.e. stems, branches, twigs, etc., (see Figure 1.2) and sawdust and other residues from logging and wood processing activities (such as saw-milling, manufacturing of plywood and particle board), as well as charcoal from these sources. The primary sources of wood fuels are both forest and non-forest land. Forest and other wood-land include natural forests, scrub lands, wood and timber plantations, woodlots and dedicated fuel wood plantations. Non-forest land here includes agricultural land, agro-forestry systems, wasteland, line trees, home gardens, etc.
Biomass productivity of different plants is affected by many interacting factors relating to tree biology, community interactions and environmental constraints. Usually, yield of biomass in plantation is higher than that from natural communities. For example, in a natural forest, the annual average increment of biomass could be in the range of 500 kg of dry matter/ha, while even tenfold increase could be achieved in dedicated fuel wood plantation. In the case of short-rotation fuel wood plantation even much higher yield of 30 dry tons/ha/yr could be expected. Global fuel wood consumption is estimated to be about 2 billion cubic meters per year.

The process of conversion from trees to logs and subsequently to sawn wood is associated with number of waste streams. These biomass materials can be in various forms of logging as well as other processing wastes. In the timber industry, about 80% of the original trees goes to waste while only the balance 20% ends up in the form of kiln dried sawn wood, generating a significant amount of biomass. Some useful information on characteristics of wood residues is presented in Chapter 2.

### 1.2.3 Perennial Plantation Crop Residues

Perennial plantation crops, such as coconut, rubber, tea, cinnamon, cocoa, coffee, oil palm, and palmyra palm, generate considerable amounts of wood residues from pruning and replanting activities and a variety of processing residues. For example, coconut trees generate residues in the form of wood, fronds, husks and shells. Some estimates indicate generation of...
about 5 tons/ha/yr of fronds, husks and shells alone from coconut plantation having a productivity of 7200 nuts/ha/yr [5]. In addition, tree trunks are available during re-plantation, which are used both as a fuel and as timber. Rubber plantation is also an important source of fuel wood. In the last few decades rubber wood has become an important source of timber for the furniture industry. Rubber trees have a productive lifetime of about 25-35 years. During replanting they yield about 80 tons dry wood/ha. Cocoa trees are planted and used for production for a period of about 25 years, during which they have to be pruned regularly to keep them small, resulting generation of significant amount of biomass. In case of oil palms, tree trunks and fronds become available during re-plantation generating about 80 tons of dry matter per ha on 25 year cycle. Further, about 6 tons of fiber, shells and empty bunches are generated during processing per ha.

![Figure 1.3: Wood branches extracted from tea plantation for cooking applications](image)

Besides the plantation crops mentioned above, there are other sources of residues in the crop plantation industry, for example tea where pruning is done in every 7 - 10 years of tea bushes and uprooting after productive life (see Figure 1.3) generating sizable amount of biomass and coffee in which pruning of shade trees and uprooting generate biomass [6].

### 1.2.4 Agricultural Residues (Annual Crops)

Agriculture is an important part of the economy in most of the developing countries. Besides the crop itself, large quantities of residues are generated every year, amounting to about 140 billion tons. The term agricultural residue is used to describe all the organic materials which are produced as the by-products from agriculture activities. These residues constitute a major part of the total annual production of biomass residues and are an important source of energy both for domestic as well as industrial purposes.
Agricultural residues could be divided into field-based residues and process-based residues. The biomass materials, which are generated on the agricultural farm or field are defined as field-based residues (e.g. rice straw, sugar cane tops, cocoa pods, tobacco stalks, soybean straw/pods, maize stalks, etc.). Whereas those generated during processing of agricultural products are called process-based residues (e.g. rice husk, bagasse, maize cob/husk, coffee husk, peanuts shell, etc.). Such classification is important, especially under the context of energy application, as the availability of and accessibility to these sources critically depend on this attribute. Availability of field-based residues for energy application is usually limited since collection for utilization is difficult and there are other alternative uses such as for fertilizing and animal feed. However processed based residues are usually available in relatively high concentration and may be used as an energy source for the same industry making no or little transportation and handling cost.

![Figure 1.4: Agricultural residues: rice husk, bagasse and corn stalks](image)

Although agricultural residues are used as fuel, a large amount is wasted via open dumping or open burning in the field, and therefore referred to as waste agricultural biomass. As such, use of these materials for energy applications would be an effective way of managing the waste, while becoming a useful resource than a waste under conventional management practices. More details of the generation potential and characteristics of different waste agricultural biomass are presented in Chapter 2.

### 1.2.5 Energy Crops

Energy crops are grown specifically for the use as fuel. In general, the principle purpose is to maximize the output of the desired harvest with a minimum input. This may simply be measured in terms of tons of biomass per hectare, or it may be vegetable oil for conversion to biodiesel or sugar or starch for fermentation to bioethanol. Classes of energy crops include
short rotation energy crops, grasses and non-woody energy crops, agricultural energy crops (biofuel plants) and aquatics (hydroponics). The liquid biomass generated for energy application is usually referred to as bio-fuels, most common types of which are ethanol and biodiesel that are used as transportation fuels.

Sugar containing materials (or sugar crops) are becoming an important category of energy crops. The basic process of the derivation of fuel involves converting sugar to ethanol which can be used as a valuable liquid fuel for running engines. Sugarcane is the best known sugar crop. Sweet sorghum is another attractive sugar crop that can give the highest alcohol yield per ha per year of all sugar crops. Cane molasses, a by-product of sugar production, is also a common raw material for alcohol production. Molasses production is directly related to sugar production and represents a relatively small resource.

Figure 1.5: Sugar containing materials: sweet sorghum and sugarcane plantations

Another important category of energy crops is represented by starch containing materials, such as cassava and corn. Cassava is a root crop that can give high alcohol yield per ha of land and can be grown on marginal land. Corn is used for alcohol production in the United States. It is mainly used as a food in the developing countries and animal feed. It is grown in rich agricultural land and can be considered for large scale alcohol production only in countries having large areas of production but unused land. Oil and hydrocarbon substances produced by certain plants can be used as engine fuel after various degree of processing. Sunflower and coconut oils for example have been successfully used for running internal combustion engines. The yield of oil producing ground crops is normally low and ranges from 0.6 to 1.2 ton per ha per growing season of 120-160 days. Coconut palm and oil palm yield about 1.5 and 5 ton of oil per ha per year respectively and more promising for energy plantations.
Due to the much higher productivity, aquatic plants have attracted substantial interest as a valuable feedstock for second and third generation bio-fuels. It is a possible source for a variety of bio-fuels: biodiesel, bioethanol, biogas, pellets and charcoal briquettes. Sources for aquatic biomass could be categorized as free floating plants, emergent (rooted) fast growing plants (reeds, cattail), and algae. The biomass can be harvested from ‘nature’ or it can be grown in dedicated facilities such as ponds and bioreactors.

The growth rate of certain aquatic plants is very high with yield over 50 tons of dry matters per ha per year. Some plants, such as water hyacinth, water lettuce, salvinia and duckweeds are available in many places, have no significant use, and are often regarded as nuisance. Potentially these can be used as viable sources for biofuels, in particular for biogas. They are also gathering interest as a source for bioethanol. Large amounts of biomass could be grown in the oceans too for use as energy source. Use of aquatic plants to meet the energy needs is however a relatively new concept and may not often be financially viable because of costs involved in harvesting, transporting and conversion. The production and processing of algae currently receives most attention as a source for biofuels, especially biodiesel. Algae
production is the most efficient method to benefit from solar radiation in the production of biomass. Microalgae are considered to become a major source for transport fuels in the future. More information on biofuels production is presented in Chapter 5 and Chapter 6.

A number of grasses, such as Napier, Switchgrass, Miscanthus, are characterized by very high biomass yield. The average yield of Napier grass, for example, has been reported to be over 100 dry tons/ha/yr. Research into production and utilization of grasses for energy is still in its early days.

Figure 1.8: Herbaceous crops: napier, switchgrass and miscanthus

1.2.6 Animal Waste

The livestock farms, which grow animals such as cattle, buffalo, pig, goats and poultry (chicken & ducks), sheep, horses, etc, represent an important industry in many countries. These farms produce polluting wastes. Traditionally their disposal has been by direct use as fertilizers or in some instances by land-filling, which cause severe environmental problems. An environmentally acceptable disposal route with potential financial benefits lies in biomass-to-energy schemes which generate energy and often produce fertilizer as a by-product. Animal waste can be decomposed in an anaerobic environment to generate biogas, which contains methane (CH₄) up to about 60%. Methane, which is the main constituent in natural gas, is a superior gaseous fuel. Therefore biogas is an excellent fuel for use in burners, boilers, engines and gas turbines. There is large potential of producing biogas from animal waste due to the large annual manure production.

The dung production from animal depends on factors such as body weight of the animal, type and quality of the feed, physiological state etc. Accessibility of the animal dung is an important factor to take into account, particularly where livestock are range fed, and consequently the dung not easily accessible. When the animals are entirely stall fed, all the
dung is produced in the shed. When animals are free grazed for all part of the day, dung becomes more difficult to collect.

1.2.7 Municipal Solid Waste
MSW is the waste generated by sectors such as residential, commercial, industrial, and institutional. Economic development and urbanization have lead to increase in the quantity and complex composition of MSW in cities of developing countries, leading to serious concerns over the proper waste management for local governments. The majority of substances composing MSW include putrescible/organic matter, glass, paper, plastic, textiles, metal, rubber, etc. In general, the composition and volumes of MSW differs between high and low-income countries. In most of the developing countries it is composed of high organic matter with food and vegetable waste as compared to the developed nations, where more combustible materials such as plastic and paper are contained.

![Figure 1.9: MSW - Organic waste (food/vegetables) and Inorganic materials](image)

The above attributes demand for distinct waste management techniques for MSW in different countries and local regions. Basically, there are four main types of MSW management: landfilling, incineration, composting and anaerobic digestion. Principally, it has been recognized that the most environmental friendly approach to combat the challenges and problems associated with MSW is by the adoption of the integrated waste management: reduction, reuse and recycling, and effective treatment and ultimate disposal in environmentally acceptable strategy. Waste to energy option is thus considered to be one of the most effective ways of final disposal. The feasibility of waste to energy option in a given city in a developing country is greatly influenced by the waste collection, scavenging and waste disposal practices in that city and by the composition of residential wastes.
1.3. CHARACTERISTICS OF BIOMASS

1.3.1 Composition of Biomass

Biomass fuel is the stored solar energy in the form of chemical energy of its constituents, as a result of photosynthetic reaction. The components of biomass include cellulose, hemicelluloses, lignin, lipids, proteins, simple sugars, starches, water, hydrocarbons (HCs), ash, and other compounds. The concentrations of each class of compound vary depending on species, type of plant tissue, stage of growth, and growing conditions. Yet, in general terms, most land biomass is composed primarily of cellulose, hemicelluloses and lignin. Celluloses consist of many sugar molecules linked together in long chains or polymers. The lignin fraction consists of non-sugar type molecules that act as a glue holding together the cellulose fibers, and contributes to structural rigidity of plant tissues. It has very high energy content structure (i.e. hard) and difficult to decompose. These are present in the complex macroscopic polymeric forms as [7]:

\[
\begin{align*}
\text{Cellulose} & : (C_{6}H_{10}O_{5})_{x} \\
\text{Hemicellulose} & : (C_{5}H_{8}O_{4})_{y} \text{ and} \\
\text{Lignin} & : (C_{9}H_{10}O_{3}(CH_{3}O)_{0.9 - 1.7})_{z},
\end{align*}
\]

where \(x\), \(y\) and \(z\) represent parameters of large magnitudes which define the composition of a given biomass material. Woody plants are typically characterized by slow growth and composed of tightly bound fibres, giving a hard external surface, while herbaceous plants are usually perennial, with more loosely bound fibres, indicating a lower proportion of lignin, which binds together the cellulosic fibres: both materials are examples of polysaccharides; long-chain natural polymers. The relative proportions of cellulose and lignin is one of the determining factors in identifying the suitability of plant species for subsequent processing as energy crops. Table 1.2 provides typical compositions of some biomass materials [8], [9].

Table 1.2: Composition of biomass

<table>
<thead>
<tr>
<th>Type of Biomass</th>
<th>Composition (% by weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cellulose</td>
</tr>
<tr>
<td>Hardwood</td>
<td>40 - 55</td>
</tr>
<tr>
<td>Softwood</td>
<td>45 - 50</td>
</tr>
<tr>
<td>Wheat Straw</td>
<td>33 - 40</td>
</tr>
<tr>
<td>Nut Shells</td>
<td>25 - 30</td>
</tr>
<tr>
<td>Grasses</td>
<td>25 - 40</td>
</tr>
</tbody>
</table>
Biomass consists of three basic elements: carbon, oxygen and hydrogen. Nitrogen, sulfur, chlorine, potassium and silica can also be found in quantity, usually less than 1% dry matter but occasionally well above this. Due to the carbohydrate structure, biomass is highly oxygenated with respect to conventional fossil fuels including HC liquids and coals.

### 1.3.2 Properties of Biomass

Many elementary properties of biomass have been determined for a wide range of fuel types. These properties include physical size and shape, elemental composition (ultimate analysis), moisture content, proximate analysis, heating value, bulk density, specific gravity, thermal conductivity, and mechanical, acoustic, and electrical properties.

One of the key differences between biomass and other fuels is the presence of considerable amount of moisture in biomass. The moisture content of woody biomass often regarded as an unavoidable nuisance. It increases the weight (or density) of biomass making transportation more difficult and costly, reduces the amount of net utilization of heat from combustion (heating value) and enhances putrefaction of biomass during storage.

Proximate analysis is the standard test method for evaluating solid fuels, which classifies the raw material in terms of moisture, volatile matter, ash and fixed carbon contents. The moisture content of biomass is the weight loss observed when it is dried under standard conditions. Volatile matter is the weight of biomass lost in the form of vapours and gases when heated in the absence of air under prescribed conditions. Ash is the inorganic residue left after biomass is burnt under standard condition. Fixed carbon content in terms of percentage is estimated by subtracting the total percentage of the other three parameters from 100. Proximate analysis can also be presented on dry basis, i.e. in terms of volatile matter, fixed carbon and ash.

Ultimate analysis of biomass shows its composition in terms of ash and chemical elements such as carbon, hydrogen, nitrogen, sulfur and oxygen. Since biomass materials contain moisture, the amount which varies depending on storage conditions and the absorbed moisture is reflected in the forms of additional hydrogen and oxygen, ultimate analysis is better represented on moisture free basis. Biomass materials have lower carbon, sulfur and nitrogen but higher oxygen and hydrogen content than coal. Carbon, hydrogen and sulfur contribute positively towards the heating value, whereas oxygen and nitrogen tend to lower it.
The standard measure of the energy content of a fuel is its heating value, sometimes called calorific value or heat of combustion. Heating value of biomass depends on its composition. Dry woody biomass consists of cellulose, hemicelluloses, lignin and ash. Its heating value can therefore be estimated from the heating value and weight fraction of each constituent. Table 1.3 provides carbon content and heating value of each component in biomass.

### Table 1.3: Heating values of biomass components

<table>
<thead>
<tr>
<th>Biomass Component</th>
<th>Carbon Content (% by weight)</th>
<th>HHV (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose</td>
<td>40 – 44</td>
<td>17</td>
</tr>
<tr>
<td>Hemi-cellulose</td>
<td>40 – 44</td>
<td>17</td>
</tr>
<tr>
<td>Lignin</td>
<td>63</td>
<td>25</td>
</tr>
<tr>
<td>Ash</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Three different conventions are commonly used in deriving the value of biomass fuels:

- Gross Calorific Value (or Gross Heating Value-GHV or Higher Heating Value-HHV)
- Net Calorific Value (or Net Heating Value-NHV or Lower Heating Value-LHV) and
- Usable Heat Content

Each of these measures is useful to the engineers or scientists when applied in its correct context. Definitions of these quantities are presented in Chapter 2.

Direct combustion is the most commonly used and effective means of deriving useful energy from biomass. Particle size directly affects the rate of combustion and heat content per unit bulk volume of the fuel. As biomass fuels burn principally in the gaseous state, the rate of combustion is proportional to the time it takes for the required heat to reach and ignite volatile constituents, this in turn is dependent on the exposed surface area per unit volume of fuel. Theoretically the minimum particle size should be chosen since the total surface area of a given quantity of fuel is inversely proportional to the square of the average particle diameter. However the size of voids in the fire-bed decreases as the particle size is reduced and a point is reached where individual voids become so small that the resistance to passage of combustion air is unacceptable. Consequently, the volume and velocity of excess air through the furnace must be increased; this results the loss of a considerable amount of heat energy to raise ambient air to exhaust temperature and the high velocity may cause entrainment of light fuel particles in the flue gases.
Biomass resources include a wide variety of materials diverse in both physical and chemical properties. Depending on the application, these variations may be critical for the final performance of the system. In particular, some advanced applications require fairly narrow specifications for moisture, ash content, physical size, etc. Both the physical and chemical characteristics vary significantly within and between the different biomass raw materials. However, biomass feed-stocks are more uniform for some of their properties compared with competing feed-stocks such as coal or petroleum. For example, coals show HHV ranges from 20 to 30 MJ/kg. However, nearly all kinds of biomass feed-stocks destined for combustion fall in the range 16-19 MJ/kg. The values for most woody materials are 18-19 MJ/kg, while for most agricultural residues, the heating values are in the region of 16-18 MJ/kg.

Some typical characteristics of biomass fuels compared to oil and coal are shown in Table 1.4. The volume required to substitute 1 m³ of oil by some other fuels is also given in the table. Typically energy density of biomass fuels is relatively lower and therefore the volume oil equivalent is quite high, which is a main disadvantage of biomass fuels.

Table 1.4: Typical characteristics of biomass fuels compared to oil and coal

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Typical Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MJ/kg</td>
</tr>
<tr>
<td>Fuel oil</td>
<td>41.9</td>
</tr>
<tr>
<td>Coal</td>
<td>25.0</td>
</tr>
<tr>
<td>Pellets 8% moist.</td>
<td>17.5</td>
</tr>
<tr>
<td>Pile wood (stacked, 50%)</td>
<td>9.5</td>
</tr>
<tr>
<td>Industrial softwood chips 50% moist.</td>
<td>9.5</td>
</tr>
<tr>
<td>Industrial softwood chips 20% moist.</td>
<td>15.2</td>
</tr>
<tr>
<td>Forest softwood chips 30% moist.</td>
<td>13.3</td>
</tr>
<tr>
<td>Forest hardwood chips 30% moist.</td>
<td>13.3</td>
</tr>
<tr>
<td>Straw chopped 15% moist.</td>
<td>14.5</td>
</tr>
<tr>
<td>Straw big bales 15% moist.</td>
<td>14.5</td>
</tr>
</tbody>
</table>
1.4. BIOMASS ENERGY TECHNOLOGIES–AN OVERVIEW

1.4.1 Classification of Conversion Technologies

Direct combustion of raw biomass is the simplest method of extracting energy with lowest cost, and therefore is the most common method of conversion. However, such a use emphasizes the worst features of biomass - bulk and inconvenience. Therefore, before bioenergy is used for end-use activities, it may have to be converted from its primary form into a secondary form that is more convenient for transport and use. This may involve simple physical processing before combustion or upgrading to a variety of convenient secondary fuels (in solid, liquid or gas form) by means of certain conversion processes. Figure 1.10 shows the methods of utilizing biomass as a source of energy (adopted from [10]).
Different beneficiation processes are presented in Figure 1.11.

In general, the methods for extracting energy from biomass can be categorized as:

- Direct combustion of the raw biomass,
- Combustion after relatively simple physical processing, which may involve sorting, chipping, compressing and/or air-drying (beneficiation),
- Thermochemical processing to upgrade the biofuel: Processes in this category include pyrolysis (carbonization, destructive distillation & fast pyrolysis), gasification or liquefaction,
- Biological processing: Natural processes such as anaerobic digestion and fermentation encouraged by the provision of suitable conditions leading to a useful secondary fuel (gaseous or liquid).

The first two methods in principle are directly concerned with primary fuels, e.g. the fuels are used as they are found or after some form of processing such as size reduction, drying, compaction (densification) and carbonization, etc.

1.4.2 Direct Combustion

Combustion of biomass has been widely used in the past to generate heat (and electricity). At present, it is making a comeback in many industrial applications. This can range from simple systems such as stoves, furnaces and boilers to more advanced systems like fluidized bed combustion technology. However, straightforward conversion of thermal energy into mechanical or electric power results in considerable losses: it is not possible to raise the ratio
of thermal to mechanical power above 60%. However, if the low temperature waste heat can be used productively, for instance for drying or heating purposes, much higher overall efficiencies can be obtained. The fundamental concepts on combustion of biomass fuels are presented in Chapter 4.

### 1.4.3 Densification

Densification is used to improve characteristics of materials, especially low density biomass, for transport and use as energy source. Through various densification technologies, raw biomass is compressed to densities in the order of 7–10 times its original bulk density. Conventional processes for biomass densification can be classified into baling, pelletization, and briquetting, which are carried out using a bailer, pelletizer, screw press, piston or a roller press. Raw materials used for densification processes include sawdust, loose crop residues, and charcoal fines. The material is compacted under pressure, and depending on the material, the pressure, and the speed of densification, additional binders may be needed to bind the material.

Bales are a traditional method of densification commonly used to harvest crops. A bale is formed using farm machinery (called a baler) that compresses the chop. The shape of the bales can be square, rectangular or round, depending on the type of baler used. Pelletization and briquetting are the most common processes used for biomass densification for solid fuel applications. The two main briquetting technologies are the piston press and the screw press. In the piston press the material is punched into a die by a ram with a high pressure. In the screw press, the material is compacted continuously by a screw. With the screw generally briquettes of higher quality can be produced. The Pelletization is similar to briquetting, except that it uses smaller dies to produce smaller densified products called pellets.

The quality of the densified biomass depends on a number of process variables, like die diameter, die temperature, pressure, usage of binders, and preheating of the biomass mix. The chemical composition of the biomass, which includes compounds like cellulose, hemicelluloses, protein, starch, lignin, crude fiber, fat, and ash, also affect the densification process [11].

In Chapter 3, more details of different processes and technologies of physical processing of waste agricultural biomass are presented.
1.4.4 Thermochemical Conversion

In thermochemical conversion, biomass is subjected to appropriate temperatures and pressures and normally a restricted supply of oxygen. Pyrolysis is the basic thermochemical process to convert biomass into more valuable or more convenient products. In fact, it is the oldest method of processing one fuel in order to produce better one. Conventional pyrolysis involves heating the original material in the near-absence of air, typically at 300 - 500°C, until the volatile matters has been driven off. The residue is then the char (more commonly known as charcoal), a fuel which has about twice the energy density of the original fuel and burns at a much higher temperature. For many centuries, and in much of the world still today, charcoal is produced by pyrolysis of wood. Depending on the moisture content and the efficiency of process, 4 - 10 kg of wood is required to produce 1 kg of charcoal.

With more sophisticated pyrolysis techniques, the volatile matters can be collected, and careful choice of the temperature at which the process takes place allows the control of their composition. The products formed in pyrolysis are normally a gas, an oil-like liquid and charcoal. The distribution of these products is dependent on the feedstock, temperature and pressure of reaction, the time spent in the reaction zone and the heating rate. High temperature pyrolysis (order of 1000°C) maximizes the production of gas (gasification) while lower temperature pyrolysis processes (<600°C) have been used for the production of charcoal (carbonization). Another approach to produce liquid fuels and chemicals from biomass is direct catalytic liquefaction. More details on thermo-chemical conversion processes and technologies applicable for waste agricultural biomass are given in Chapter 4.

1.4.5 Biological Conversion

Biological conversion consists of exposing biomass to certain microorganisms. The secondary fuels produced are the result of metabolic activity of the microorganisms. Production of ethanol through fermentation and biogas through anaerobic digestion are the two most common biological conversion processes. Ethanol fermentation from carbohydrates is probably one of the oldest processes known to man. Today, it is widely regarded as an important potential alternative source of liquid fuels for the transport sector.

In case of biogas generation, the highest degree of market maturity can be found in the area of municipal sludge treatment, industrial wastewater purification and treatment of agricultural
wastes, especially animal waste. The use of the technology in municipal wastewater treatment is currently experiencing an upswing in Asia. Agricultural biogas plants in developing countries are usually promoted on a large scale in connection with energy and environmental issues, and are installed particularly where water pollution through liquid manure from agriculture is most severe. Details on process technologies relevant to biological conversion of waste agricultural biomass materials are presented in Chapter 5.

### 1.4.6 Biofuels

The term biofuels generally refers to liquid biomass made from biological sources, which include pure plant oil (PPO), bioethanol and biodiesel. The raw oil can be obtained from a variety of annual and perennial plant species. Annuals include sunflower, groundnut, soybean and rapeseed, while perennials include oil palms, coconut palms, physica nut and Chinese tallow tree. Many of these plants can produce high yields of oil, with positive energy and carbon balances. Use of raw oil for energy generation could cause problems through incomplete combustion, resulting in the buildup of sooty residues, waxes, gums etc. Also, incorrect viscosities can result in poor atomization of the oil also resulting in poor combustion. Oil polymerization can lead to deposition on the cylinder walls [12]. Therefore, raw oils must first be treated to improve their fuel characteristics and transformed to resemble petroleum-based fuels more closely. Bioethanol and biodiesel have been emerged as biofuels in the above context. Global production of biofuels consists primarily of ethanol. Biodiesel comes second. Figure 1.12 presents the global production of ethanol and biodiesel from year 2000 to 2011 [13].

![Figure 1.12: Global biofuel production from year 2000 to 2011](image-url)
Production and uses of biofuels are presented in Table 1.5 [14].

Table 1.5: Production and uses of liquid biofuels

<table>
<thead>
<tr>
<th>Biofuel Type</th>
<th>Specific Names</th>
<th>Biomass Feedstock</th>
<th>Production Process</th>
<th>Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>First Generation (Conventional) Biofuels</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vegetable/Plant Oil</td>
<td>Straight Vegetable Oil (SVO); Pure Plant Oil (PPO)</td>
<td>Oil crops (e.g. Rapeseed, Corn, Sunflower, Soybean, Jatropha, Jojoba, Coconut, etc.)</td>
<td>Cold pressing/ extraction</td>
<td>Diesel engines, generators, pumping (all after modifications); Use for cooking and lighting, as possible; Transportation</td>
</tr>
<tr>
<td>Biodiesel</td>
<td>Cold pressing/ extraction &amp; trans-esterification</td>
<td>Cotton, Palm, etc.) Algae</td>
<td></td>
<td>Diesel engines for power generation, mechanical applications, pumping; Transportation (diesel engines)</td>
</tr>
<tr>
<td>Bioethanol</td>
<td>Conventional bioethanol</td>
<td>Sugarcane, Sweet sorghum, Sugar beet, Cassava Grains</td>
<td>Hydrolysis &amp; fermentation</td>
<td>Internal combustion engine for motorized transport</td>
</tr>
<tr>
<td>Bio-ETBE</td>
<td>Ethyl Tertiary; Butyl; Ether</td>
<td>Bioethanol</td>
<td>Chemical synthesis</td>
<td></td>
</tr>
<tr>
<td><strong>Second Generation Biofuels</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biodiesel</td>
<td>Hydro-treated biodiesel</td>
<td>Vegetable oils and animal fat</td>
<td>Hydro-treatment</td>
<td></td>
</tr>
<tr>
<td>Bioethanol</td>
<td>Cellulosic bioethanol</td>
<td>Lignocellulosic material</td>
<td>Advanced hydrolysis &amp; fermentation</td>
<td></td>
</tr>
<tr>
<td>Synthetic biofuels</td>
<td>Biomass-to-liquids (BTL): Fischer-Tropsch (FT) diesel; Biomethanol Biodimethyl-ether (Bio-DME)</td>
<td>Lignocellulosic material</td>
<td>Gasification &amp; synthesis</td>
<td>Internal combustion engine for motorized transport</td>
</tr>
<tr>
<td>Bio-hydrogen</td>
<td>Lignocellulosic material</td>
<td></td>
<td>Gasification &amp; synthesis or bio1.</td>
<td></td>
</tr>
</tbody>
</table>
Biodiesel can be used in pure form or may be blended with petroleum diesel at any concentration for use in most modern diesel engines. Biodiesel can be produced from a variety of feedstock, such as oil feedstock (rapeseed, soybean oils, jatropha, palm oil, hemp, algae, canola, flax and mustard), animal fats, and/or waste vegetable oil. The largest single use of ethanol is as a fuel for transportation or as a fuel additive. It can be produced from a variety of feedstocks such as sugar cane, corn, and sugar beet. It can also be produced from cassava, sweet sorghum, sunflower, potatoes, hemp or cotton seeds, or be derived from cellulose waste [14].

The last few years has seen tremendous growth in biofuels. During this period, the industry has evolved from first generation feedstocks and processes to their second and third generation counterparts (see Figure 1.13).

![Figure 1.13: First, second and third generation biofuels](image)

It is increasingly understood that 1st generation biofuels, which are primarily produced from crops such as grains, sugar beet and oil seed, are limited in their ability to achieve targets for fossil oil product substitution, climate change mitigation and economic growth. Their sustainable production is under review, as is the possibility of creating undue competition for land and water used for food and fibre production (see Table 1.6). The 2nd and 3rd generation biofuels have the potential to avoid many of the concerns associated with 1st generation ones. The terms first, second and third generation can be used in the contexts of both feedstocks and processes. For instance, corn and maize represent first generation ethanol feedstocks, and fermentation represents first generation ethanol production process. Similarly, Switchgrass is
one of the popular second generation ethanol feedstocks, while the production of cellulosic ethanol represents the second generation process for ethanol.

### Table 1.6: First vs second generation biofuels

<table>
<thead>
<tr>
<th>Parameters</th>
<th>1st Gen.</th>
<th>2nd Gen.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct food vs. fuel competition</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Feedstock cost per unit of production</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Land-use efficiency</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Feasibility of using marginal lands for feedstock production</td>
<td>Poor</td>
<td>Good</td>
</tr>
<tr>
<td>Ability to optimize feedstock choice for local conditions</td>
<td>Limited</td>
<td>High</td>
</tr>
<tr>
<td>Potential for net reduction in fossil fuel use</td>
<td>Medium</td>
<td>Medium-High</td>
</tr>
<tr>
<td>Potential for net reduction in greenhouse gas emissions</td>
<td>Medium</td>
<td>Medium-High</td>
</tr>
<tr>
<td>Readiness for use in existing petroleum infrastructure</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Proven commercial technology available today</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Simplicity of processes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Capital costs per unit of production</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Total cost of production</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Minimum scale for economical production</td>
<td>Medium</td>
<td>High</td>
</tr>
</tbody>
</table>

Algae are considered to belong to the third generation of biodiesel feedstock. Third generation biofuel feedstock are considered ideal in that they even overcome the challenges faced by the second generation biofuels. These feedstock offer superior yields when compared to second generation feedstock and at the same time do not have adverse effects on the human food chain, which first generation feedstock typically have. In addition, third generation crops such as algae can be grown in places that are not suitable for agriculture, thus providing superior ecological performances as well. In addition to feedstock such as algae, third generation biofuels could also refer to processes such as biomass to liquid, as well as other unique processes such as bacterial biodiesel.

### 1.4.7 Emissions from Biomass Energy Systems

- Emission Characteristics

The emergence of renewable energy resources is primarily stirred by the global climate change associated with excessively high emissions of greenhouse gases, especially $\text{CO}_2$
generated by combustion of fossil fuels. In general, renewable energy technologies have much lower carbon emissions per unit energy output than that of fossil fuel-based technologies (see Table 1.7).

<table>
<thead>
<tr>
<th>Technology</th>
<th>CO₂ Emissions (Tonnes per GWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fuel Extraction</td>
</tr>
<tr>
<td>Coal-fired</td>
<td>1</td>
</tr>
<tr>
<td>AFBC*</td>
<td>1</td>
</tr>
<tr>
<td>IGCC**</td>
<td>1</td>
</tr>
<tr>
<td>Oil-fired</td>
<td>-</td>
</tr>
<tr>
<td>Gas-fired</td>
<td>-</td>
</tr>
<tr>
<td>Geothermal</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Small hydro</td>
<td>N/A</td>
</tr>
<tr>
<td>Nuclear</td>
<td>~2</td>
</tr>
<tr>
<td>Wind</td>
<td>N/A</td>
</tr>
<tr>
<td>Photovoltaic</td>
<td>N/A</td>
</tr>
<tr>
<td>Large hydro</td>
<td>N/A</td>
</tr>
<tr>
<td>Solar thermal</td>
<td>N/A</td>
</tr>
<tr>
<td>Wood</td>
<td>-1509</td>
</tr>
</tbody>
</table>

* AFBC: Atmospheric fluidized bed combustion
** IGCC: Integrated gasification combine cycle

Biomass, when produced sustainably, emits roughly the same amount of carbon during conversion as is taken up during plant growth, thus becomes carbon neutral (short carbon cycle). However, plantation of species for biomass production for energy application may have variety of adverse effects on environment and biodiversity. For instance, sustained production on the same surface of land can have negative impacts on soil fertility, water use, agrochemical use, biodiversity, and landscape, unless proper mitigation planning is made. In the case of large-scale energy farming, not much is known about the effects on landscapes and biodiversity. Basically, energy crop plantations have to fit into the landscape both ecologically and aesthetically. In addition to minimizing the environmental impact, attention
should be paid to fitting biomass production into existing agricultural systems. Such concerns
do not have much relevance to the use of waste agricultural biomass for energy application,
since such interventions will have much improved environment performance than that of
traditional waste management practices.

Although sustainable biomass resources are considered to be carbon neutral, their conversion
to energy (through the processes such as direct combustion, gasification, incineration and
pyrolysis) leads to emission of various air pollutants that contribute to ambient air quality
degradation (both indoor and outdoor) that has serious concerns over health, unless
appropriate pollution control technologies are incorporated. Furthermore, the collection and
transport of biomass increases the use of vehicles and infrastructure and the emissions to the
atmosphere. Emissions from biomass combustion can generally be divided into emissions
that are mainly influenced by combustion technology and process conditions, and emissions
that are mainly influenced by fuel properties. The amount of pollutants emitted to the
atmosphere from various types of biomass combustion appliances is highly dependent on the
combustion technology implemented. When available, such data generally refer to a single
fuel-technology combination. In order to obtain an objective view of emission levels from
various combustion applications, it is necessary to collect emission data from a wide range of
fuel-technology combinations.

Emissions that are mainly influenced by combustion technology and process conditions
include particulate matter (PM$_{10}$, PM$_{2.5}$), Carbon monoxide (CO), volatile organic
compounds (VOC), Polycyclic aromatic hydrocarbon (PAH). Emissions that are mainly
influenced by fuel properties include nitrogen oxides (NO$_X$), Hydrogen chloride (HCl),
particulate matter (PM$_{10}$, PM$_{2.5}$), heavy metals such as Pb, Zn, Cd, Cu and small quantity of
sulfur oxides (SO$_X$). Another notable pollutant is dioxins (i.e. Polychlorinated dibenzo-p-
dioxin and polychlorinated dibenzofuran - PCDD/F), the largest sources of which is waste
incineration. Any air pollution control strategy should take into consideration of the
properties of the fuel including the moisture, ash, chlorine, sulfur contents as well as the
physical characteristics. As most of the biomass materials are not as homogeneous or as
predictable as fossil fuels, and may vary, perhaps due to poor quality control by the fuel
supplier, changes in fuel availability or swapping of fuel sources in response to price
variations. Such changes can have an impact on burner operation and the pollution control
equipment and may lead to increased emissions. Consequently, the achievement of very low
emission levels requires ongoing and high levels of operational monitoring and control as well as ensuring that the fuel properties (sizing, moisture, ash and contaminant contents) are restricted to the combustion and pollution control process.

Different combustion technologies can result in very different particulate matter emission profiles (before flue gas treatment), with gasifiers currently producing the lowest uncontrolled emissions, for example, < 70 mg/m³ compared to levels of 300 to > 540 mg/m³ for direct combustion systems. Biomass contains much less sulfur and nitrogen than coal. For non-wood waste agricultural biomass fuels, sulfur content may also be important [15].

- Emission Control

Control of emission of pollutants in energy conversion systems can be obtained by either avoiding creation of such substances (primary measures) or removing the substances from the flue gas (secondary measures). Primary emission reduction measures aim at preventing or reducing formation of emissions and/or reduction of emissions within the combustion chamber. Several control measures have been developed, which could be categorized as under the following types (which often are interrelated in practice):

- modification of the moisture content of the fuel,
- modification of the particle size of the fuel,
- selection of the type of combustion equipment,
- combustion process control optimization,
- staged-air combustion,
- staged fuel combustion and re-burning.

Secondary measures are applied to remove emissions from the products of energy conversion process (e.g. combustion) once they leave the device. Among the pollutants listed above, emission control of PM particularly becomes important for waste agricultural biomass. Several types of PM control technologies are available, notably the following:

- settling chambers,
- cyclones,
- multi-cyclones,
- electrostatic filters,
- bag filters,
- scrubbers,
- rotating particle separator.

It should be noted that every particle control technology is not appropriate for every application. Among the determining factors are the particle's size, required collection efficiency, gas flow rate, allowed time between cleanings, the detailed nature of the particles, and the presence of tars in the flue gas [16].

NO\textsubscript{X} emissions control by The secondary emission reduction measures involve chemical treatment of the flue gas after the combustion chamber aimed at converting NO\textsubscript{X} to N\textsubscript{2}. These measures applicable to biomass combustion applications are mainly categorized as Selective Catalytic Reduction (SCR) and Selective Non-Catalytic Reduction (SNCR) methods. Both utilize injection of a reducing agent, mainly ammonia or urea, to reduce NO\textsubscript{X} to N\textsubscript{2}, with or without a catalyst, respectively. For the removal of SO\textsubscript{X} (mainly SO\textsubscript{2}) wet, dry and wet-dry throwaway processes have been developed. SO\textsubscript{X} emission levels from wood combustion are usually not significant. HCl emission levels are reduced in wet throwaway processes applied for SO\textsubscript{X} reduction. Furthermore, adsorptives such as activated lignite can be used for a combined extraction of HCl, SO\textsubscript{2}, and dioxins. Emission levels of dioxins can be reduced by an efficient particle separation at temperatures well below the temperature range of the de novo synthesis. Emissions of heavy metals can be significantly reduced in particle-collecting devices such as bag filters or electrostatic filters.

Maximum emission limits allowed for biomass combustion plants vary significantly from country to country, and are expressed in various units. The common unit used for emission concentrations is mg/Nm\textsuperscript{3}, in which the notation N means Normal, which implies that the volume is measured at the normal temperature and pressure conditions. In practical measurement of emission concentrations in flue gases, in addition to the temperature and pressure, excess air and moisture content become important parameters to be considered. Therefore, it is a common practice to define the reference levels of these two parameters.

- **Impacts of Emissions from Biomass Energy Conversion**

Impacts of air pollutants generated in energy conversion systems are generally classified under three sectors: Climate, Environment and Health. Potential impacts of major pollutants associated with biomass energy conversion systems are presented in Table 1.8.
### Table 1.8: Impacts of emissions from biomass combustion

<table>
<thead>
<tr>
<th>Component</th>
<th>Biomass Sources</th>
<th>Climate, environmental and health impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide (CO₂)</td>
<td>Major combustion product from all biomass fuels</td>
<td><strong>Climate:</strong> Direct GHG. However, biomass is a CO₂-neutral fuel</td>
</tr>
<tr>
<td>Carbon monoxide (CO)</td>
<td>Incomplete combustion of all biomass fuels</td>
<td><strong>Climate:</strong> Indirect GHG through ozone formation.</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Health:</strong> Reduced oxygen uptake especially influences people with asthma, and embryos. Suffocation in extreme cases.</td>
</tr>
<tr>
<td>Methane (CH₄)</td>
<td>Incomplete combustion of all biomass fuels</td>
<td><strong>Climate:</strong> Direct GHG. Indirect GHG through ozone formation.</td>
</tr>
<tr>
<td>Non Methane Volatile Organic Components (NMVOC)</td>
<td>Incomplete combustion of all biomass fuels</td>
<td><strong>Climate:</strong> Indirect GHG through ozone formation.</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Health:</strong> Negative effect on human respiratory system.</td>
</tr>
<tr>
<td>Polycyclic Aromatic Hydrocarbons (PAH)</td>
<td>Incomplete combustion of all biomass fuels</td>
<td><strong>Environment:</strong> Smog formation</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Health:</strong> Carcinogenic effects</td>
</tr>
<tr>
<td>Particles</td>
<td>Soot, char and condensed heavy hydrocarbons (tar) from incomplete combustion of all biomass fuels. Fly ash and salts</td>
<td><strong>Climate and environment:</strong> Reversed greenhouse effect through aerosol formation. Indirect effects of heavy-metal concentrations in deposited particles. <strong>Health:</strong> Negative effect on the human respiratory system. Carcinogenic effects</td>
</tr>
<tr>
<td>Nitric oxides (NOₓ = NO and NO₂)</td>
<td>Minor combustion product from all biomass fuels containing nitrogen. Additional NOₓ may be formed from nitrogen in the air under certain conditions</td>
<td><strong>Climate and environment:</strong> Indirect greenhouse effect through ozone formation. Reversed greenhouse effect through aerosol formation. Acid precipitation. Vegetation damage. Smog formation. Corrosion and material damage. <strong>Health:</strong> Negative effect on the human respiratory system.</td>
</tr>
<tr>
<td>Nitrous oxide (N₂O)</td>
<td>Minor combustion product from all biomass fuels containing nitrogen</td>
<td><strong>Climate:</strong> Direct GHG.</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Health:</strong> Indirect effect through ozone depletion in the stratosphere</td>
</tr>
<tr>
<td>Ammonia (NH₃)</td>
<td>Small amounts may be emitted as a result of incomplete conversion of NH₃ from pyrolysis/gasification</td>
<td><strong>Environment:</strong> Acid precipitation. Vegetation damage. Corrosion and material damage. <strong>Health:</strong> Negative effect on the human respiratory system.</td>
</tr>
<tr>
<td>Sulphur oxides (SOₓ = SO₂ and SO₃)</td>
<td>Minor combustion product from all biomass fuels containing sulphur.</td>
<td><strong>Climate and environment:</strong> Reversed greenhouse effect through aerosol formation. Acid precipitation. Vegetation damage. Smog formation. Corrosion and material damage. <strong>Health:</strong> Negative effect on the human respiratory system, asthmatic effect</td>
</tr>
<tr>
<td>Component</td>
<td>Biomass sources</td>
<td>Climate, environmental and health impact</td>
</tr>
<tr>
<td>-------------------</td>
<td>---------------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Heavy metals</td>
<td>All biomass fuels contain heavy metals to some degree, which will remain in the ash or evaporate</td>
<td><strong>Health</strong>: Accumulate in the food chain. Some are toxic and some have carcinogenic effects</td>
</tr>
<tr>
<td>Ground level ozone (O₃)</td>
<td>Secondary combustion product from atmospheric reactions, including CO, CH₄, NMVOC and NOₓ</td>
<td><strong>Climate and environment</strong>: Direct GHG. Vegetation damage. Smog formation. Material damage. <strong>Health</strong>: Indirect effect through ozone depletion in the stratosphere. Negative effect on the human respiratory system, asthmatic effect</td>
</tr>
<tr>
<td>Hydrogen Chloride (HCl)</td>
<td>Minor combustion product from all biomass fuels containing chlorine</td>
<td><strong>Environment</strong>: Acid precipitation. Vegetation damage. Corrosion and material damage. <strong>Health</strong>: Negative effect on the human respiratory system. Toxic</td>
</tr>
<tr>
<td>Dioxins and Furans PCDD/PCDF</td>
<td>Small amounts may be emitted as a result of reactions including carbon, chlorine, and oxygen in the presence of catalysts (Cu)</td>
<td><strong>Health</strong>: Highly toxic. Liver damage. Central nervous system damage. Reduced immunity defense. Accumulate in the food chain</td>
</tr>
</tbody>
</table>

### 1.4.8 Choice of Technology

The choice of the biomass energy conversion technology depends on the type of biomass resource (such as plant species, residues, wastes, etc.) and intended end-use application of interest. Some biomass material are amenable to nearly all of the potential conversion technologies: e.g. oil seed rape can be processed via combustion, gasification, pyrolysis or mechanical extraction, while others such as wood and cereal crops, are suitable for combustion, gasification, pyrolysis and fermentation. It is important to note that, while particular biomass material may have specific benefits for subsequent processing technologies, the amount of energy potentially available from a given biomass source is the same, irrespective of the conversion technology used. What will vary between conversion technologies is the actual amount of energy recovered from the biomass source and the form of that energy.

The selection of a conversion technology for a practical energy application is usually governed by the comprehensiveness of the information available on its performance characteristics under different conditions so that the risk of failure could be minimized. Some
advance technologies are deemed to have very promising energy and environment performances, yet lack of proven performance characteristics in the field make them less attractive for project developers. Therefore, it is important to recognize the level of use of the different conversion technologies described above. One such classification employs three levels given by Research, Pilot Demonstration and Commercial, as shown in Figure 1.14 (adopted from [17]).

Since there would be differences with regards to the socio-economic benefits and environment impacts depending on the technology selected for a given resource and specific energy application, and therefore a sound methodology has to be adopted in selecting the optimum the biomass resource-technology-application combinations. One such methodology is the Sustainable Assessment of Technology (SAT), which is fundamentally the integration of sustainable development in technology assessment, i.e. integration of three important aspects: environmental soundness, social/cultural acceptability and economic feasibility.

The need for promotion of Environmentally Sound Technologies (ESTs) in the context of sustainability was recognized in the early 1990s. In particular, at the United Nations Conference on Environment and Development (UNCED) in 1992, the need to promote ESTs was highlighted in Agenda 21. Chapter 34 of Agenda 21 defines ESTs as those technologies that protect the environment, are less polluting, use all resources in a more sustainable manner, recycle more of their waste and products and handle residual waste in a more sustainable manner than the technologies for which they are substitutes. ESTs include a variety of cleaner production process and pollution prevention technologies, as well as end-
of-pipe and monitoring technologies. Apart from just technologies, they can be considered as total ‘systems’ that may include knowledge and skills transfer, operating procedures, goods, services and equipment, and also organizational and managerial procedures [18]. Many initiatives have been developed in relation to promotion of ESTs in developing countries and countries with economies in transition.

SAT methodology uses a progressive assessment procedure through tiers on screening, scoping and detailed assessment allowing entry points for diverse stakeholders and optimizing information requirements. Another important characteristic of this methodology is that it operates both strategic and operational levels, addressing thereby choices to be made on a more robust basis. It is also a quantitative procedure that allows more objective assessment, sensitivity analyses and incorporation of scenarios. The SAT Methodology comprised of a number of basic steps that follow typical Plan-Do-Check-Act cycle of continuous improvement, as illustrated in Figure 1.15 [18].

![Figure 1.15: Basic structure of SAT methodology](image-url)
CHAPTER 02: WASTE AGRICULTURAL BIOMASS

2.1. INTRODUCTION
The term waste agricultural biomass refers to describe all the organic materials which are produced as the by-products from agriculture activities such as leaves, straws, husks, hulls, shells and animal wastes. Huge amount of biomass is generated as by-products of agricultural (and wood) harvesting and processing activities every year particularly in developing countries, where in many cases agriculture continues to be the main economic activity. As per the UNEP [19], annual production of waste is 5 billion metric tons and this is equivalent to approximately 1.2 billion tons of oil. But in many situations these are considered to be waste materials and their proper management becomes a critical task. Use of these agricultural residues as a fuel is considered to be carbon neutral (as with other biomass resources) because plants and trees remove carbon dioxide from the atmosphere and store it while they grow. Thus, burning agricultural residues returns this sequestered carbon dioxide into atmosphere. The use of agricultural residues as a source of energy can offer developing countries the twin benefits of properly managing their waste as well generating renewable energy.

Agricultural residues are divided into three types namely; field based residues, process based residues and animal waste. Agricultural residues, generated on the farm or field, are defined as field based residues (e.g. paddy straw, sugar cane tops, cocoa pods, tobacco stalks, soybean straw/pods, maize stalks, etc.). Whereas those generated during processing are called processing based residues (e.g. paddy husk, bagasse, maize cob/husk, coffee husk, etc.). Animal wastes basically come from livestock, poultry, and dairy production. It can be manure from farm animals, or the byproducts of meat processing, byproduct from inland fish farm etc. This classification is often necessary in the assessment of potential as an energy source.

Availability of field based residues for energy application is usually assumed to be negligible since collection for utilization is difficult and there are other uses such as for fertilizing and animal feed. However, the situation with regard to field-based residues such as straws could change if suitable equipment / mechanisms for the collection and baling of straw are utilized. Processed based residues are usually available in relatively high concentration and may be used as an energy source for the same industry making no or little transportation and handling
Process-based residues would appear to have a greater potential, since they are produced at a central site and their accumulation represents a disposal problem with an environmental cost. However, some agro-processing residues have a potential for making high-value products, for example, use of coir dust / coconut husk briquettes as a soil conditioner. Farmers frequently use animal waste as fertilizer and apply it to the soil. If too much animal waste is applied, or if it is applied incorrectly, it can pollute lakes and streams, contaminate ground water, and harm human health. Animal waste can be decomposed into its constituents either in an anaerobic environment or aerobic environment. Under anaerobic conditions, biogas (CH₄, CO₂) and stabilized organic materials are produced. Under aerobic conditions, CO₂ and stabilized organic materials are produced. There is large potential of producing methane from animal waste due to the large annual manure production.

2.2. CHARACTERIZATION OF WASTE AGRICULTURAL BIOMASS FOR ENERGY APPLICATIONS

2.2.1 Basis
In the context of energy applications, biomass materials could be characterized under a wide variety of aspects including physical, thermo-chemical properties and behaviours. Availability of such information is an essential requirement for the selection of a conversion technology, system design and estimation of operational performance in relation to technical, environmental, social and financial aspects. However, all the properties may not become important or significant for a particular material-technology-resource combination. For instance, heating value of each material component of MSW is required for the design of incineration-based waste to energy system. However, for energy recovery from land-filling, the heating values of the raw materials have no use in the system design. Availability of required characteristics of biomass materials becomes desirable not only for system design and sizing, but also for evaluation of the performances in terms of technical, environmental, social and financial aspects. Moreover, generation potential of biomass materials and its availability for energy (both qualitatively and quantitatively) too would become decisive factors in developing a biomass energy projects/systems.

This section is devoted to detail the key properties and characteristics, which are relevant to waste agricultural biomass for energy applications.
2.2.2 Composition of Waste Agricultural Biomass

The chemical composition of waste agricultural biomass varies among different types. Yet, as highlighted in Section 1.3.1, most land biomass is composed primarily of cellulose, hemicelluloses and lignin. Table 2.1 provides typical compositions of several waste agricultural biomass materials [20], [21], [22]. Note that there could be significant variations of these values for the same type of material, which depend on many factors including the variety, agro-climatic zone, cultivation practice, etc.

Table 2.1: Composition of dry waste agricultural biomass materials

<table>
<thead>
<tr>
<th>Type of Biomass</th>
<th>Composition (% by weight)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Cellulose</td>
<td>Hemi-cellulose</td>
</tr>
<tr>
<td>Bagasse</td>
<td></td>
<td>41.3</td>
<td>22.6</td>
</tr>
<tr>
<td>Coconut coir</td>
<td></td>
<td>47.7</td>
<td>25.9</td>
</tr>
<tr>
<td>Coconut shell</td>
<td></td>
<td>36.3</td>
<td>25.1</td>
</tr>
<tr>
<td>Coir pith</td>
<td></td>
<td>28.6</td>
<td>15.3</td>
</tr>
<tr>
<td>Corn cob</td>
<td></td>
<td>40.3</td>
<td>28.7</td>
</tr>
<tr>
<td>Corn stalks</td>
<td></td>
<td>42.7</td>
<td>23.6</td>
</tr>
<tr>
<td>Groundnut shell</td>
<td></td>
<td>35.7</td>
<td>18.7</td>
</tr>
<tr>
<td>Paddy husk</td>
<td></td>
<td>31.3</td>
<td>24.3</td>
</tr>
<tr>
<td>Paddy straw</td>
<td></td>
<td>37.0</td>
<td>22.7</td>
</tr>
<tr>
<td>Wheat straw</td>
<td></td>
<td>30.5</td>
<td>28.9</td>
</tr>
<tr>
<td>Switchgrass</td>
<td></td>
<td>32.5</td>
<td>26.5</td>
</tr>
<tr>
<td>Miscanthus</td>
<td></td>
<td>44</td>
<td>24</td>
</tr>
<tr>
<td>Giant Reed</td>
<td></td>
<td>31</td>
<td>30</td>
</tr>
<tr>
<td>Sweet sorghum</td>
<td></td>
<td>27</td>
<td>25</td>
</tr>
<tr>
<td>Bamboo</td>
<td></td>
<td>45</td>
<td>26</td>
</tr>
<tr>
<td>Water Hyacinth</td>
<td></td>
<td>16.2</td>
<td>55.5</td>
</tr>
<tr>
<td>Bermuda Grass</td>
<td></td>
<td>31.7</td>
<td>40.2</td>
</tr>
<tr>
<td>RDF (waste)</td>
<td></td>
<td>65.6</td>
<td>11.2</td>
</tr>
<tr>
<td>Polar Wood</td>
<td></td>
<td>41.3</td>
<td>29.4</td>
</tr>
<tr>
<td>Pine Wood</td>
<td></td>
<td>40.4</td>
<td>24.9</td>
</tr>
</tbody>
</table>
2.2.3 Moisture Content

There are two ways of reporting moisture content of biomass materials: moisture content on wet basis ($MC_{wb}$) and moisture content on dry basis ($MC_{db}$). $MC_{wb}$ is the amount of moisture in the biomass expressed as a percentage of total weight of the wet biomass. $MC_{db}$ is the amount of moisture expressed as a percentage of weight of the moisture free biomass. A simple relationship between the two representations could be derived as

$$MC_{db} = \frac{MC_{wb}}{1 - MC_{wb}}.$$  

The same relationship is presented graphically in Figure 2.1. Note that, though at lower moisture contents the two quantities are quite the same, there is a considerable variation of the two values in general. For instance, when $MC_{wb} = 0.10$, $MC_{db} = 0.11$, and whereas when $MC_{wb} = 0.5$, $MC_{db} = 1.0$.

![Figure 2.1: Relationship between $MC_{db}$ and $MC_{wb}$.

Table 2.2 shows possible ranges in moisture content for selected biomass resources [23].
Table 2.2: Moisture content of selected biomass resources on wet basis

<table>
<thead>
<tr>
<th>Biomass resource</th>
<th>$MC_{wb}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial fresh wood chips and sawdust</td>
<td>40 - 60</td>
</tr>
<tr>
<td>Industrial dry wood chips and sawdust</td>
<td>10 - 20</td>
</tr>
<tr>
<td>Fresh forest wood chips</td>
<td>40 - 60</td>
</tr>
<tr>
<td>Waste wood</td>
<td>10 - 30</td>
</tr>
<tr>
<td>Chips from wood stored and air-dried several months</td>
<td>30 - 40</td>
</tr>
<tr>
<td>Wood pellets</td>
<td>8 – 12</td>
</tr>
<tr>
<td>Paddy husk</td>
<td>8.5 – 12.5</td>
</tr>
<tr>
<td>Dry paddy straw</td>
<td>12 - 15</td>
</tr>
<tr>
<td>Cotton stalks</td>
<td>10-20</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>30-70</td>
</tr>
<tr>
<td>Sweet Sorghum</td>
<td>20 - 70</td>
</tr>
<tr>
<td>Sugar cane bagasse</td>
<td>40 – 60</td>
</tr>
<tr>
<td>Sugar cane barbojo</td>
<td>40 - 50</td>
</tr>
<tr>
<td>Rubber seeds</td>
<td>12.4</td>
</tr>
<tr>
<td>Coconut Husks</td>
<td>10.3</td>
</tr>
<tr>
<td>Coconut Shells</td>
<td>8.7</td>
</tr>
<tr>
<td>Rubber seeds</td>
<td>12.4</td>
</tr>
<tr>
<td>Maize cob</td>
<td>7.5</td>
</tr>
<tr>
<td>Maize stalks</td>
<td>20</td>
</tr>
</tbody>
</table>

2.2.4 Proximate Analysis

Proximate analysis, which classifies the raw material in terms of moisture, volatile matter, ash and fixed carbon contents, for several waste agricultural biomass materials is presented in Table 2.3 [20]. Proximate analysis indicates the percentage of fuel burned in the gaseous and solid states, and also shows the quantity of non-combustible ash remaining on the fire grates or ash pit, or entrained with flue gases. Such information provides the furnace designer with important information for the sizing and location of primary and secondary air supplies, refractory equipment, ash removal and exhaust handling equipment. The proximate analysis given in Table 2.3 indicates that the main contribution to the total calorific content of the biomass fuel is from the volatile constituents. This shows the importance of efficiency in
burning the volatile constituents and in extracting heat from the flames, as the volatile constituents are usually burned as flames.

**Table 2.3: Proximate analysis of selected fuels (dry basis)**

<table>
<thead>
<tr>
<th>Biomass Fuel</th>
<th>Volatile Matter (% dry ash free basis)</th>
<th>Fixed Carbon (% dry ash free basis)</th>
<th>Ash (% dry basis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bagasse</td>
<td>84.2</td>
<td>15.8</td>
<td>2.9</td>
</tr>
<tr>
<td>Coconut coir</td>
<td>82.8</td>
<td>17.2</td>
<td>0.9</td>
</tr>
<tr>
<td>Coconut shell</td>
<td>80.2</td>
<td>19.8</td>
<td>0.7</td>
</tr>
<tr>
<td>Coir pith</td>
<td>73.3</td>
<td>26.7</td>
<td>7.1</td>
</tr>
<tr>
<td>Corn cob</td>
<td>85.4</td>
<td>14.6</td>
<td>2.8</td>
</tr>
<tr>
<td>Corn stalks</td>
<td>80.1</td>
<td>19.9</td>
<td>6.8</td>
</tr>
<tr>
<td>Groundnut shell</td>
<td>83.0</td>
<td>17</td>
<td>5.9</td>
</tr>
<tr>
<td>Paddy Husk</td>
<td>81.6</td>
<td>18.4</td>
<td>23.5</td>
</tr>
<tr>
<td>Paddy Straw</td>
<td>80.2</td>
<td>19.8</td>
<td>19.8</td>
</tr>
<tr>
<td>Wheat Straw</td>
<td>83.9</td>
<td>16.1</td>
<td>11.2</td>
</tr>
<tr>
<td>Peanut Shell</td>
<td>78.4</td>
<td>21.6</td>
<td>7.2</td>
</tr>
<tr>
<td>Cotton Stalk</td>
<td>80.0</td>
<td>20.0</td>
<td>5.3</td>
</tr>
<tr>
<td>Wood</td>
<td>77 - 87</td>
<td>13 - 21</td>
<td>0.1 - 2.0</td>
</tr>
<tr>
<td>Lignite</td>
<td>48.0</td>
<td>52.0</td>
<td>10.4</td>
</tr>
<tr>
<td>Anthracite Coal</td>
<td>5.9</td>
<td>94.1</td>
<td>15.0</td>
</tr>
</tbody>
</table>

As an example let wood fuel consists of 77% volatile and 20% fixed carbon (dry basis). If the calorific value of fuel wood and carbon are taken as 18.5 MJ/kg and 32 MJ/kg, respectively, contribution to the calorific content from fixed carbon and volatile constituents become \(0.2 \times 32 = 6.4\) MJ/kg and \(18.5 - 6.4 = 12.1\) MJ/kg, for which the percentage contributions are 35% and 65%, respectively.

### 2.2.5 Ultimate Analysis

Table 2.4 shows the ultimate analysis of some selected biomass materials [9], [20]. The ultimate analysis is useful in calculating the quantity of oxygen (and thus combustion air) required to sustain the combustion reactions. It also permits the estimation of the amount of water formed by burning hydrogen in the fuel. During the combustion heat is absorbed to vapourise and exhaust this moisture in addition to the inherent fuel moisture. Consequently
the recoverable heat energy of the fuel is reduced. As biomass fuels have very low sulfur and nitrogen, they produce minimal SO\textsubscript{x} and NO\textsubscript{x} pollutants, but particulate emissions of unburned carbon in the flue gases can present pollution control problems.

Table 2.4: Ultimate analysis of selected fuels (dry basis)

<table>
<thead>
<tr>
<th>Biomass Fuel</th>
<th>C</th>
<th>H</th>
<th>O</th>
<th>N</th>
<th>S</th>
<th>Ash</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paddy Straw</td>
<td>39.2</td>
<td>5.1</td>
<td>35.8</td>
<td>0.6</td>
<td>0.1</td>
<td>19.2</td>
</tr>
<tr>
<td>Paddy Husk</td>
<td>38.5</td>
<td>5.7</td>
<td>39.8</td>
<td>0.5</td>
<td>0</td>
<td>15.5</td>
</tr>
<tr>
<td>Corn Cob</td>
<td>46.2</td>
<td>7.6</td>
<td>42.3</td>
<td>1.2</td>
<td>0.3</td>
<td>2.4</td>
</tr>
<tr>
<td>Bagasse</td>
<td>46.4</td>
<td>5.4</td>
<td>42.6</td>
<td>0.7</td>
<td>0</td>
<td>4.9</td>
</tr>
<tr>
<td>Cotton Stalk</td>
<td>45.3</td>
<td>5.6</td>
<td>45.3</td>
<td>0.5</td>
<td>0</td>
<td>3.3</td>
</tr>
<tr>
<td>Hard Wood</td>
<td>50.8</td>
<td>6.4</td>
<td>41.5</td>
<td>0.4</td>
<td>0</td>
<td>0.9</td>
</tr>
<tr>
<td>Soft Wood</td>
<td>52.9</td>
<td>6.3</td>
<td>39.7</td>
<td>0.1</td>
<td>0</td>
<td>1.0</td>
</tr>
<tr>
<td>Miscanthus</td>
<td>48.1</td>
<td>5.4</td>
<td>42.2</td>
<td>0.5</td>
<td>0.1</td>
<td>3.7</td>
</tr>
<tr>
<td>Barley Straw</td>
<td>45.7</td>
<td>6.1</td>
<td>38.3</td>
<td>0.4</td>
<td>0.1</td>
<td>9.4</td>
</tr>
<tr>
<td>Wheat Straw</td>
<td>48.5</td>
<td>5.5</td>
<td>39.9</td>
<td>0.3</td>
<td>0.1</td>
<td>5.7</td>
</tr>
<tr>
<td>Lignite</td>
<td>64.0</td>
<td>4.2</td>
<td>19.2</td>
<td>0.9</td>
<td>1.3</td>
<td>10.4</td>
</tr>
<tr>
<td>Anthracite Coal</td>
<td>78.8</td>
<td>2.3</td>
<td>2.5</td>
<td>0.9</td>
<td>0.5</td>
<td>15</td>
</tr>
</tbody>
</table>

2.2.6 Energy Content

- Heating Values

As described in Section 1.3.2, the energy content of waste agricultural biomass is predicted through the parameter referred to as heating value (or calorific value), which could be represented by the following three different conventions:

- Higher Heating Value - \( HHV \)
- Lower Heating Value - \( LHV \)
- Usable Heat Content

If 1 kg of biomass is imagined to be burned in the absence of heat loss, the products of combustion would be at a high temperature. The amount of thermal energy that would be extracted from the gases to bring them to the ambient temperature and condense all the water vapour present is called \( HHV \). This value of dry lingo-cellulosic materials (i.e. \( HHV_D \)) is normally in the range 15 MJ/kg to 20 MJ/kg depending on ash and extractive contents. \( HHV_D \) for various waste agricultural biomass is given in Table 4.3 in Chapter 4.
Estimation of Higher Heating Value

Usually, heating values of biomass materials are determined through direct experimental measurement by means of a device called bomb calorimeter. The standard method of experimentation, a small mass of biomass is burned in the presence of oxygen inside a sealed container (or bomb). The heat released from combustion is transferred to a mass of fluid (air or water) that surrounds the container. The heating value is calculated from the product of mass of fluid × specific heat of fluid × net temperature increase. The calculated heating value must be corrected for heat losses to the mass of container, heat conduction through the container wall, and heat losses to the surrounding of the device. In modern calorimeters the corrections are made automatically using sensors and controllers. The resulting measured heating value is considered as HHV at constant volume because the biomass combustion in the container has taken place inside the fixed volume of the container. The resulting \( HHV_D \) can be expressed based on dry mass content of the sample biomass as

\[
HHV_D = \frac{HHV}{1 - m},
\]

where \( m \) is the fractional moisture content \( m \) in biomass on wet basis and \( HHV \) is the higher heating value determined by the calorimeter.

In practice, the gases evolving from combustion of a biomass are expanded inside the combustion chamber without much constraint (i.e. external combustion systems). In such case, during combustion the volume expands but the pressure in the combustion zone does not change much. This situation is often present in a boiler combustion chamber with unrestricted exhaust system. For these cases, above expression developed from constant volume measurement has to be converted in to the heating value at constant pressure, for which the following equation can be used [21]:

\[
HHV_p = HHV_D - 0.212 \times \alpha_H - 0.0008 \times (\alpha_O + \alpha_N),
\]

where \( HHV_p \) is the higher heating value at constant pressure for dry biomass and \( \alpha_H \), \( \alpha_O \) and \( \alpha_N \) are the mass fraction of hydrogen, oxygen and nitrogen (percent dry mass) of the biomass.

Alternative to the practical measurements, approximate estimations for \( HHV_D \) could be obtained through analytical equations that are derived based on composition of the materials. Several such models could be found in the literature, some of which use ultimate analysis, while others are based on proximate analysis. For example, three models, designated here as
Model 1 [24], Model 2 [25] and Model 3 [26], for the estimation of $HHV_D$ of a biomass materials based on its ultimate analysis are presented below:

**Model - X:** \[ HHV_D = 0.352 \times \alpha_C + 1.162 \times \alpha_H - 0.111 \times \alpha_O + 0.063 \times \alpha_N + 0.105 \times \alpha_S; \]

**Model - Y:** \[ HHV_D = 0.349 \times \alpha_C + 1.178 \times \alpha_H - 0.103 \times \alpha_O - 0.015 \times \alpha_N + 0.101 \times \alpha_S - 0.021 \times \alpha_{Ash}; \]

**Model - Z:** \[ HHV_D = 0.341 \times \alpha_C + 1.323 \times \alpha_H - 0.120 \times \alpha_O - 0.120 \times \alpha_N + 0.680 \times \alpha_S - 0.015 \times \alpha_{Ash}; \]

where $\alpha_C$, $\alpha_H$, $\alpha_O$, $\alpha_N$, $\alpha_S$ and $\alpha_{Ash}$ are the % mass fraction of carbon, hydrogen, oxygen, nitrogen, sulfur and ash in dry biomass. The unit of $HHV_D$ in the above equations is in MJ/kg dry mass. The ultimate analysis data presented in Table 2.4 for selected fuels could be used with each of the above three models to estimate $HHV_D$ values. The results, as presented in Table 2.5, show very good agreements in each fuel with maximum difference of only 3%.

**Table 2.5: Estimated $HHV_D$ for selected biomass materials based on ultimate analysis**

<table>
<thead>
<tr>
<th>Biomass Fuel</th>
<th>Higher Heating Values of Dry Matter (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model-X</td>
</tr>
<tr>
<td>Paddy Straw</td>
<td>15.8</td>
</tr>
<tr>
<td>Paddy Husk</td>
<td>15.8</td>
</tr>
<tr>
<td>Corn Cob</td>
<td>20.5</td>
</tr>
<tr>
<td>Bagasse</td>
<td>17.9</td>
</tr>
<tr>
<td>Cotton Stalk</td>
<td>17.4</td>
</tr>
<tr>
<td>Hard Wood</td>
<td>20.7</td>
</tr>
<tr>
<td>Soft Wood</td>
<td>21.5</td>
</tr>
<tr>
<td>Miscanthus</td>
<td>18.5</td>
</tr>
<tr>
<td>Barley Straw</td>
<td>18.9</td>
</tr>
<tr>
<td>Wheat Straw</td>
<td>19.0</td>
</tr>
<tr>
<td>Lignite</td>
<td>25.4</td>
</tr>
<tr>
<td>Anthracite Coal</td>
<td>30.2</td>
</tr>
</tbody>
</table>

As considerable resource requirement is required to perform the ultimate analysis of biomass materials, some attempts have been taken to develop correlations of $HHV_D$ with proximate analysis of the biomass materials, which requires the composition in terms of volatile matter (VM), fixed carbon (FC) and Ash. The proximate analysis only requires standard laboratory
equipments, relatively less technical expertise, and therefore less complicated to carry out than ultimate analysis. As in the above case, three models have been selected from the literature to demonstrate the application of proximate analysis data to predict $HHV_D$ of biomass materials. These models are designated as Model-A [27], Model-B [28] and Model-Z [29], for the estimation of based on its ultimate analysis are presented below:

\[
\begin{align*}
\text{Model-A: } HHV_D &= 0.1559 \times \alpha_{VM} + 0.3536 \times \alpha_{FC} - 0.0078 \times \alpha_{Ash}; \\
\text{Model-B: } HHV_D &= 0.1708 \times \alpha_{VM} + 0.3543 \times \alpha_{FC}; \\
\text{Model-C: } HHV_D &= 0.3133 \times (\alpha_{VM} + \alpha_{FC}) - 10.8141,
\end{align*}
\]

where $\alpha_{VM}$, $\alpha_{FC}$ and $\alpha_{Ash}$ are the mass fraction (as %) of VM, FC and ash in dry biomass, respectively and $HHV_D$ in MJ/kg dry mass. The proximate analysis data presented in Table 2.3 could be used with each of the above three models to estimate $HHV_D$ values. The results for waste agricultural biomass materials are presented in Table 2.6. Again, close agreements between the models could be seen, when considering the simplicity of the basic approach. Comparison of the estimated values derived from these models with experimental measurements show fairly satisfactory agreement, indicating the applicability.

**Table 2.6: Estimated $HHV_D$ for selected biomass materials based on proximate analysis**

<table>
<thead>
<tr>
<th>Biomass Fuel</th>
<th>Higher Heating Values of Dry Matter (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model-A</td>
</tr>
<tr>
<td>Bagasse</td>
<td>18.1</td>
</tr>
<tr>
<td>Coconut coir</td>
<td>18.8</td>
</tr>
<tr>
<td>Coconut shell</td>
<td>19.4</td>
</tr>
<tr>
<td>Coir pith</td>
<td>19.3</td>
</tr>
<tr>
<td>Corn cob</td>
<td>17.9</td>
</tr>
<tr>
<td>Corn stalks</td>
<td>18.1</td>
</tr>
<tr>
<td>Groundnut shell</td>
<td>17.8</td>
</tr>
<tr>
<td>Paddy Husk</td>
<td>14.5</td>
</tr>
<tr>
<td>Paddy Straw</td>
<td>15.5</td>
</tr>
<tr>
<td>Wheat Straw</td>
<td>16.6</td>
</tr>
<tr>
<td>Peanut Shell</td>
<td>18.4</td>
</tr>
<tr>
<td>Cotton Stalk</td>
<td>18.5</td>
</tr>
</tbody>
</table>
Another useful application of the three models presented previously based on ultimate analysis is to estimate $\text{HHV}_D$ for the individual constituents of biomass materials, viz., cellulose, hemicelluloses and lignin. The elementary chemical equations presented in Section 1.3.1 could be used to determine the $\alpha_C$, $\alpha_H$, and $\alpha_O$, the % mass fraction of carbon, hydrogen, and oxygen, and thereby $\text{HHV}_D$ from Model-X, Model-Y and Model-Z. The results are presented in Table 2.7.

### Table 2.7: Estimated $\text{HHV}_D$ for cellulose, hemicelluloses and lignin

<table>
<thead>
<tr>
<th>Biomass constituent / Chemical equation</th>
<th>Ultimate Analysis (%)</th>
<th>$\text{HHV}_D$ (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>H</td>
</tr>
<tr>
<td>Cellulose / $(C_6H_{10}O_5)_x$</td>
<td>44.4</td>
<td>6.2</td>
</tr>
<tr>
<td>Hemicelluloses / $(C_5H_8O_3)_y$</td>
<td>45.5</td>
<td>6.1</td>
</tr>
<tr>
<td>Lignin / $(C_9H_{10}O_3(CH_3O)_{0.9-1.7})_z$</td>
<td>58.7 – 61.3</td>
<td>6.5 – 6.9</td>
</tr>
</tbody>
</table>

These results show very good agreement with the measured values depicted in Table 1.3.

- **Effects of Moisture on Heating Value**

Note that the $\text{HHV}$ correspond to the maximum potential energy released during complete oxidation of a unit of fuel. It includes the thermal energy recaptured by condensing and cooling all products of combustion. The $LHV$ was created in the late 1800s when it became obvious that condensation of water vapour or sulfur oxide in smoke stacks lead to corrosion and destruction of exhaust systems. As it was technically impossible to condense flue gases of sulfur-rich coal, the heat below 150°C was considered of no practical use and therefore excluded from energy considerations.

In case of wet biomass having a fractional moisture content $m$ on a wet basis, the heat released on combustion is only due to the dry fraction $(1-m)$. Thus

$$\text{HHV of wet biomass } = (1 - m) \times \text{HHV}_D.$$  

If the water vapour produced as a result of combustion is not condensed, thermal energy amounting to its latent heat of condensation remains un-extracted. The moisture content in the producer gas is the sum of the fraction moisture content $m$ of biomass and moisture produced due to combustion of dry wood. The thermal energy output per kg of fuel is then become $LHV$, given by
where latent heat of evaporation is taken as 2.447 MJ/kg at 25 °C and \( \alpha_H \) is the mass fraction of hydrogen in dry biomass. For example, consider hardwood having the properties given in Table 2.1 (i.e. the composition in terms of cellulose, hemicelluloses and lignin) and Table 2.4 (i.e. the ultimate analysis) together with the heating values of its constituents (i.e. cellulose, hemicelluloses and lignin) given in Table 1.2. Then, \( HHV_D \) could be estimated by knowing the composition of the biomass material (take cellulose = 42%, semi-cellulose = 38% and lignin = 20% on ash-free basis and ash = 0.9%) and heating values of individual components (i.e. cellulose = 17 MJ/kg, semi-cellulose = 17 MJ/kg and lignin = 25 MJ/kg), as

\[
HHV_D = (1-0.009) \times (0.42 \times 17 + 0.38 \times 17 + 0.2 \times 25) \text{ MJ/kg} = 18.43 \text{ MJ/kg}
\]

If the moisture content on wet basis is given by \( m \), the heating values of hard wood are given by

\[
HHV = (1-m) \times HHV_D \quad \text{and} \quad LHV = (1-m) \times HHV_D - 2.447 \times [m + (1-m) \times 0.064 \times 9],
\]

where the hydrogen content of dry wood is taken from Table 2.3 as 6.4%. The two quantities in the square brackets represent the moisture content of biomass and moisture produced due to combustion of dry wood, respectively. The variations of \( HHV \) and \( LHV \) with moisture content, given by above equations, are presented in Figure 2.3.
The effects of moisture level on the energy content of biomass could be seen clearly in the above figure. The \( \text{LHV} \) of fresh (green) hardwood having a moisture content of 50\% on wet basis is about 7.4 MJ/kg, while reducing the moisture content to 20\% would enhance it to about 13.3 MJ/kg (78\% increase). Further, \( \text{LHV} \) of wood pellets having 8\% moisture content is about 15.6 MJ/kg. \( \text{LHV} \) of waste agricultural biomass materials is given in Table 2.8 [5].

**Table 2.8: \( \text{LHV} \) of waste agricultural biomass materials**

<table>
<thead>
<tr>
<th>Product</th>
<th>Residue</th>
<th>MC(_{wb}) (%)</th>
<th>LHV (MJ/kg)</th>
<th>Product</th>
<th>Residue</th>
<th>MC(_{wb}) (%)</th>
<th>LHV (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paddy</td>
<td>Paddy Husk</td>
<td>9.0</td>
<td>14.0</td>
<td>Sawn wood</td>
<td>Sawdust</td>
<td>7.0</td>
<td>19.4</td>
</tr>
<tr>
<td></td>
<td>Paddy Straw</td>
<td>12.7</td>
<td>16.0</td>
<td>Sugar</td>
<td>Bagasse</td>
<td>20.0</td>
<td>15.4</td>
</tr>
<tr>
<td>Coconut</td>
<td>Coconut Shell</td>
<td>8.7</td>
<td>18.1</td>
<td>Barbajo</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nuts</td>
<td>Coconut Husk</td>
<td>10.3</td>
<td>18.6</td>
<td>Maize</td>
<td>Stalks</td>
<td>20.0</td>
<td>12.6</td>
</tr>
<tr>
<td></td>
<td>Coir Dust</td>
<td>15.0</td>
<td>13.4</td>
<td>Seeds</td>
<td>Cobs</td>
<td>7.5</td>
<td>16.3</td>
</tr>
</tbody>
</table>

In an actual combustion systems the flue gas is not cooled back to the ambient temperature, nor is the water vapour condensed. The amount of utilizable thermal energy is therefore less than the \( \text{LHV} \), the difference being the sensible energy of the exhaust combustion products above the level of the ambient temperature. Thus

\[
\text{Utilizable heat content} = \text{LHV} - \sum [(\text{mass fraction}) \times (\text{specific heat at constant pressure}) \times (\text{temperature of exhaust - ambient temperature})]
\]

For example, consider the above example corresponding to hardwood with ultimate analysis of C – 50.8\%, H – 6.4\%, O – 41.8\%, N – 0.4\% and Ash – 0.9\%. In order to identify the combustion products, consider the following reaction related to complete combustion of wood (neglecting nitrogen in biomass)

\[
\text{CH}_x\text{O}_y + \left[1 + \frac{y - 2x}{4}\right] \text{O}_2 + 3.76\text{N}_2 \rightarrow \text{CO}_2 + \frac{y}{2}\text{H}_2\text{O} + 3.76\left[1 + \frac{y - 2x}{4}\right] \text{N}_2 + \text{Heat}
\]

where \( x = 0.62 \), and \( y = 1.51 \) for the above composition (refer Section 4.2 for more information on combustion).

Theoretical air requirement for complete combustion

\[
= \frac{[1+(1.51-2\times0.62)/4] \times (32+3.76\times28)](12+1.51+16\times0.62)}{146.81 \text{ kg}/23.39 \text{ kg} = 6.28 \text{ kg}/\text{kg of dry wood}}
\]
As the recommended excess oxygen requirement for wood combustion is about 7% (i.e. excess air = 7×100/(21-7) = 50%), the total air requirement for the combustion becomes 1.5×6.28 = 9.42 kg/kg of dry wood

The heat loss due to dry flue gas is given by \( m \times C_p \times (T_f - T_a) \), where \( m = \text{mass of CO}_2 + \text{mass of N}_2 + \text{mass of O}_2 \), \( T_f \) is the temperature of exhaust and \( T_a \) is the ambient temperature. Then

\[
m = 44 + 3.76 \times [1+(1.51-2\times0.62)/4] \times 28 + 0.5 \times 6.28 = 159.53 \text{ kg}
\]

For the case of \( T_f = 270 \) °C, \( T_a = 30 \) °C, and \( C_p = 0.97 \text{ kJ/kg/K} \), the heat loss per kg of dry wood becomes

\[
H_{loss} = 159.53 \times 0.97 \times (270 - 30)/23.39 = 37138/23.39 = 1587.80 \text{ kJ/kg}
\]

If wood contains 20% moisture content on wet basis, the utilizable heat content becomes;

Utilizable heat content = \( LHV - \text{heat loss of dry flue gas} = 13.13 - 1.59 \times 0.8 = 11.59 \text{ MJ/kg} \),

which is about 10% lower than the \( LHV \).

Note that the utilizable heat content may be raised by (i) drying the fuelwood so that \( LHV \) is higher and (ii) lowering the exhaust gas temperature by extracting more heat energy from it.

- **Measurement of Moisture Content**

  With the development of bio energy usage, several quality assurance and standards have been developed for bio-fuels for the sustainability of the sector. Such standards are developed by several country specific institutions (such as Germany - DIN, DIN Plus; Sweden – SS; The Netherlands – NTA; Denmark – DK; UK – BSI; Australia – AS; USA – ASTM; Japan - JIS) and international organizations (such as International Organization for Standardization - ISO, European standards – EN). In general, the key areas covered in these standards include the following [30]:
  - Terminology, Definitions and Descriptions
  - Fuel Specifications, Classes, Quality Assurance
  - Sampling and Sample Reduction
  - Physical and Mechanical Testing Methods
  - Chemical Testing Methods

  The majority of the standards set out how each of different physical and chemical properties of biomass, which include moisture content, must be measured. Each one sets out the
equipment to be used, the procedures to be employed, the level of precision, etc. for the
determination of one or a number of parameters. Many of these are only of relevance to test
laboratories and cannot be performed without specialist equipment and facilities. The
reference method for determining the water content in biomass is the standard gravimetric
method. This method consists of first weighing a sample of the material, drying the sample in
an oven and then weighing the dry material. The weight difference between the wet and dry
material is considered to be the mass of water in the sample. This method is fully described in
the standard [31]. In case of watery waste agricultural biomass materials such as animal
manure, the water content is determined by first evaporating free water on steam table and
followed by standard oven dry method.

The application of the reference method requires sampling of the material whose moisture
content is to be determined. The procedure for sampling biomass for moisture content
determination with the standard oven method is described in the standard [32].

- **Energy Content of Wastes in Biochemical Conversion Route**

The above thermal characterization is applicable for biomass energy system based on thermo-
chemical conversion routs (see Figure 1.10). In case of technologies based on biochemical
conversion, for instance biogas generation from anaerobic digestion, the heating values of the
raw material do not have a bearing on the energy potential. Here the energy potential is
estimated through the biogas generation potential of a given waste material, a methodology of
which is described below.

Biogas yield of a biomass material depends on the organic fraction of dry matter in the
material and the waste management system associated with it. The dry matter (DM) of the
waste is the matter left after removal of its moisture content. It may be obtained as the weight
loss on heating to a temperature of 105 °C. Whereas, Volatile Solids (VS) are defined as the
organic fraction of dry matter in waste.

**Methodology of Estimation**

- Amount of animal wastes which can be recovered for energy use (kg/year)
  
  \[= \text{Amount of dry matter (kg/head/day)} \times 365 \text{ (day/year)} \times \text{No. of animals \times Fraction recoverable} \]
• Amount of biogas that can be potentially produced from recoverable wastes
  \[= \text{Amount of dry matter recoverable (kg DM/year)} \times \text{Volatile solids fraction in dry matter (kg VS/kg DM)} \times \text{Biogas yield (m}^3/\text{kg VS)}\]

• Energy potential of the biogas recoverable (MJ/year)
  \[= \text{Amount of biogas recoverable (m}^3/\text{year}) \times \text{Heating value of biogas (MJ/m}^3\)]

Accurate estimation of values of different characteristics of animal wastes, such as dry matter, fraction recoverable as well as physical and chemical properties is difficult. As a result, substantial differences exist in the values reported by various authors. Some indicative values of the above waste parameters relevant to animal waste are given in Table 2.9 [5]. The heating value of the biogas depends on its composition, especially the amount of methane. HHV of methane is about 35.8 MJ/m³ and therefore biogas with 60% methane, HHV could be taken as 20 MJ/m³.

Table 2.9: Selected values for animal waste characteristics

<table>
<thead>
<tr>
<th>Animal Type</th>
<th>Amount of Dry Matter DM (kg/head/day)</th>
<th>Fraction Recoverable</th>
<th>Fraction of Volatile Solid (VS/DM)</th>
<th>Biogas Yield (m³/kg of VS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cattle</td>
<td>2.860</td>
<td>0.50</td>
<td>0.934</td>
<td>0.20</td>
</tr>
<tr>
<td>Buffalo</td>
<td>2.526</td>
<td>0.50</td>
<td>0.796</td>
<td>0.30</td>
</tr>
<tr>
<td>Chicken</td>
<td>0.043</td>
<td>1.00</td>
<td>0.465</td>
<td>0.18</td>
</tr>
<tr>
<td>Duck</td>
<td>0.051</td>
<td>1.00</td>
<td>0.392</td>
<td>0.22</td>
</tr>
<tr>
<td>Goat</td>
<td>0.552</td>
<td>0.33</td>
<td>0.598</td>
<td>0.31</td>
</tr>
<tr>
<td>Horse</td>
<td>3.300</td>
<td>0.33</td>
<td>0.876</td>
<td>0.16</td>
</tr>
<tr>
<td>Sheep</td>
<td>0.329</td>
<td>0.33</td>
<td>0.912</td>
<td>0.31</td>
</tr>
<tr>
<td>Pigs</td>
<td>0.661</td>
<td>0.23</td>
<td>0.893</td>
<td>0.31</td>
</tr>
</tbody>
</table>

2.2.7 Generation and Availability of Waste Agricultural Biomass for Energy

Generation and availability of waste agricultural biomass depend on several factors including cropping patterns, yields in use, processing technologies, collection practice, alternative uses, etc. There are such large variations in these factors that any generalization is impossible. However, even in the most under-developed agricultural area, it is possible to generate aggregate numbers based on amount of crop produced or the extent of land cultivated together with residue to product ratio (RPR) for each crop category. Estimates of RPR values from different crops are given in Table 2.10 [33].
Table 2.10: RPR of waste agricultural biomass materials

<table>
<thead>
<tr>
<th>Crop</th>
<th>RPR</th>
<th>Crop</th>
<th>RPR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat Residue</td>
<td>0.9-1.6</td>
<td>Cotton hulls</td>
<td>0.26</td>
</tr>
<tr>
<td>Maize Stalks</td>
<td>0.9-4.0</td>
<td>Cotton stalks</td>
<td>3.0-5.5</td>
</tr>
<tr>
<td>Rice husks</td>
<td>0.17-0.22</td>
<td>Groundnut shells</td>
<td>0.25-0.55</td>
</tr>
<tr>
<td>Rice Straw</td>
<td>0.8-2.5</td>
<td>Coffee Residues</td>
<td>0.3-1.8</td>
</tr>
<tr>
<td>Barley Residue</td>
<td>1.4-2.0</td>
<td>Coconut Shells</td>
<td>1.9</td>
</tr>
<tr>
<td>Millet/Sorghum Stalks</td>
<td>1.5-3.7</td>
<td>Palm Empty Fibre Bunch</td>
<td>0.39</td>
</tr>
<tr>
<td>Sugarcane Bagasse</td>
<td>0.05-0.2</td>
<td>Palm Fibres</td>
<td>0.2-1.1</td>
</tr>
<tr>
<td>Sugarcane Barbojo</td>
<td>0.09-0.28</td>
<td>Palm Shells</td>
<td>0.2-1.0</td>
</tr>
</tbody>
</table>

RPR is the ratio of the amount of residue generated to the total amount of agricultural (or forest) product produced. Then

\[
\text{Annual residue generated} = \text{RPR} \times \text{Annual crop production}
\]

In order to estimate the potential of deriving additional energy from a residue, it is important to determine the present utilization pattern of the residue. To accomplish this task, Surplus Availability Factor and Energy Use Factor are introduced. Where energy use factor is defined as the fraction of residue currently being used as a fuel and surplus availability factor is defined as the ratio of presently surplus (wasted) amount to the total residue generated.

\[
\text{Amount of surplus residue} = \text{Annual residue generated} \times \text{Surplus availability factor}
\]

\[
\text{Amount of residue used as fuel} = \text{Annual residue generated} \times \text{Energy use factor}
\]

The potential of deriving additional energy from a residue is then estimated by determining the potential savings due to efficiency improvement and the surplus available.

\[
\text{Total amount available for energy} = \text{Amount of surplus} + \text{Amount of saving}
\]

\[
\text{Energy Potential} = \text{Total amount available for energy} \times \text{Heating value}
\]

Note that, a large variation in RPR could be seen in different literature and one should be very careful in applying the values given in the table. It is always advisable to cross-check these values with actual measured data.
2.3. TYPES OF WASTE AGRICULTURAL BIOMASS

2.3.1 Categories

Table 2.11 presents some frequently available crops and residues, categorized under field-based and process-based. More details on the characteristics of some selected waste agricultural biomass residues are presented in the following sections.

Table 2.11: Frequently available crops and residues

<table>
<thead>
<tr>
<th>Crop</th>
<th>Category</th>
<th>Residues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paddy</td>
<td>Field-based</td>
<td>Straws</td>
</tr>
<tr>
<td></td>
<td>Process-based</td>
<td>Husks, Bran</td>
</tr>
<tr>
<td>Wheat</td>
<td>Field-based</td>
<td>Straws</td>
</tr>
<tr>
<td></td>
<td>Process-based</td>
<td>Husks</td>
</tr>
<tr>
<td>Coconut</td>
<td>Field-based</td>
<td>Fronds</td>
</tr>
<tr>
<td></td>
<td>Process-based</td>
<td>Husks, Coir, Pith, Shells</td>
</tr>
<tr>
<td>Maize</td>
<td>Field-based</td>
<td>Straws / Stovers</td>
</tr>
<tr>
<td></td>
<td>Process-based</td>
<td>Cobs</td>
</tr>
<tr>
<td>Sugar Cane</td>
<td>Field-based</td>
<td>Barbajo</td>
</tr>
<tr>
<td></td>
<td>Process-based</td>
<td>Bagasse, Molasses</td>
</tr>
<tr>
<td>Rubber</td>
<td>Field-based</td>
<td>Pods, Seeds, Shell</td>
</tr>
<tr>
<td></td>
<td>Process-based</td>
<td>Saw dust, Wood chips / savings, off-cuts</td>
</tr>
<tr>
<td>Tea</td>
<td>Field-based</td>
<td>Prune branches</td>
</tr>
<tr>
<td></td>
<td>Process-based</td>
<td>Refuse tea</td>
</tr>
<tr>
<td>Coffee</td>
<td>Field-based</td>
<td>Prune branches</td>
</tr>
<tr>
<td></td>
<td>Process-based</td>
<td>Hull, Husk, Ground</td>
</tr>
<tr>
<td>Banana</td>
<td>Field-based</td>
<td>Leaves</td>
</tr>
<tr>
<td></td>
<td>Process-based</td>
<td>Refused fruits</td>
</tr>
<tr>
<td>Vegetables</td>
<td>Field-based</td>
<td>Leaves</td>
</tr>
<tr>
<td></td>
<td>Process-based</td>
<td>Spoiled vegetables</td>
</tr>
<tr>
<td>Animals</td>
<td>Field-based</td>
<td>Manure</td>
</tr>
<tr>
<td></td>
<td>Process-based</td>
<td>Wastewater</td>
</tr>
</tbody>
</table>
2.3.2 Paddy

Paddy, wheat and corn are the most important crops in the world. Paddy is the staple food for half of the world population. The residues generated through harvesting and processing of paddy include straws, husks and bran. Husk is the outermost hard coat of paddy. Bran is the thin papery layer present between husk and rice. Most of the paddy straw generated is burned in the field, with the ash being used as organic fertilizer. Relatively small quantities are used as animal fodder, animal bedding, raw material for paper and board making or building material. Paddy straw also plays a vital role as a candidate raw material for biogas production systems. Due to the low density, bulkiness, and high combustion rate, paddy straw ranked somewhat low in terms of energy source.

The paddy husk is produced at the rice mill at the time the paddy is milled. Normally rice is processed for consumption in two methods as raw and parboiled. In parboiling mills, paddy husk is used for combustion in the par-boiler or steam boiler. In most of the time, the surplus paddy husk is considered as a waste material creating environmental problems. Some of these husks are used as a domestic fuel for cooking, poultry industry and bricks manufacturing.

![Figure 2.3: Paddy residues - straws and husks](image)

2.3.3 Coconut

Coconut tree, scientifically known as *Cocos nucifera* L., which belongs to *Palmae* family. Coconut tree grows preferably in tropical and rainforest climate, especially along the coastline zones where it enjoys the sun irradiation as well as water (high humidity). Coconut trees generate residues in the form of wood residues, fronds, husks and shells. Fronds are left in the field (especially in large scale plantation) or used as a domestic fuel (mainly small holder planting) or as a shelter. Tree trunks are used both as a fuel and as timber. Husks are used as fuel for coconut processing, as a domestic fuel and as a source of fiber for rope, mats.
and filling mattresses. The shells are a good fuel and an excellent source for activated carbon production.

About 12 to 14 fronds are shed per tree per year, yielding about 1.5 kg dry woody biomass per frond or, assuming a density of 120 trees per ha, about 2400 kg per ha. The productive life of the tree varies between 50 and 100 years. After replanting, a part of the wood is used as timber while another part is available as a source of energy. On wet basis, coconuts consist of 33-35% husks, 12-15% shell, 28-30% copra and 22-25% water. The same source indicates that about 2220 kg of dry husks and 1040 kg of dry shells become available per ha per year.

2.3.4 Rubber

Wood from the rubber tree is both used as fuel and as timber. In particular, in the last decade rubber wood has become an important source of timber for the furniture industry. Rubber trees have a productive lifetime of about 25-35 years. During replanting they yield about 180 cubic meter green wood per ha. This is equivalent to about 81 tons dry wood per ha at 0.72
ton per cubic meter green wood and a moisture content of 60% (dry basis). Rubber trees shed their leaves every year resulting in a residue resource of about 1400 kg per ha. However, removal of these may affect soil moisture and fertility, and may increase erosion.

Figure 2.5: Rubber plantation and seeds, pods and shell

2.3.5 Maize

Maize is a source of renewable energy that can be used to produce bioethanol by fermenting the starch in the kernel, to produce biogas through methanation or produce heat and power through combustion of residues. Residues generated from maize include stalks, cob and husk. In many cases the stalks are left in the field or used for other purposes such as fodder. Maize cob and husks, generated as a process-based residues, are wasted without much use in general.

Figure 2.6: Maize plantation, products and residues (cob, husk)
2.3.6 Sugarcane

Residues generated in sugarcane industry include both field based residues such as sugar cane tops and leaves (commonly known as barbajo) and process-based residues such as bagasse and sugar molasses. The portion of sugarcane after the extraction of juice is called bagasse. When produced from press roles, it contains 40% - 55% moisture. Bagasse is normally used as an energy source for steam generation and barbojo and leaves are used as cattle feed or burnt in the field. In addition, sugarcane tops and leaves (commonly known as barbajo) generate as field-based residue in sugarcane plantation. Residue to product ratio of bagasse is about 0.29 with 50% moisture content and that of sugarcane tops is about 0.3.

![Figure 2.7: Sugarcane plantation, bagasse and leaves](image)

2.3.7 Cashew

Cashew nut tree is a wild plant species found mainly in tropical countries, in Asia, Africa and Latin America. This tree enjoys dry sand soils and sun-drenched environment. In general, it has a thick and tortuous trunk plenty of branches. Cashew nut tree, or *Anacardium occidentale* L., from *Anacardiaceae* family. While cashew nut or kernels are appreciated as edible material and enjoyed in different ways as snacks or as condiment in different delicacies, the shells are, in most cases, just dumped as waste.

![Figure 2.8: Cashew tree, fruits and nuts](image)
Further, the major portion of fruits (cashew nut bulb) too is wasted, which may have a potential as a feedstock for biogas generation.

### 2.3.8 Animal Waste

Animal manure can be dried into cakes for use as solid fuel (direct combustion) or converted to a gaseous fuel, biogas. Dung cake is used as a traditional fuel in many countries and biogas production is an established technology in certain countries, notably China and India. As animal wastes are relatively wet biomass (around 80% moisture in wet basis), the most attractive method of converting these waste materials to useful form is biogas production through anaerobic digestion. The composition of biogas is Methane 50-70%, Carbon Dioxide 30-40% and small amount of Hydrogen Sulfide, Nitrogen and Hydrogen. Biogas can be used as a fuel for internal combustion engines (for mechanical energy applications, electricity generation or transport), to generate electricity from small gas turbines, burnt directly for cooking, or for space and water heating.

![Figure 2.9: Fresh cow dung and dried cow dung cakes](image)

When estimating the quantity of animal dung available for energy conversion, production of manure per unit animal type and then the total number of animals from same type have to be considered. The dung production from animal depends on factors such as body weight of the animal, type and quality of the feed, physiological state etc. Accessibility of the dung is an important factor to take into account, particularly where livestock are range fed, and consequently the dung not easily accessible. When the animals are entirely stall fed, all the dung is produced in the shed. When animals are free grazed for all part of the day, dung becomes more difficult to collect. The quantity of dung needed for fertilizer also needs to be taken into consideration.
3.1. INTRODUCTION
Utilization of waste agricultural biomass materials and forestry residues is often difficult due to their uneven and troublesome properties and characteristics as sources of energy. A variety of beneficiation processes, methods and technologies is available to overcome these drawbacks and enhance the fuel properties and characteristics, in prior to use with typical energy conversion processes. These beneficiation processes basically improve the physical and thermal characteristics of the original biomass materials via change in shape, size, size distribution, density, water content, etc. Some of the key processes, as given in Figure 1.11 in Chapter 1, include the following:

- Sizing / Shaping
- Separation
- Drying
- Dewatering
- Densification (Baling, Pelletization and Briquetting)
- Torrefaction

In many situations, more than one of the above types is required. For example, separation and drying are pre-processing requirement for the briquetting of sawdust. This chapter is dedicated to present the descriptions of the above processes applicable for biomass materials in general and waste agricultural biomass in specific.

3.2. SIZING, SHAPING AND SEPARATION
Biomass materials take many shapes and sizes, while a particular biomass energy conversion technology (feeding system, conversion reactor and the conversion process itself) usually could accept a specific range of physical forms and deviations from the design features could lead to not only fuel handling and maintenance issues but also considerable reduction in energy conversion efficiencies. In case of fuel wood, the most common process is the size reduction, which involves splitting, chopping, chipping, etc., as the original forms of the material such as tree trunks, stems and branches are too large to feed into the relevant machines and equipment (see Figure 3.1). Further, smaller sizes improve drying process and
thereby improve the fuel value. It also leads to reduction of volume and increase bulk density and facilitates the transport of the material (in solid state or slurry or pneumatically).

![Figure 3.1: Size reduction of woody biomass](image)

- (a) Splitting of wood logs
- (b) Chipping of wood stems
- (c) Wood stem chippers

The optimum size characteristic of the biomass particles for energy conversion is determined by the following reactor parameters:

- combustion chamber and heat exchanger designs
- the operating conditions
- the method of delivering of biomass
- removing the ash
For thermal gasification and liquefaction processes the following can influence the rate of conversion:

- particle size
- size distribution

In the case of agricultural and wood residues too, size reduction may be required for optimum performances of conversion technologies, for example pelletizing, briquetting, and even for bio-fuel processing including biogas generation.

The choppers are mainly used for stalk forage, such as rice straw, wheat straw and maize stover. These machines can be classified by size into small, medium and large. The small-size chopper is mainly adapted for chopping dry straw or silage on small-scale farms. The large chopper - also called a silage chopper - is mainly used for silage on cattle farms. The medium chopper is normally suited to cutting dry straw and silage, so it is called a straw-silage chopper. According to the mode of cutting, choppers can be divided into cylinder or flywheel types. Large- and medium-size choppers are generally flywheel types, to facilitate throwing silage, but the majority of small choppers are cylinder type. Large and medium choppers are usually equipped with road wheels for easy movement, while small-size choppers are normally stationary.

The machine consists primarily of mechanisms for feeding, chopping, and throwing. The main parts of the feed mechanism are a chain conveyor, pressing rollers, and feed rollers. The chopping and throwing mechanism is in one unit, which consists of a main shaft, a blade rotor, rotating blades, a throwing vane and stationary blades. By changing the gear used in the mechanical transmission system, the speed can be adjusted to obtain various cutting lengths.
3.3. DEWATERING AND DRYING

Reduction of moisture in biomass fuels improves combustion efficiency, usually reduces net air emissions and improves equipment operation. In a furnace or a gasifier, moisture in the fuel must first be heated and evaporated, carrying with it a large quantity of heat up the stack. Therefore, removal of moisture becomes an important stage of the pre-processing of biomass materials for energy applications. While removal of moisture in the fuel needs energy and therefore increases the pre-processing energy requirement, the improvements in the subsequent stages of the energy conversion process could lead to enhancement of the overall efficiency. If heat for the dryer is recovered from the flue gas or other waste heat sources, efficiency is further increased. For example, wood chips with a moisture content of 45%, the maximum boiler efficiency with standard equipment is about 74%. If the same standard equipment uses dry wood of 10% to 15% moisture content, the efficiency can be as high as about 80% [34]. If the fuel is too wet, it may be impossible to sustain the combustion (unless supplementary use of fossil fuels). With dry fuel, the flame burns more evenly at higher temperature, resulting complete combustion. For example, Dry wood burns at a flame temperature of about 1300 °C, while green wood burns at about 950 °C. Air emissions are also get reduced as more complete combustion results in lower quantities of volatile organic compounds and ash produced (although emissions from the dryer must also be considered).

With the reduction of moisture, the fuel requirement to meet a given energy output becomes lower, which in turn provides further benefits. Reduced fuel requirements also mean smaller fuel handling equipment. Further, excess air can be reduced significantly, reducing air velocities through the combustion devices. This reduces entrained particulates in the flue gas,
erosion of dryer surfaces, and fan power. If the fuel is to be transported, drying reduces transportation costs. In addition, dry biofuels are less subject to microbiological degradation in storage.

As with any technology, there are drawbacks as well. The moisture removal process and equipment increases the complexity of the system and so may reduce overall system availability and increase operation & maintenance costs. Ash fouling and slagging tend to increase. Therefore selection of appropriate process and equipment for the purpose of moisture reduction in biomass fuel becomes an important activity in the design of biomass energy conversion system. The basic processes of moisture removal in biomass fuels include dewatering and drying.

Wet biomass materials can be dewatered prior to drying, which refers to the removal of all or part of the contained moisture from biomass as a liquid. Drying is a similar process, except that the moisture is removed as vapor. Overall efficiency can often be improved by dewatering wet feed stocks prior to thermal drying. On the downside, mechanical dewatering equipment itself can consume a large amount of energy and have high maintenance requirements, which must be weighed against the reduction in drying energy. Basic dewatering technologies include

- Open air storage,
- Filters,
- Presses,
- Screening devices,
- Centrifuges,
- Hydro cyclones extrusion and expression process.

As an example, Figure 3.4 shows belt filter press, in which the wet biomass material is sandwiched between two porous belts, which are passed over and under rollers to squeeze moisture out. Another type of mechanical press used for dewatering is the drum press, which consists of a perforated drum with a revolving press roll inside it that presses material against the perforated drum. In a bowl centrifuge, the material enters a conical, spinning bowl in which solids accumulate on the perimeter. Belt filter presses have lower capital, energy and operation & maintenance costs and have longer lives than centrifuges [35].
Drying is another essential pre-treatment process required in biomass energy conversion systems. There are many types of dryers that could be used to dry biomass materials, including direct- and indirect fired rotary dryers, conveyor dryers, cascade dryers, flash or pneumatic dryers, superheated steam dryers, microwave dryers, etc. These systems could be classified in several ways, as given in Table 3.1 [35].

**Table 3.1: Classification of dryers**

<table>
<thead>
<tr>
<th>Classification</th>
<th>Alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drying media (i.e. the stream passing through the material to be dried)</td>
<td>Flue gas, hot air or superheated steam</td>
</tr>
<tr>
<td>Firing</td>
<td>Direct- or indirect-fired</td>
</tr>
<tr>
<td>Heat transfer media</td>
<td>Flue gas, hot air, steam, or hot water</td>
</tr>
<tr>
<td>Pressure</td>
<td>Atmospheric, vacuum or high pressure</td>
</tr>
<tr>
<td>Heat source</td>
<td>Dryer burners, boiler (flue gas or steam), recovered waste heat from facility processes</td>
</tr>
</tbody>
</table>

There are several steps for drying. First, the material must be heated up to the wet bulb temperature to produce a driving force for moisture to leave the wet material. Next, any surface moisture is evaporated very quickly. Once all the surface moisture is removed, the material must be heated to drive water from the inside of biomass to the surface so it can evaporate. This happens when the rate of drying drops as the material remains close to the wet bulb temperature. Once the material is completely dry, it begins to heat up to the
surrounding temperature, because water is no longer present to keep the temperature low [36].

Drying systems could be characterized in terms of the main requirements for drying as (i) Source of heat, (ii) Method of removing the water evaporated, and (iii) Form of agitation to expose new materials for drying. There are two main types of drying that can be applied to the feedstock, namely; passive drying and active drying. The drying without external heat source is referred to as passive drying, the performance of which is highly dependent on the ambient conditions in order for the biomass to dry and reach equilibrium moisture content. Passive drying is often slow and difficult to control. The drying is influenced by the factors such as vapor pressure and relative humidity of the air surrounding the biomass materials and level of air movement. Unlike passive drying, active drying needs external source of heat. This form of drying offers the user better control over the entire process as conditions such as drying temperature and air movement can be controlled more effectively and accurately. Active drying is a more widely used technique in the biomass industry.

Figure 3.5 shows a schematic arrangement of a direct rotary dryer for drying of sawdust with flue gases at a pellet plant [37].
Dryers can also be divided into two categories on how heat is provided for drying as direct and indirect. In direct dryers, the material receives heat from direct contact with the heat carrying fluid (either hot air or hot steam). Whereas, with indirect dryers, the material is separated from the heat source by a heat exchange surface. Most common type of dryer used in biomass systems is the rotary dryers. There are several variations of rotary dryers, but most widely used one is the directly heated single-pass design. Here, hot gases are contacted with the biomass material inside a rotating drum. The rotation of the drum lifts the solid materials so that they tumble through the hot gas, facilitating better heat and mass transfer (see Figure 3.6).

Figure 3.6: Single-pass rotary drum dryer [38]

Figure 3.7: Triple-pass rotary drum dryer [39].

The basic single-pass rotary dryer can be modified to allow three passes of the air and material through the dryer (see Figure 3.7 above). This design works best with materials smaller than 2.5 cm as larger materials can cause plugging. Single-pass dryer can take larger materials.
Other categories of dryers include belt/ conveyer dryers, flash or pneumatic dryers, disk dryers, cascade dryers, superheated steam dryers, bed/grate dryers, tray dryers and open air drying systems. Figure 3.8 shows a conveyer dryer system [40].

![Conveyer dryer diagram](image)

**Figure 3.8: Conveyer dryer**

A comparison of performances of different dryer types is presented in Table 3.2.

**Table 3.2: Basic performance comparison of biomass dryers [35]**

<table>
<thead>
<tr>
<th>Dryer Type</th>
<th>Feedstock Requirements</th>
<th>O&amp;M Requirements</th>
<th>Energy Efficiency &amp; Heat Recovery</th>
<th>Fire Hazard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotary</td>
<td>Less sensitive to particle size. High content paper sludge tends to ball up. Coarse bark can be problematic.</td>
<td>Low</td>
<td>Less opportunity to recover waste heat</td>
<td>Greater than lower temperature dryers</td>
</tr>
<tr>
<td>Conveyor</td>
<td>Fines may need to be screened out first and added back.</td>
<td>Greater than for rotary dryer</td>
<td>High opportunity for heat recovery due to lower temperature.</td>
<td>Low.</td>
</tr>
<tr>
<td>Cascade</td>
<td>Requires fairly uniform particle size. Can handle large particle size.</td>
<td>Subject to corrosion and erosion</td>
<td>Heat recovery is difficult. High blower costs.</td>
<td>Medium. Risk after the dryer and in shut down</td>
</tr>
<tr>
<td>Flash</td>
<td>Requires small particle size.</td>
<td>Subject to corrosion and erosion</td>
<td>Heat recovery is difficult. High blower costs.</td>
<td>Medium</td>
</tr>
<tr>
<td>Superheated Steam</td>
<td>Requires small particle size.</td>
<td>High. Subject to corrosion.</td>
<td>Very efficient if low pressure steam is recovered. No heat losses from heating air.</td>
<td>No fire hazard.</td>
</tr>
</tbody>
</table>
In addition to above drying methods, passive techniques such as open sun drying, solar dryers and natural convection could be used for drying and dehumidification of biomass materials. Figure 3.9 illustrates some practical applications. The main advantage of these processes is low cost. However, issues such as very slow processing, local climate dependency, semi-labor intensiveness, and biomass decomposition make these methods suitable for small scale applications.

![Figure 3.9: Passive drying techniques](image)

### 3.4. DENSIFICATION

#### 3.4.1 Basics

Low bulk density is a common drawback of waste agricultural biomass materials as fuels for energy applications (see Figure 3.10). This drawback could be overcome by means of compaction of the residues into high density and regular shape, thereby improving the fuel quality. The process of compaction of residues into a product of higher bulk density than the original raw material is known as densification. The output for densification process is known by number of terms including briquettes (relatively larger size) and pellets (small).
Advantages of densification:
- The process increase the net calorific value of material per unit volume
- End product is easy to transport and store
- The fuel produce is uniform in size and quality
- The process often helps to solve the problem of residue disposal
- The process helps to reduce deforestation by providing a substitute for fuel wood.
- The process reduces/eliminates the possibility of spontaneous combustion in storage
- The process reduces biodegradation of residues

Disadvantages of densification:
- High investment cost and energy input to the process
- Undesirable combustion characteristics often observed in case of briquettes, e.g. poor ignitability, smoking, etc
- Tendency of briquettes to loosen when exposed to water or even high humidity weather.

Densification, especially briquetting, has been applied for many years in several developing countries. However, briquetting technology is yet to get a strong foothold in many developing countries because of the technical constraints involved (such as fast wear of components) and the lack of knowledge to adapt the technology to suit local conditions. Overcoming the many operational problems associated with this technology and ensuring the quality of the raw
material used are crucial factors in determining its commercial success. Apart from technical constraints, the viability of briquetting depends on a number of key factors, such as: the markets for briquettes (i.e. costs as compared to other fuels), the acceptance of briquettes by potential users, the availability of raw materials as a resource, and the modes of production. Briquettes or pellets can be produced with a density of 1200 kg/m³ from loose biomass of bulk density 100 to 200 kg/m³. Several densified products are shown in Figure 3.11. Densification has stimulated a great deal of interest in developing countries all over the world in recent years as a technique of beneficiation of residues for utilization as an energy source.

Figure 3.11: Densified biomass products – bales, briquettes and pellets
3.4.2 Raw Materials

Both field-based and process-based agricultural residues as well as wood processing residues are potential raw materials for densification. Field-based agricultural residues are of a variety of shapes and densities such as straw, stalks, sticks, leaves, haulms, fibrous material, roots, etc. These residues are diffuse in nature which makes the process of collection, which is un-mechanized, time consuming and expensive, thus rendering them unsuitable for densification. Moreover, some types of residues form an important source of materials for many village applications, for example, animal fodder and supplementary domestic fuels. However, the situation with regard to straws could change if suitable equipment for the collection and baling of straw is developed. Mechanization of collection could substantially alter the economics of utilization of straws.

Process-based residues would appear to have a greater potential, since they are produced at a central site and their accumulation represents a disposal problem with an environmental cost. However, some agro-processing residues have a potential for making high value products, for example, use of coir dust / coconut husk briquettes as a soil conditioner. Hence, it is better to consider residues with the lowest opportunity costs for densification for energy application. These appear to be rice husk, groundnut shells, bagasse, cotton ginning waste, cotton hulls, coconut shell, husk and pith, sawdust, and woodchips. The amount of residues available depends upon the type of industry and most importantly upon the type of process employed. The type and variety of crop also affects the quantity of residue produced.

The present commercial production of briquettes has utilized two main residues: rice husk and sawdust. There are examples of the commercial use of other residues and many different materials are currently undergoing experimental trials throughout South and Southeast Asia.

3.4.3 Mechanism of Densification

Densification essentially involves two parts; the compaction under pressure of loose material to reduce its volume and to agglomerate the material so that the product remains in the compressed state. The deformation mechanisms of powder particles under compression is illustrated in Figure 3.12 [41]. If the material is compacted with low to moderate pressure (0.2-5 MPa), then the space between particles is reduced. Increasing the pressure will, at a certain stage particular to each material, collapse the cell walls of the cellulose constituent; thus approaching the physical, or dry mass, density of the material. The pressures required to
achieve such high densities are typically 100 MPa plus. This process of compaction is entirely related to the pressure exerted on the material and its physical characteristics [41].

The reduction of material density is the reason for undertaking briquetting as it determines both the savings in transport and handling costs and any improvement in combustion efficiency over the original material. The ultimate density of a briquette will depend to some extent on a range of factors including, most importantly, the nature of the original material and the machine used and its operating condition as well as other minor factors. However, the ultimate apparent density of a briquette from nearly all materials is to a rough approximation constant; it will normally vary between 1200-1400 kg/m³ for high pressure processes. The ultimate limit is for most materials between 1450 to 1500 kg/m³. Gains in bulk densities of up to 200 times can be expected when briquetting biomass.

It is yet to known the mechanism by which compacted biomass attains self-bonding. It is suggested that under the influence of high pressure, pectin and other low molecular substances are squeezed out of the plant cells and act as binding agents for the particles. Lignin shows softening between 130-190°C and is said to shift below 100°C under the plasticizing influence of water. It is believed that the softened lignin acts as an internal glue during densification. However it is not universally accepted. Some researcher suggested that self-bonding may be partly attributed to adhesive degradation products of hemicelluloses.

- **Energy Required for Densification**

Energy input constitutes a sizable fraction of densified biomass production cost. Biomass densification systems require energy for the two main processes normally involved;
- fuel preparation, i.e., drying and size reduction,
- the densification process itself.

For example, rice husk obtained from the mills can be normally densified without drying and needs no size reduction. On the other hand, if the raw material needs both size reduction and drying, the amount of energy needed for fuel preparation may be significant.

- **Factors Affecting the Densification [42]**
  - **Temperature and Pressure:**
    It was found that the compression strength of densified biomass depended on the temperature at which densification was carried out. Maximum strength was achieved at a temperature around 220°C. It was also found that at a given applied pressure, higher density of the product was obtained at higher temperature. It is reported that for pellets produced in a laboratory scale device in the temperature range 130°C to 170°C, both strength and moisture stability increased with increasing press temperature.
  - **Moisture Content:**
    Moisture content has an important role to play as it facilitates heat transfer. Too high moisture causes steam formation and could result an explosion. Most suitable moisture content could be of 8-12% on wet basis.
  - **Particle Size and Size Reduction:**
    The particle size is another decisive parameter affecting the densification process. The finer the particle size, the easier is the compaction process. Fine particles give a larger surface area for bonding. The particle size should be less that 25% of the densified product. Size reduction could be done by means of a hammer mill. Wood, straw may require chopping before hammer mill.
  - **Drying:**
    Depends on factors like initial moisture content, particle size, types of densifier, and throughput.

### 3.4.4 Classifications of Densification Technologies

Different densification processes and technologies could be classified based on number of factors including applied pressure, operating condition and mode of operation, as given below:
Based on Applied Pressure:
- Low pressure up to 5 MPa
- Intermediate pressure 5-100 MPa
- High pressure above 100 MPa

Based on Operating Condition
- Hot and high pressure densification
- Cold and low pressure densification

Based on Mode of Operation
- Batch densification
- Continuous densification

Different combination of operating conditions and mode of operation are possible in practice. The most widely used densification process is the hot and high pressure continuous process.

3.4.5 Hot and High Pressure Densification

This is the most common type of densification, and it is essentially a process of compaction of biomass under heated condition. The heating of the biomass is mostly or totally generated by friction during compaction. Usually no binding agent is required for this type of densification.

Depending on the types of equipment used, densification could be categorized into three main types:
- Piston press densification
- Screw press densification
- Pelletizing

The products from first two types of processes are larger in size and known as briquettes.

Historically, biomass briquetting technology has been developed in two distinct directions. Europe and the United States has pursued and perfected the reciprocating ram/piston press while Japan has independently invented and developed the screw press technology. Although both technologies have their merits and demerits, it is universally accepted that the screw
pressed briquettes are far superior to the ram pressed solid briquettes in terms of their storability and combustibility.

At present two main high pressure technologies: ram or piston press and screw extrusion machines, are used for briquetting. While the briquettes produced by a piston press are completely solid, screw press briquettes on the other hand have a concentric hole which gives better combustion characteristics due to a larger specific area. The screw press briquettes are also homogeneous and do not disintegrate easily. Having a high combustion rate, these can substitute for coal in most applications and in boilers.

- **Piston Press**

The piston press consists of a reciprocating piston that forces the raw material falling from the feed hopper into a tapered die, as shown in Figure 3.13 [42].

![Figure 3.13: Schematic diagram of a piston press](image)

The material is pushed by a piston press against the frictional force caused by die taper and is heated to 150-200°C during the process. The piston presses are normally provided with a relatively long channel, which serves to maintain the shape of the briquettes while they undergoing cooling after emerging from the die. The cooling is necessary to condense steam formed and contained inside the briquettes; otherwise the pressure of the steam would result in surface cracks and fragility of the briquettes. The briquettes are usually cylindrical with diameter in the range 50 to 100 mm. The capacity of commercial piston presses is in the range 40 to 1500 kg/hr. Mechanical presses are normally driven electrically and fitted with flywheels. Piston presses with hydraulic drives employ hydraulic transmission system, which represent a relatively recent development.
- **Conical Screw Press**

As shown in Figure 3.14, in this type of press, a conical screw compresses the raw material. The screw forces the material into the compression chamber. A rotating die head extrudes the material through a perforated matrix to produce briquettes of diameter about 2.5 cm. A knife cuts the densified product to a specified length. This type of press can also be used to produce briquettes diameters of about 10 cm by using a single-die matrix.

![Figure 3.14: Schematic diagram of a conical screw press [42]](image)

- **Screw Press with Heated Die**

In this type of press, the material is forced by a screw having no or small taper through a slightly tapered die, which is heated from outside normally by electric heaters (see Figure 3.15).

![Figure 3.15: Schematic diagram of a heated-die screw press [42]](image)
The die temperature is normally maintained at about 300°C. The raw materials get heated up to about 200°C during the process, most of the heating is caused by friction. The biomass materials often get partially pyrolyzed at the surface causing significant amount of smoke generation during the process.

The die cross-section can be circular or square with rounded corners. The briquettes are 5-10 cm in diameter. The design of the screw results in the formation of a central circular hole in the briquette, which acts as an escape route for steam formed during briquetting. Capacity of this type of presses ranges from 50 to 800 kg/hr. The major maintenance problems of these briquetting machines are due to the wear of the screw and the die.

- **Pelletizing Press**

Pellets are the result of a process which is closely related to the briquetting processes described above. The main difference is that the dies have smaller diameters (usually up to approx. 30 mm) and each machine has a number of dies arranged as holes bored in a thick steel disk or ring. Pelletization presses normally consist of a die and a roller. The die rotates in contact with the roller. The raw material is frictionally heated and forced through holes in the die. The densified material emerges from the die as strands of uniform section and cut with knives into the desired length.

As shown in Figure 3.16, there are two types of roller and die press arrangements:
- Ring matrix press consisting of a die in the form of a ring and inside rollers;
- Dick matrix press consisting of a die in the form of a plane disk and rollers.

The capacities of these types of pelletizing machines are in the range 1 to 30 ton/hr.

![Figure 3.16: Pelletizing Presses - (a) Disk-matrix; (b) Ring-matrix [42]](image-url)
Another variety of palletizing press is the punch press, as shown in Figure 3.17. In this type of press, a punch forces the raw material through holes in the die.

![Figure 3.17: Schematic diagram of punch presses](image)

A relatively recent development in the field of pelletization technology is the “cog-wheel” pelleting principle, in which the densification is carried out by forcing the raw material through radial passages in two externally matching wheels, corrugated as illustrate in Figure 3.18. The end product is normally in the form of pellets. The pellets are normally 5 -15 mm in diameter and the length is below 30 mm. The capacity of the machines is in the range 3 – 8 ton/hr.

![Figure 3.18: Cog-wheel pelleting principle](image)
3.4.6 Cold and Low Pressure Densification

Cold and low pressure densification processes require low pressure and temperature. In this process, the densification is carried out with or without binder. In the case of densification using binder, a binding agent is added to glue together the biomass particles. Since there is no need to soften lignin, the temperature and pressure required are low. The binders used in biomass densification could be categorized as the matrix type and the film type. Matrix type binders are in the form of more or less continuous matrix of the binding material in which the particles to be agglomerated are densely embedded. The amount of binder in the densified product is rather high. Clay, paraffin, pitch, wood tar belong to this category. Film type binders are generally used as solutions or dispersions, water being the most common solvent or dispersing medium. The product acquires its desired strength on drying after densification. Sodium silicate, bentonite, molasses, starch, gums, glues, etc. belong to this category.

3.5 TORREFACTION

As discussed in the previous section, a biomass pelletization process typically consists of drying and size reduction prior to the densification itself. After densification the hot bio-pellets are cooled. Steam conditioning of the biomass is commonly applied to enhance the densification process through softening of the fibres. Torrefaction typically consist of pre-drying of the biomass, torrefaction and product cooling. Hence great similarity is present between the basic structure of both processes. The TOP process combines torrefaction and pelletization, as illustrated in Figure 3.19 [43]. Torrefaction is introduced as a functional unit after drying and before size reduction.

![Figure 3.19: Combination of torrefaction with pelletization - the TOP process](image-url)
Torrefaction is a method of changing the properties of biomass materials by slowly heating it in an inter-environment to a maximum temperature of 300°C. The process is also called a mild pyrolysis as most of the smoke-producing compounds and other volatiles are removed resulting in a final product that has approximately 70% of the initial weight and 80–90% of the original energy content. Thus, treatment yields a solid uniform product with lower moisture content and higher energy content compared to the initial biomass [41]. Figure 3.20 presents visual comparison of wood pellets and torrefied wood pellets.

![Figure 3.20: Wood pellets and torrefied wood pellets](image)

During the initial heating process, biomass undergoes drying and heating until most of the water is removed due to chemical reactions through a thermo-condensation process. This happens at over 160°C and also results in the formation of CO₂. Between 180 and 270°C, the reaction is more exothermal, and the degradation of hemicellulose continues. At this point, the biomass begins to brown and give off additional moisture, carbon dioxide, and large amounts of acetic acid with some phenols that have low energy values. The biomass retains most of its energy and simultaneously loses its hygroscopic properties. At about 280°C, the reaction is entirely exothermic and gas production increases, resulting in the formation of carbon monoxide, hydrocarbons like phenols and cresols, and other, heavier products. Temperatures over 300°C are not recommended as these initiate the pyrolysis process [44].

There are many advantages in the pretreatment of biomass using torrefaction before densification. Torrefaction reduces variability in the feedstock caused by differences in types and species of raw materials, climatic and seasonal variations, storage conditions, and time. It also helps develop a uniform feedstock. Furthermore, torrefaction affects biomass physical
characteristics like grindability, hydrophobicity, pelletability, and heating value. Torrefaction not only improves the physical properties of biomass, but also significantly changes its proximate and ultimate composition, making it more suitable for fuel applications. In general, an increase in torrefaction temperature results in an increase in carbon content and a decrease in hydrogen and oxygen content due to the formation of water, carbon monoxide, and carbon dioxide. Table 3.3 presents the physical properties torrefied woody biomass properties compared to the original raw materials.

Table 3.3: Properties of wood, torrefied biomass, wood pellets and TOP pellets [43]

<table>
<thead>
<tr>
<th>Physical Property</th>
<th>Wood Chips</th>
<th>Wood Pellets</th>
<th>Torrefied Biomass</th>
<th>TOP Pellets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture content (%)</td>
<td>35</td>
<td>7 - 10</td>
<td>3</td>
<td>1 - 5</td>
</tr>
<tr>
<td>LHV (MJ/kg)</td>
<td>10.5</td>
<td>15.6 - 16.2</td>
<td>19.9</td>
<td>19.9 - 21.6</td>
</tr>
<tr>
<td>Bulk density (kg/m³)</td>
<td>300 - 500</td>
<td>500 - 650</td>
<td>230</td>
<td>750 - 850</td>
</tr>
<tr>
<td>Energy density (GJ/m³)</td>
<td>5.8</td>
<td>7.8 - 10.5</td>
<td>4.6</td>
<td>14.9 - 18.4</td>
</tr>
<tr>
<td>Hygroscopic nature</td>
<td>Water uptake</td>
<td>Swelling / water uptake</td>
<td>hydrofobic</td>
<td>Poor swelling / hydrofobic</td>
</tr>
<tr>
<td>Behavior in storage</td>
<td>Gets moldy, Dry matter loss</td>
<td>Deteriorates, gets moldy</td>
<td>Stable</td>
<td>Stable</td>
</tr>
</tbody>
</table>
CHAPTER 04: THERMOCHEMICAL CONVERSION OF BIOMASS

4.1. INTRODUCTION

As briefed in Section 1.4, thermo-chemical conversion methods represent one of the two main categories of biomass energy conversion technologies. Processes in this category include direct combustion, gasification, liquefaction and pyrolysis (carbonization, destructive distillation & fast pyrolysis). Figure 4.1 illustrates these processes, together with secondary fuels produced and the final energy forms. Each of these processes is described in details in the following sections.

![Figure 4.1: Direct combustion and thermo-chemical conversion of biomass](image)

4.2. DIRECT COMBUSTION

4.2.1 Combustion Basics

- **Combustion Reactions**

Combustion is a kind of chemical reaction, where a substance (called a fuel) is converted into chemical compounds (known as products of combustion) by combination with an oxidizer. In almost all chemical reactions heat is either supplied to the reaction or a product of the reaction. If heat must be added to a reaction, the reaction is said to be endothermic. If heat is
a product of a reaction, the reaction is said to be exothermic. The combustion process is an exothermic chemical reaction, i.e., a reaction that releases energy as it occurs. Thus combustion may be represented symbolically by:

\[
\text{Fuel} + \text{Oxidizer} \rightarrow \text{Products of Combustion} + \text{Energy}
\]

The above equation implies that the reactants (the fuel and the oxidizer) produce combustion products and energy. In combustion processes the oxidizer is usually air but could be pure oxygen. Chemical fuels exist in gaseous (e.g. natural gas, biogas), liquid (diesel, gasoline, fuel oil, bio fuel), or solid form (coal, biomass), which are each a complex mixture of reacting and inert compounds. The chemical energy released during combustion is either transferred to the surroundings, or it remains in the combustion products in the form of elevated internal energy (temperature), or some combination thereof. The amount of energy or heat released per unit mass of a fuel during combustion is known as the calorific value (or heating value), which is the negative of the standard enthalpy change of combustion.

Fossil fuels are hydrocarbons, meaning they are composed primarily of carbon and hydrogen. When fossil fuels are burned, carbon dioxide (CO₂) and water (H₂O) are the principle chemical products, formed from the reactants carbon and hydrogen in the fuel and oxygen (O₂) in the air. The simplest example of hydrocarbon fuel combustion is the reaction of methane (CH₄) with O₂, as given below:

\[
\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O} + \text{Heat Energy}
\]

The amount of a substance present in a reaction may be indicated by its mass or by the number of moles of the substance. A mole is defined as the mass of a substance equal to its molecular mass or molecular weight (a few molecular weights commonly used in combustion analysis are given in Table 4.1). When this reaction is balanced, each molecule of methane reacts with two molecules of O₂ producing one molecule of CO₂ and two molecules of H₂O.

While not evident in the above example, it is not necessary that there be the same number of moles of products as reactants. It will be seen in numerous other cases that a different number of moles of products is produced from a given number of moles of reactants. Thus although the numbers of atoms of each element must be conserved during a reaction, the total number of moles need not. Because the number of atoms of each element cannot change, it follows that the mass of each element and the total mass must be conserved during the reaction. Thus, using the atomic weights (masses) of each element, the sums of the masses of the reactants and products in the above equation are both 80.
Table 4.1: Molecular weights of substances associated with combustion

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Molecular Weight (kg/kg-mole)</th>
<th>Molecule</th>
<th>Molecular Weight (kg/kg-mole)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>12</td>
<td>CO₂</td>
<td>44</td>
</tr>
<tr>
<td>H</td>
<td>1</td>
<td>H₂O</td>
<td>18</td>
</tr>
<tr>
<td>O</td>
<td>16</td>
<td>CO</td>
<td>28</td>
</tr>
<tr>
<td>N</td>
<td>14</td>
<td>SO₂</td>
<td>64</td>
</tr>
<tr>
<td>S</td>
<td>32</td>
<td>SO₃</td>
<td>80</td>
</tr>
<tr>
<td>O₂</td>
<td>32</td>
<td>NO₂</td>
<td>46</td>
</tr>
<tr>
<td>N₂</td>
<td>28</td>
<td>N₂O</td>
<td>44</td>
</tr>
</tbody>
</table>

During combustion, a number of chemical reactions take place. These reactions do not simply involve the addition of oxygen to carbon and hydrogen in the fuel to produce heat. The reaction equations represent initial and final results and do not indicate the actual path of the reaction, which may involve many intermediate steps and intermediate species. There is a combination of number of primary reactions as well as secondary reactions (in which the products of the primary reactions also take part). In the case of biomass gasification too, some of these reactions occur, resulting combustible gaseous products than the final products shown above (see Section 4.3.2). The principal reactions can be summarized as [7]:

\[
\begin{align*}
\text{C (Graphitic)} + \text{O}_2 \text{ (Gas)} & \rightarrow \text{CO}_2 \text{ (Gas)} + 178,430 \text{ kJ} \\
\text{C (Graphitic)} + \text{CO}_2 \text{ (Gas)} & \rightarrow 2\text{CO} \text{ (Gas)} - 78,210 \text{ kJ} \\
2\text{CO} \text{ (Gas)} + \text{O}_2 \text{ (Gas)} & \rightarrow 2\text{CO}_2 \text{ (Gas)} + 256,640 \text{ kJ} \\
2\text{H}_2 \text{ (Gas)} + \text{O}_2 \text{ (Gas)} & \rightarrow 2\text{H}_2\text{O} \text{ (Gas)} + 219,300 \text{ kJ} \\
\text{C (Graphitic)} + \text{H}_2\text{O} \text{ (Gas)} & \rightarrow \text{CO} \text{ (Gas)} + \text{H}_2 \text{ (Gas)} - 59,540 \text{ kJ} \\
\text{C (Graphitic)} + 2\text{H}_2\text{O} \text{ (Gas)} & \rightarrow \text{CO}_2 \text{ (Gas)} + 2\text{H}_2 \text{ (Gas)} + 40,870 \text{ kJ} \\
\text{CO} \text{ (Gas)} + \text{H}_2\text{O} \text{ (Gas)} & \rightarrow \text{CO}_2 \text{ (Gas)} + \text{H}_2 \text{ (Gas)} + 18,670 \text{ kJ}
\end{align*}
\]

The heat of reaction corresponds to a base temperature of 25°C at constant pressure. The extent of completion of these reactions is dependent on a number of factors, such as equilibriums, specific reaction rate, and contact catalysis. The first reaction given above predominates at temperatures below 600°C, while second reaction predominates at temperatures above 800°C. The performance of a combustion system on the whole depends on the physico-chemical and thermo-chemical properties of the fuel.
- **Heating Value and Bond Energy**

As the energy transferred in a chemical process originates on the braking and making of bonds, the enthalpy of reaction and thereby the heating value can be calculated by bond energies, as illustrated in Figure 4.2 and Table 4.2 for combustion of CH$_4$ in O$_2$.

**Table 4.2: Average bond energies**

<table>
<thead>
<tr>
<th>Single Bond</th>
<th>Bond Energy (kJ/mol)</th>
<th>Double/Triple Bond</th>
<th>Bond Energy (kJ/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O-O</td>
<td>139</td>
<td>O=O</td>
<td>498</td>
</tr>
<tr>
<td>O-H</td>
<td>470</td>
<td>C=O</td>
<td>800</td>
</tr>
<tr>
<td>H-H</td>
<td>435</td>
<td>C=C</td>
<td>615</td>
</tr>
<tr>
<td>C-C</td>
<td>348</td>
<td>N=O</td>
<td>607</td>
</tr>
<tr>
<td>C-H</td>
<td>414</td>
<td>C=N</td>
<td>615</td>
</tr>
<tr>
<td>C-O</td>
<td>32</td>
<td>N=N</td>
<td>418</td>
</tr>
<tr>
<td>N-O</td>
<td>222</td>
<td>C ≡ C</td>
<td>812</td>
</tr>
<tr>
<td>S-S</td>
<td>214</td>
<td>N ≡ N</td>
<td>946</td>
</tr>
<tr>
<td>N-N</td>
<td>161</td>
<td>C ≡ N</td>
<td>890</td>
</tr>
</tbody>
</table>
The above methodology of calculating heating value is generally applicable to fuels with known chemical bonds, such as gaseous fuels. In solid and liquid fuels the chemical bond type of the components is not known so that the heating value must always be determined experimentally.

In fuels, the combustion reactions are more complex than above, as, in general, air is used in combustion than pure oxygen and fuels consists of many elements such as C, H, N, S, and O (see Table 2.4 for composition of waste agricultural biomass). However, in many waste agricultural biomass materials, the amounts of N and S are negligible, and the composition could be represented by $C_xH_yO_z$. For example, the coefficients of $x$, $y$ and $z$ for several waste agricultural biomass materials are presented in Table 4.3, along with average values [20], [45]. It is evident that these coefficients are more or less same in all the cases. Consequently, the heating values too become very similar. Further, the table also gives density of the waste agricultural biomass. Except for coconut shell, all other materials have considerably lower density indicating bulkiness of agro residues.

Table 4.3: Elementary composition of waste agricultural biomass materials

<table>
<thead>
<tr>
<th>Biomass</th>
<th>Composition ($C_xH_yO_z$) (Moisture and Ash free basis)</th>
<th>Ash (Moisture and Ash free basis)</th>
<th>HHV (MJ/kg)</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$x$</td>
<td>$y$</td>
<td>$z$</td>
<td>(% by weight)</td>
</tr>
<tr>
<td>Bagasse</td>
<td>3.65</td>
<td>5.8</td>
<td>2.94</td>
<td>2.9</td>
</tr>
<tr>
<td>Coconut coir</td>
<td>3.97</td>
<td>5.7</td>
<td>2.85</td>
<td>0.9</td>
</tr>
<tr>
<td>Coconut shell</td>
<td>4.18</td>
<td>5.7</td>
<td>2.71</td>
<td>0.7</td>
</tr>
<tr>
<td>Coir pith</td>
<td>3.67</td>
<td>4.7</td>
<td>2.71</td>
<td>7.1</td>
</tr>
<tr>
<td>Corn cob</td>
<td>3.97</td>
<td>5.0</td>
<td>2.79</td>
<td>2.8</td>
</tr>
<tr>
<td>Corn stalks</td>
<td>3.49</td>
<td>5.3</td>
<td>2.88</td>
<td>6.8</td>
</tr>
<tr>
<td>Cotton gin waste</td>
<td>3.56</td>
<td>6.0</td>
<td>3.10</td>
<td>5.4</td>
</tr>
<tr>
<td>Ground nut shell</td>
<td>4.03</td>
<td>5.7</td>
<td>2.46</td>
<td>5.9</td>
</tr>
<tr>
<td>Millet husk</td>
<td>3.56</td>
<td>6.0</td>
<td>2.063</td>
<td>18.1</td>
</tr>
<tr>
<td>Paddy husk</td>
<td>3.24</td>
<td>5.1</td>
<td>2.0</td>
<td>23.5</td>
</tr>
<tr>
<td>Paddy straw</td>
<td>3.08</td>
<td>5.0</td>
<td>2.37</td>
<td>19.8</td>
</tr>
<tr>
<td>Subabul wood</td>
<td>4.02</td>
<td>5.9</td>
<td>2.82</td>
<td>0.9</td>
</tr>
<tr>
<td>Wheat straw</td>
<td>3.96</td>
<td>5.4</td>
<td>2.24</td>
<td>11.2</td>
</tr>
<tr>
<td>Average</td>
<td>3.72</td>
<td>5.48</td>
<td>2.61</td>
<td>8.2</td>
</tr>
</tbody>
</table>
Combustion in Air

Dry air is a mixture of about 20.9% O₂, 78.1% N₂, and 0.9% other constituents (such as CO₂, Ar, He, Ne and H₂) by volume. For combustion calculations it is usually satisfactory to represent air as 21% O₂, 79% N₂, by volume. Thus for every 21 moles of oxygen that react when air oxidizes a fuel, there are also 79 moles of nitrogen involved. Therefore, 79/21 = 3.76 moles of nitrogen are present for every mole of oxygen in the air.

Now consider the complete combustion of methane in air. The same combustion products are expected as with combustion in oxygen, the only additional reactant present is nitrogen. At ordinary combustion temperatures, N₂ is inert, but nonetheless greatly affects the combustion process because its abundance, and hence its enthalpy change, plays a large part in determining the reaction temperatures. Since in air every mole of oxygen is accompanied by 3.76 moles of nitrogen, the reaction equation can be written as

\[
\text{CH}_4 + 2\left[\text{O}_2 + 3.76\text{N}_2\right] \rightarrow \text{CO}_2 + 2\text{H}_2\text{O} + 7.52\text{N}_2 + \text{Heat.}
\]

Nitrogen reduces combustion efficiency by absorbing heat from the combustion of fuels and diluting the flue gases. This reduces the heat available for transfer through the heat exchange surfaces. It also increases the volume of combustion by-products. A small quantity of nitrogen can combine with oxygen (particularly at high flame temperatures) to produce oxides of nitrogen (NOₓ), which are toxic pollutants.

The complete combustion equation presented in Section 2.2.3 could be rewritten for a general fuel with a composition represented by CₓHᵧOₖ as

\[
\text{C}_x\text{H}_y\text{O}_z + \left(x + \frac{y-2z}{4}\right)\left[\text{O}_2 + 3.76\text{N}_2\right] \rightarrow x\text{CO}_2 + \frac{y}{2}\text{H}_2\text{O} + 3.76\left(x + \frac{y-2z}{4}\right)\text{N}_2 + \text{Heat.}
\]

Further, in addition to complete combustion, fuels undergo incomplete combustions too, generating other products such as carbon monoxide (CO), methane (CH₄), hydrogen (H₂), etc.

Air-Fuel Ratio

It is important to know how much oxygen or air must be supplied for complete combustion of a given quantity of fuel. This information is required in sizing fans and ducts that supply oxidizer to combustion chambers or burners and for numerous other design purposes. The mass air-fuel ratio, AFR, or oxygen-fuel ratio, OFR, for complete combustion may be determined by calculating the masses of oxidizer and fuel from the appropriate reaction
equation. Oxidation all the elements or components in a fuel is known as complete combustion or “Stoichiometric Combustion”. The amounts of fuel and air taking part in a combustion process are often expressed as the ‘air to fuel’ ratio:

\[ AFR = \frac{m_{air}}{m_{fuel}}. \]

For stoichiometric combustion of a fuel with a composition \( C_xH_yO_z \), the \( AFR \) for becomes

\[ AFR_{Stoich} = \frac{34.32 \times (4x + y - 2z)}{(12x + y + 16z)} \]

For example, in case of combustion of methane, \( x = 1, y = 4 \) and \( z = 0 \), \( AFR_{Stoich} = 17.16 \). In case of waste agricultural biomass with average composition given in Table 4.3, \( AFR_{Stoich} \) becomes 5.66. \( AFR_{Stoich} \) for some fuels is given in Table 4.3. An equivalent term to the \( AFR \) is the fuel/air ratio \( FAR \). Minimum amount of air (or oxygen) required to have a complete combustion is represented by Stoichiometric Ratio \( FAR_{stoich} \).

**Table 4.4: \( AFR_{Stoich} \) for some fuels**

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Phase</th>
<th>( AFR_{Stoich} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very light fuel oil</td>
<td>liquid</td>
<td>14.27</td>
</tr>
<tr>
<td>Light fuel oil</td>
<td>liquid</td>
<td>14.06</td>
</tr>
<tr>
<td>Medium heavy fuel oil</td>
<td>liquid</td>
<td>13.79</td>
</tr>
<tr>
<td>Heavy fuel oil</td>
<td>liquid</td>
<td>13.46</td>
</tr>
<tr>
<td>Generic Biomass</td>
<td>solid</td>
<td>5.88</td>
</tr>
<tr>
<td>Coal</td>
<td>solid</td>
<td>6.97</td>
</tr>
<tr>
<td>Methane</td>
<td>gas</td>
<td>17.16</td>
</tr>
<tr>
<td>LPG (90 Propane : 10 Butane)</td>
<td>gas</td>
<td>15.55</td>
</tr>
<tr>
<td>Carbon</td>
<td>solid</td>
<td>11.44</td>
</tr>
</tbody>
</table>

In order to obtain complete combustion, supply of excess amount of air (or oxygen) is required in practice. The amount of excess air required depends on the properties of the fuel and the technology of the combustion device. This quantity is usually represented by the equivalence ratio, \( \phi \), or the excess air factor \( \lambda \):

\[ \phi = \frac{1}{\lambda} = \frac{FAR}{FAR_{stoich}} \]
Excess air is defined as the difference between the actual and the theoretical air supplied. Accordingly, the percentage of excess air is

\[
\text{\% excess air} = 100 \left[ \frac{\text{AFR}_{\text{actual}} - \text{AFR}_{\text{stoich}}}{\text{AFR}_{\text{stoich}}} \right]
\]

Table 4.5 presents usual amount of excess air supplied to fuel-burning equipment [46].

**Table 4.5: Typical amount of excess air supplied to fuel burning equipment**

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Type of Furnace or Burners</th>
<th>Excess air % by weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulverized Coal</td>
<td>• Completely water-cooled furnace for slag-tap or dry-ash-removal</td>
<td>15 – 20</td>
</tr>
<tr>
<td></td>
<td>• Partially water cooled furnace for dry-ash-removal</td>
<td>15 - 40</td>
</tr>
<tr>
<td>Crushed coal</td>
<td>Cyclone furnace – pressure or suction</td>
<td>10 - 15</td>
</tr>
<tr>
<td>Coal</td>
<td>• Spreader stroker</td>
<td>30 – 60</td>
</tr>
<tr>
<td></td>
<td>• Water-cooled vibrating grate stroker</td>
<td>30 – 60</td>
</tr>
<tr>
<td></td>
<td>• Chain-grate and traveling grate strokers</td>
<td>15 – 50</td>
</tr>
<tr>
<td></td>
<td>• Underfeed stroker</td>
<td>20 - 50</td>
</tr>
<tr>
<td>Fuel oil</td>
<td>• Oil burners, register type</td>
<td>5 – 10</td>
</tr>
<tr>
<td></td>
<td>• Multi-fuel burners and flat-flame</td>
<td>10 - 20</td>
</tr>
<tr>
<td>Acid sludge</td>
<td>Cone and flat-plate-type burners, steam-atomized</td>
<td>10 - 15</td>
</tr>
<tr>
<td>Natural coke ovens and refinery gas</td>
<td>• Register-type burners</td>
<td>5 – 10</td>
</tr>
<tr>
<td></td>
<td>• Multi-fuel burners</td>
<td>7 - 12</td>
</tr>
<tr>
<td>Blast furnace gas</td>
<td>Intertube nozzle-type burners</td>
<td>15 - 18</td>
</tr>
<tr>
<td>Wood</td>
<td>Dutch oven and Hoftt-type</td>
<td>35 – 50</td>
</tr>
<tr>
<td>Bagasse</td>
<td>All furnaces</td>
<td>25 - 35</td>
</tr>
<tr>
<td>Black liquor</td>
<td>Recovery furnace for kraft and soda-pulping processes</td>
<td>5 - 7</td>
</tr>
</tbody>
</table>

However, supplying too much excess air will decrease combustion efficiency. The extra or excess air must be drawn through the process’s fans, thus requiring extra power, and the air must be heated in the process before being exhausted out of the stack or vent, thus causing an added heat loss. A fine line must always be drawn between too much excess air and incomplete combustion, which will manifest in high levels of carbon monoxide. Figure 4.3 illustrates this concept.
3-T Principle in Combustion

The objective of good combustion is to release all of the heat in the fuel. This is accomplished by controlling the "three Ts" of combustion, which are

- **Temperature** high enough to ignite and maintain ignition of the fuel,
- **Turbulence** or intimate mixing of the fuel and oxygen, and
- **Time**, sufficient for complete combustion.

For sustained combustion the temperature of fuel/air mixture must be at temperature above ignition temperature. For combustion each fuel molecule must be in contact with at least required number of molecules of O₂. This is only possible when fuel and O₂ is mixed on molecule to molecule basis. This complete mixing will require turbulence in fuel in gaseous form and air. To ensure that each gaseous molecule meets the O₂ molecule, the fuel air mixture must stay for sufficient longer period in region where temperature is more than the ignition temperature. These three conditions govern the speed and completeness of a combustion reaction. They depend on each other, because changing one affects the other two.
- **Industrial Combustion Modes**

A wide variety of solid, liquid and gaseous fuels is used in domestic, commercial and industrial and transport sectors as combustion fuels for energy generation. Conventionally solid fuels (originally biomass and later coal and solid waste material) were used, followed by introduction of liquid (petroleum and bio-fuels), and more recently gaseous fuels. This shift of physical form of fuels from solid to liquid and then to gas is basically linked to energy and environmental performances. A comparative picture of heating values of commonly available fuels is presented in Figure 4.4.

![Bar chart showing heating values of different fuels](image)

**Figure 4.4: Heating values of different fuels**

Traditional industrial combustion processes were primarily based on the concept of atmospheric air being encouraged to rise through a bed of fuel originally containing wood but later various forms of lump coal with the aid of a grate (fixed or moving). Systems with moving grates are described as a stoker fired furnaces of which there a several basic types. Modern coal-fired power stations burn pulverized coal, which is blown into the combustion chamber of a power plant through a specially designed burner. The burner mixes air with the powdered coal, which then burns in a flame in the body of the combustion chamber. This is suspension combustion and in this type of plant there is no grate. Finely ground wood, rice husk, bagasse, or sawdust can be burned in a similar way.

Most recently, there has been a trend towards the development of various forms of fluidized beds for combustion of coal and other solid fuels. Liquid fuels have been traditionally burned
in various forms of pot burners, but modern liquid fuel burners employ atomizing devices to produced fine droplets of the fuel. Finally gaseous fuels are exclusively fired in burners which give rise to flames. These may be produced by premixing the gaseous fuel and the air to give a “premixed” flame. Figure 4.5 above presents different types of flames formed in industrial combustion systems, which depend upon the fuel and the burner design (adopted from [47]).

![Flames in industrial combustion systems](image)

**Figure 4.5: Flames formed in industrial combustion systems**

- **Heat Transfer**

Another important aspect associated with heat generation in combustion process is the transfer of thermal energy from one place to another. This process occurs in one of three ways: conduction, convection, and radiation. The flow of heat by conduction occurs via collisions between atoms and molecules in the substance and the subsequent transfer of kinetic energy. Conduction occurs when two bodies of different temperatures are in contact with each other. Here, rapidly moving molecules in a hot material collide with slower moving molecules in a cool material. The fast-moving molecules slow down and the slow-moving molecules increase their speed.
Convection is the flow of heat through a bulk, macroscopic movement of matter from a hot region to a cool region, as opposed to the microscopic transfer of heat between atoms involved with conduction. For example, when water in a container is heated, it expands. Cooler water around it pushes the lighter water upward. As the warm water rises, it begins to cool and starts to move downward in the liquid again. Eventually, a circular motion is produced within the liquid, forcing heat to be transferred throughout the liquid. Thermal energy can also be transferred by radiation. Hot bodies emit electromagnetic radiation that corresponds to their temperature. This radiation passes through space until it comes into contact with a body with less thermal energy. The cooler body then absorbs this radiation and becomes warmer.

4.2.2 Biomass Combustion

As discussed in Section 1.3, biomass materials mainly comprised of cellulose, hemicelluloses and lignin, each consists of three basic elements: carbon, oxygen and hydrogen. In addition, elements such as sulfur and nitrogen could also be present. In such case, the chemical equation can be expressed in a very convenient form, as a stoechiometry formula written for one atom of carbon as \( \text{CH}_x\text{O}_y\text{N}_z\text{S}_u \). For pure and dry biomass fuels of the ligno-cellulosic type, nitrogen and sulfur are usually negligible and the chemical formula may be rewritten as follows: \( \text{CH}_x\text{O}_y \) with \( x \cong 1.44 \) and \( y \cong 0.66 \) describing the average composition of typical biomass used for combustion, i.e., wood, straw, or similar material.

As a result of the combustion process, different types of pollutants can be distinguished:

- Unburned pollutants such as CO, \( C_xH_y \), PAH, tar, soot, unburnt carbon, H\(_2\), HCN, NH\(_3\), and N\(_2\)O;
- Pollutants from complete combustion such as NO\(_X\) (NO and NO\(_2\)), CO\(_2\), and H\(_2\)O; and
- Ash and contaminants such as ash particles (KCl, etc.), SO\(_2\), HCl, PCDD/F, Cu, Pb, Zn, Cd, etc.

Biomass combustion is a complex process in which processes of devolatilization, cracking and combustion take place almost simultaneously. The amount of energy released during combustion reaction depends on the temperature, pressure, the products of reaction and the state of water produced. These last two factors are important because incomplete combustion will result in the production of carbon monoxide and other combustible materials, which results in the loss of potential energy of fuel. Liquid or vapour state of water, produced during
The combustion of hydrogen in the fuel, will affect the net heat released. This complex process occurs in 3-stages [7], as described below (also refer Figure 4.6).

**Figure 4.6: Processes and temperatures in a burning piece of wood**

- **Stage 1 Combustion**
  Easily combustible kindling (such as tree leaves, wood shavings, and kerosene) on burning raises the temperature of the spot on which the radiation from the flame is incident. This heat gets distributed throughout the material due to conductive heat transfer, thus raising the temperature of the material. When the temperature rises to 100°C, drying of wood takes place due to loss of absorbed and weakly bound water. This process continues into the deep interior; a part of the heat of combustion is utilized in this heat consuming (endothermic) process. Hence, the higher the moisture content of the wood, the greater is the loss of energy.

- **Stage 2 Combustion**
  As the temperature is raised further, the pyrolytic decomposition of the wood starts. At a temperature of about 150°C, the release of volatile matter begins along with the appearance of semi-liquid tar. In case this stage gets prolonged due to quenching of the flame, the fuel starts smoldering and dark or gray/blue smoke with a strong smell is given off. This results in the loss of some useful energy of wood. The tar gets deposited in the tunnels/chimney resulting in choking. There is also the danger of fire due to the spontaneous combustion of the deposited tar. Tar also gets deposited on the cold surface of the pots resulting in their blackening.
- **Stage 3 Combustion**

Volatile matter, being at a higher temperature, rises due to the buoyancy force. During the rise, it mixes with the surrounding air. If sufficient heat is available, this mixture of volatile matter may reach the combustible limit and get ignited. The flame resulting from combustion may persist if the heat released from the flame is sufficient for sustained release of more volatiles from the burning surface. Otherwise, it will flash back to the surface. Self-sustained combustion commences at around 225°C and reaches a peak at about 300°C. During this stage, heat released by the combustion process is more than the combined losses and hence there is a net positive release of heat. Thus, the understanding of the pyrolysis process and the subsequent burning of the released volatile matter and char is necessary for the evaluation of the combustion process. The second stage determines the extent and nature of volatiles and the char generated while the third stage determines the extent to which the potential heat in the volatile matter and char is released. For the best design of the combustion chamber, the following factors (which govern the rate of pyrolysis) must be taken into full consideration: the temperature, rate of heating, residence time of biomass in the combustion chamber and physical characteristics of the fuel such as size and shape. Furthermore, an understanding of the heat level required for ignition as well as for the maintenance of combustion and their dependence on the thermo-physical properties such as density, specific heat, thermal conductivity, calorific value and moisture content is essential.

- **Combustion of the Products of Pyrolysis**

Combustion of the products of pyrolysis of biomass, in particular, char and volatiles, takes place in two modes, flaming combustion of the volatiles and glowing combustion of the char. The complete process is shown in Figure 4.7 and Figure 4.8 (adopted from [7]).

![Figure 4.7: Schematic view of wood combustion](image-url)
(i) *Combustion of volatiles*

The composition of the volatiles is variable and depends on the temperature of pyrolysis and the length of time that these volatiles are subjected to an elevated temperature. Thus, the combustion of volatiles is a complex process. The higher the temperature of the pyrolytic zone, more severe is the cracking of the higher molecules into smaller ones, which in turn burn more readily. Wood fires generally produce a diffusion flame. This consists of a jet of flammable gas with a combustion reaction taking place at the air-gas interface, resulting in the formation of hot gaseous combustion products and heating the remainder of the gas to some extent. The products of combustion are lighter due to their high temperature resulting in a vertical rise-up. During the ascent, these products also entrain some surrounding air.

Another process, which takes place simultaneously, is the diffusion of air into a jet of gas through the difference in the partial pressure of the constituents. Diffusion of air into unburnt volatile material at high temperature results in the combustion of volatile material. Soot and unburnt chemical compounds are formed if the temperature of the combustion zone is not sufficient. Temperature can fall below ignition temperature due to the quenching effect of the entrained air or the contact of the flame with a cold surface. If the residence time of the flammable gas at a higher temperature is long, then hydrocarbons of progressively higher carbon contents are formed due to partial oxidation.
(ii) **Glowing combustion**

Char, which is a solid carbon residue left after the release of volatile matter, burns with a glowing flame (see Figure 4.9). When the combustion takes place at the surface, carbon dioxide is formed with the liberation of heat. However, if the combustion reaction takes place in the bed or char at high temperature, then carbon dioxide is reduced to carbon monoxide. This must be burnt with secondary air to produce carbon dioxide and heat. Otherwise, it will result in the loss of potential heat as well as cause pollution.

![Image](image.png)

**Figure 4.9: Wood combustion modes**

### 4.2.3 Combustion Controlling Factors

Important factors which influence combustion are:

- Physical and chemical properties of the fuel;
- Fuel/air ratio;
- Temperature of the flame/envelope;
- Mode of fuel supply;
- Primary and secondary air supplies.

- **Physical and chemical properties**

The combustion process is greatly influenced by the relative proportion of macroscopic constituents of the biomass, namely: cellulose, hemicelluloses and lignin. The relative proportion of these constituents varies in different species of biomass. A combustion chamber designed to burn fuels rich in cellulose will require a better control of secondary air due to production of more volatiles. On the other hand, primary air considerations become more important in a fuel containing more lignin.
- **Size and shape of the fuel**
  Volume to surface ratio of the wood fuel is dependent on its size. This ratio has an important bearing on the combustion characteristics of the wood and other woody biomass. Fire penetration rate, which is the rate at which the char boundary advances into the virgin wood is a function of volume/surface ratio. With the increase in volume/surface ratio, CO/CO2 ratio also increases due to increase in the release of volatiles, which remain unburnt as a result of insufficient availability of air.

- **Primary and secondary air supplies**
  The introduction of the right amount of air alone is not enough. 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. This will decide the area of the openings for induction of primary and secondary air. Primary air is supplied through the holes in the grate or the side opening. It has been found that it is not possible to get a power output of more than 4 kW in a shielded fire when side holes are used for the air inlet. Figure 4.10 presents a schematic diagram of a wood burning hot water boiler, showing primary and secondary combustion air supplies.

![Figure 4.10: Schematic view of a wood fired hot water boiler](image)

(A) Primary combustion air inlet  
(B) Secondary combustion air inlet  
(C) Secondary air adjustment lever  
(D) System return water inlet  
(E) Hot water flow  
(F) Combustion product outlet  
(G) Ash drawer  
(H) Coil for heat discharge
• **Fuel/air ratio**

As discussed in Section 4.2.1, a proper air to fuel ratio is essential for efficient combustion of fuel. Both rich (deficient in air) and lean (deficient in fuel) fuel/air mixtures will result in incomplete combustion. Wood contains nearly 43-44% oxygen and hence a major part of the oxygen required for combustion is supplied by the wood fuel itself while the rest is to be provided from the air. This is in contrast to other solid fuels like coal where a large amount of oxygen from the air is required.

Due to the heterogeneous nature of the solid biomass combustion process, only a part of the air entering a combustion chamber is utilized in the chemical process of combustion, while the rest of the air simply passes through the combustion chamber. Thus, it becomes necessary to admit more air, than theoretically required. An excess air factor of 1.3 to 1.5 is generally recommended for good combustion (see Table 4.5). In other words, one kg of wood needs 1.4 kg of oxygen or 6.5 kg of air. Applying the excess air factor of 1.5, then the total quantity of air needed becomes about 9.75 kg. To raise this amount of air to the average flue gas temperature of 450°C would require heat of 4.4 MJ.

The design of the air inlet in the fire box is based on the excess air factor. Experiments show that there is a sharp increase in the CO formation if the excess air factor falls below 2. However, the excess air factor required for complete combustion of fixed carbon and volatiles is not necessarily the same. It is proposed that no excess air is required to burn charcoal on the fuel bed. In that case, even if excess air is supplied to the fuel bed, it will act as secondary air and the combustion of charcoal will not benefit. The rate at which primary and secondary air must be supplied depends on the heat requirement during cooking and the way the fire is tended.

• **Temperature of the flame**

Combustion can be hindered if the flame comes in contact with a cold surface, due to the quenching effect. The temperature of the gases near the cold surface decreases below the ignition temperature, due to loss of heat to the cold surface, irrespective of the presence of hot gases nearby. Thickness over which no flame exists, known as quenching distance, is a function of temperature of the surrounding/enclosure and decreases with the temperature. Incomplete combustion is responsible for soot deposition on the cold surface or the smoke in
the flue gas. Thermal stratification due to quenching can be reduced by generating artificial turbulence, to ensure the mixing of gas and air and increase residence time. This can be easily done by introducing design innovations.

From the thermodynamic and heat transfer perspective, the flame temperature should be as high as possible. For example, in the case of biomass based cooking, one of the major reasons for the popularity of open-fire cooking is rapid cooking of food as the pot is surrounded by the flame, the temperature of which exceeds 800°C.

The thermodynamic efficiency of the combustion process is given by the ratio \((T_2 - T_1)/T_1\), where \(T_2\) is the highest temperature attained by the flame and \(T_1\) is the outlet temperature of the gas. Thermal efficiency is more dependent on the flame temperature than the flue gas outlet temperature as the latter varies within a small range. Actual temperature is difficult to measure as there is a variation in local temperature at different points in the flame, since air/fuel mixing as well as combustion processes are not instantaneous. Hence, a theoretical flame temperature is generally used in the combustion calculations. The theoretical flame temperature is not only a function of the calorific value of wood but also of the excess air factor. Under perfect combustion conditions and the use of a theoretical quantity of air for combustion, the flue gas should contain only carbon dioxide, water vapours and nitrogen. However, under actual conditions, the products of combustion contain unburnt materials such as carbon monoxide, hydrogen and solid and liquid materials which form smoke. In addition, considerable heat losses take place in the combustion chamber. Because of this the actual flame temperature is usually 30-170°C lower than the theoretical flame temperature.

- **Fuel Supply**

Combustion is also influenced by the mode of fuel supply. Fuel can be supplied in three modes, namely: continuous, stored and batch. In large scale combustion of biomass in heat and/or power generation applications, it is supplied in continuous mode. On the other hand, in cookstoves, it is generally supplied in batch mode in which fuel is supplied in charges of small quantities. A number of charges are, therefore, needed in one cooking job. A lot of heat is absorbed by the fresh charge which is responsible for low power output. Thus, it can be concluded that the smaller the charge of the fuel, the more unsteady is the behaviour of the fire. The storage mode of fuel charging requires sufficient care so that the bulk of the fuel
does not come in contact with the high temperature, which will result in uncontrollable spontaneous combustion.

4.2.4 Direct Combustion Technologies

Combustion technology is typically the lowest-cost biomass-to-energy technology to construct and operate, especially for woody fuels. Combustion systems can be designed to burn almost any type of biomass fuel, including agro residues, dry manure and MSW. Fuels can be mixed to cope with diversity in the fuel supply or to provide optimum combustion performance. In conventional biomass combustion systems such as cook stoves, furnaces, kilns, barns, etc., the hot flu gas generated is used directly or indirectly for the process heating. In addition, biomass combustion facility can produce steam, electricity, or both (CHP). At present, combustion is making a comeback in many industrial applications. This can range from simple systems such as stoves, furnaces and boilers to more advanced systems like fluidized bed combustion technology. A boiler furnace burns the biomass to create steam. If electrical output is desired, a steam-turbine generator is used to convert a portion, or all, of the steam to electricity. However, straightforward conversion of thermal energy into mechanical or electric power results in considerable losses: it is not possible to raise the ratio of thermal to mechanical power above 60%. However, if the low temperature waste heat can be used productively, for instance for drying or heating purposes, much higher overall efficiencies can be obtained.

Five basic types of combustion technologies are used for the burning of wood or biomass residues:
- Grateless combustors,
- Pile burning combustors,
- Stoker burning combustors,
- Suspension burners, and
- Fluidized bed burners.

In any wood energy application the combustion unit is designed to make the best use of temperature, turbulence, and time (3-T’s). All three of these aspects relate directly to the properties of the wood fuel to be used (moisture content, particle size, ash content, and heat value).
Grateless Combustors

These combustors are for small burning rates (< 10 kg/h) and heat release capacity is very low (0.05-0.15 MW/m²). They have very low combustion efficiency, overall efficiency and capacity; they also give lot of emissions. The technique of grateless combustion is generally used in a wide variety of cookstoves, fire places, traditional kilns, ovens and heaters in domestic and industrial sectors, where the combustor cost is a minimum (see Figure 4.11).

(a) Domestic fire-place  (b) Single-pot cookstove

Figure 4.11: Grateless combustors

The open fireplace is still a normal fixture in town houses and even apartment buildings in many countries, despite the installation of modern central heating systems, and in rural areas and in tropical countries having cold winters it is still often the only method of heating. An advance on the open fire was to enclose the flame completely, the result being the stove or furnace. The primitive stove had no grate. In short, the practice was to burn a pile of billets in an empty space enclosed by flat stones. Because of the large excess of air, combustion was poor, the temperature of combustion relatively low and it was practically impossible to regulate heat output.

Attempts were made to replace the grateless stove by one with a wrought iron base or some other such apparatus, but without much success. Yet, because of the simplicity of wood combustion, quite good results can be obtained by improving the design of the fuel chamber, the flues and the air intake. Besides, a grateless stove is always better than one with a poor grate that is too large, badly shaped or creates too strong a draft. In many places it is still thought better to burn wood in a grateless stove, but this idea is wrong. The efficiency of a grateless stove is always inferior to that of one with a good grate.
Though small in size, biomass combustion of in cookstoves has attracted much attention due to its scale of usage and impact on indoor air pollution. Many organizations have been engaged in the development, testing and dissemination of improved cookstoves (ICSs) throughout the developing world of Asia, Africa and Latin America. Burning of wood in small enclosures can be classified as controlled combustion in contrast to free burning of wood in an open fire. However, the operation of the cookstove is dynamic in nature because of the interdependence between the rate of combustion, rate of induction of air and the draft. The rate of combustion is strongly dependent on the manner in which the combustion air is supplied. In the case of small enclosures, the combustion takes place due to the pressure field set up as a result of the upward movement of combustion products and entrainment of air through the fire-box opening. On the other hand, combustion in open-fire is maintained through the laminar or turbulent entrainment of outside air, depending on the size of fire. Hence, apart from combustion, fluid flow considerations are equally important in the design.

A cookstove is best considered as a consumer-specific device. Both engineering and non-engineering parameters need to be taken into consideration in designing an appropriate ICS. Many improved cookstove designs have been proposed to suit with different consumer needs. Figure 4.12 shows some ICSs (except E: the 3-stone stove) developed in the recent past [48].

ICS design considerations can be classified into three major criteria, namely: social, engineering, and developmental and ecological. Inter-linkages between these parameters are shown in Figure 4.13 [49].
Figure 4.13: Design considerations for a stove
- **Pile burning combustors**

Pile burning combustors have fixed bed systems with grates, but no mechanical movement is provided to the grates or the fuel charge. The grates serve to support the fuel, partially separate ash from the combustion zone, air flow to the bed, promotes the turbulence and reduce emission of CO. However, large burning rates and heat fluxes cannot be achieved.

Boilers incorporating a pile burning design find applications where the anticipated woody biomass has a high moisture content (up to 65% on wet basis), as is found in whole green tree chips, bark, and green mill residue. Grate furnaces are appropriate for biomass fuels with a high moisture content, varying particle sizes (with a downward limitation concerning the amount of fine particles in the fuel mixture), and high ash content. Mixtures of wood fuels can be used, but current technology does not allow for mixtures of wood fuels and straw, cereals and grass, due to their different combustion behaviour, low moisture content, and low ash-melting point.

The most common form of pile burning is the Dutch oven (see Figure 4.14). Although the Dutch Oven can burn fuel of different consistencies and high moisture content, slow response to demand load swings due to the thermal inertia of the fuel pile can create problems.

![Dutch oven furnace diagram](image)

**Figure 4.14: Dutch oven furnace**

A good and well-controlled grate is designed to guarantee a homogeneous distribution of the fuel and the bed of embers over the whole grate surface. This is very important in order to guarantee an equal primary air supply over the various grate areas. Inhomogeneous air supply
may cause slagging, higher fly-ash amounts, and may increase the excess oxygen needed for a complete combustion. Furthermore, the transport of the fuel over the grate has to be as smooth and homogeneous as possible in order to keep the bed of embers calm and homogeneous, to avoid the formation of "holes" and to avoid the elutriation of fly ash and unburned particles as much as possible.

A pile burning system may have provision for (a) continuous/batch fuel feeding from a hopper on to a grate, (b) exhaust gas flow by an induced draft fan or (c) air flow by a forced draft fan. Such modifications can be seen in variety of ICSs designs in many countries. Some of these designs suitable for biomass residues are presented in Figure 4.15.

![Figure 4.15: Improved biomass residue-fired cookstoves](image)
Figure 4.15 (a) shows a coconut shell fired metal stove used to cook rice (and also possible to boil water). This stove was developed by National Engineering Research and Development (NERD) Center, Sri Lanka. Fueled with shells on one coconut, it could cook 1 kg of rice within 40 minutes, and keep rice warm for around 08 hrs. The stove could be used to boil 3 liters of water too [50]. Vivek Sawdust Stove shown in Figure 4.15 (b) is a portable, metallic stove that efficiently uses sawdust or any powdery biomass such as dry grass, groundnut shells, as fuel. Having a smokeless clean flame, the stove can continuously operate for about 1-2 hours. This stove is best suited for the purpose of heating on a steady flame for long hours, such as for heating water, boiling, reducing and cooking on low heat [51].

Mayo n Turbo Stove (MTS) is a metal stove (an improvement by Resource Efficient Agricultural Production – REAP, Canada to the earlier paddy husk cook stove named Lo Trau stove), which enables the use of many fuels in conjunction with rice hull including corn cobs, peanut shells, cocoa shells, crushed coconut shells, millet husk, wood chips and sawdust (see Figure 4.15 (c)). In this stove design, high quality, swirling blue flames are created from the twin primary air injectors and the extended inner cone with secondary air holes [52]. Figure 4.15 (d) shows the BioLite HomeStove™, which represents one of the recent development of cookstoves, as it can provide not only very high smoke reduction and efficiency improvement by adding fans to promote complete combustion, but also generate electricity by converting a fraction of the thermal energy into electricity via innovative thermoelectric generator (TEG) technology. The unique ability of the BioLite stoves (two designs: CampStove™ and HomeStove™) to produce electricity plays an important role in the rural energy services as it not only provides energy to drive the fan that generates the combustion air in the stove, but also to charge small electronic devices via built-in USB port [53].

Another category of cookstoves is that uses densified biomass fuels such as briquettes and pellets. Figure 4.16 presents one type of briquette stoves with unusual L-shaped combustion chamber, in which briquettes are fed continuously from the side of the stove. The briquette burns through the hole, which makes a steady burn with less smoke. The hole in the briquette acts as a combustion chamber in itself, making the flame hot enough and directed straight in to the centre of the pot. Figure 4.17 shows another type of briquette stove, in which a unique briquette having beehive like structure with holes, which allow the briquette to dry evenly and also allows flames and gases to escape evenly, resulting in an even burning process.
Figure 4.16: Biomass briquette cookstoves

Figure 4.17: Beehive charcoal briquette cookstoves

Figure 4.18 shows stoves using pellets produced from waste agricultural biomass. The quality of pellets may affect the performance of the stoves and increase the cleaning requirements.

Figure 4.18: Biomass pellet cookstoves
The basic technological concepts used in domestic cookstoves are being used for higher capacity thermal energy applications in small scale industries and commercial establishments such as for institutional cooking, vegetable, food and agricultural product drying (direct as well as indirect), etc. Figure 4.19 shows few such systems.

- Grate burning combustors

Grate burners, in combination with stokers, are the most frequently utilized wood combustion units. A variety of grates are used to support the combustible fuel bed in modern boilers, including reciprocating, stationary, sloping, moving, rotating and vibrating grates (See Figure 4.20). All of these technologies have specific advantages and disadvantages, depending on fuel properties, so that careful selection and planning is necessary. Though each type of grate has different fuel distribution and dispersion, fuel is fed into the furnace and onto the grate where combustion takes place.
Fuel is fed into the furnace either pneumatically or mechanically. A portion of the wood fuel burns in suspension; the larger pieces fall to the grate where they are burned. The bed of ash on the grates (which protects against the radiant heat of the furnace) and the air blowing through the holes in the grate keep the grates cool.

- **Suspension burners**

  Solid fuel in small sizes can be burned in suspension, that is, supported by air rather than by fixed metal grates. With adequate reduction in size, wood and agro residues such as rice husk, bagasse, or sawdust can be burned in suspension. Suspension firing requires a special furnace. The size and moisture content of the biomass must also be carefully controlled. Moisture content should be below 15% and the biomass particle size has to be less than 15mm. Control of the particle size of the fuel is critical with a suspension burner. Wood chips and green mill residue must be dried and sized accordingly. The advantages of suspension burning include low capital costs for combustion equipment because grates are not required, and ease of operation, as grate cleaning is not necessary.

Suspension firing results in boiler efficiency of up to 80% and allows a smaller sized furnace for a given heat output. However it also requires extensive biomass drying and processing facilities to ensure that the fuel is of the right consistency. The ash goes into suspension as particulate matter in the exhaust stream or falls to the furnace bottom for removal, and rapid changes in rate of combustion are possible. Entrainment of particulates in flue gases makes control of fly ash difficult; and, at high combustion rates, the residence time of the fuel may be insufficient for complete combustion.
In the case of fuels with shares of fines and coarse matter, a combination of pulverised-fuel and grate firing may be practical, too. For the combustion of straw bales, the so-called cigar burner has proved to be a reliable technology. In cigar burners, bales are not fed to the grate but first set on fire at the front before they get slowly pushed into the combustion chamber (see Figure 4.21). Unburned layers of straw, breaking away, fall as lumps onto the inclined grate where they combust completely. Alternatively, the bales could be shredded to reduce the straw density, before feeding to the combustion chamber. The ash is carried out on the grate. Minimal preparation of the fuel and continuous fuel supply as well as a relatively simple construction of the plant are some advantages of this technology. Disadvantageous features are the narrow range of fuels and the restriction to a bale type, the dimensions of which have to be well maintained [54]. Suspension firing technology is also of great interest for the basis of the co-firing of wood or other biomass with coal in pulverized coal plants.

![Combustion of straw bales – Cigar burner](image)

**Figure 4.21: Combustion of straw bales – Cigar burner**

- **Fluidized bed burners**

  Fluidized bed burners are the most recent type of technology developed for solid fuel combustion. The fluidized bed combustion process provides a means for efficiently mixing fuel with air for combustion. As the technology developed, it became apparent that the process could efficiently burn wood waste and agro-residues that are difficult to burn with conventional methods. Figure 4.22 shows a fluidized bed combustor in a steam plant.

In this method of combustion, fuel is burned in a bed of hot inert (or incombustible) particles such as silica or limestone sand suspended by an upward flow of combustion air that is
injected from the bottom of the combustor to keep the bed in a fluidized (or floating) state. Only a small fraction of the bed is combustible material; the remainder is comprised of inert material. This inert material provides a large inventory of heat in the furnace section, dampening the effect of brief fluctuations in fuel supply or heating value on boiler steam output. The hot inert particles scrub past particles of biomass and vice versa, heating the biomass and creating a great deal of turbulence. This scrubbing action enhances the combustion process by stripping away the CO\textsubscript{2} and solids residue (char) that normally forms around the fuel particles. Fuels that contain a high concentration of ash, sulfur, and nitrogen can be burned efficiently in fluidized bed boilers while meeting stringent emission limitations. Due to long residence time and high intensity of mass transfer, fuel can be efficiently burned in a fluidized bed combustor at temperatures considerably lower than in conventional combustion processes, thus reducing NO\textsubscript{X} emissions.

![Figure 4.22: Schematic diagram of a fluidized bed combustor in a steam plant](image)

Fluidized bed combustors could be categorized into two groups as atmospheric or pressurized units. Atmospheric fluidized bed combustors are further divided into bubbling-bed and circulating-bed units. The basic difference between bubbling-bed, shown in Figure 4.23 (a) and circulating-bed types, shown in Figure 4.23 (b) is the fluidization velocity, which is higher for circulating-bed combustors. Circulating fluidized bed combustors separate and capture fuel solid particles entrained in the high-velocity exhaust gas and return them to the bed for complete combustion. Atmospheric-pressure bubbling fluidized bed boilers are most commonly used with biomass fuels. Bubbling bed technology is generally selected for fuels with lower heating values. The circulating bed is most suitable for fuels of higher heating values.
Increasing the operational efficiency of the fluidized bed boilers may be achieved, among others, by modifying the bed geometry or introducing differential air pressure, resulting in pressurized fluidized bed combustion (PFBC). In a PFBC system, the entire fluidized bed combustor is encased inside a pressure vessel and burning solid fuels produces a high-pressure stream of combustion gases. After the combustion gases pass through a hot gas cleanup system, they are fed into a gas turbine to make electricity, and the heat in the hot exhaust gas stream can be recovered to boil water for a steam turbine. Therefore, a pressurized fluidized bed boiler is more efficient, but also more complicated and expensive [55].

Comparison of Direct Combustion Technologies

The description of the basic direct combustion systems given above shows a wide range of conversion processes, together with a large choice of equipment for each category, available in practical use. Each process – equipment system has its own applicability, and needs to be assessed according to the prevailing circumstances in order to develop energy conversion system based on waste agricultural biomass. An overview of the types of biomass technologies with typical capacity ranges and fuels could be used is presented in Table 4.6 [56].
Table 4.6: Types of biomass furnaces with typical applications and fuels

<table>
<thead>
<tr>
<th>Application</th>
<th>Type</th>
<th>Typical Size (MW)</th>
<th>Fuels</th>
<th>Ash (%)</th>
<th>Water content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual</td>
<td>Wood stoves</td>
<td>0.002 - 0.01</td>
<td>Dry wood logs</td>
<td>&lt; 2</td>
<td>5 - 20</td>
</tr>
<tr>
<td></td>
<td>Log wood boilers</td>
<td>0.005 - 0.05</td>
<td>Log wood, sticky wood residues</td>
<td>&lt; 2</td>
<td>5 - 30</td>
</tr>
<tr>
<td>Pellets</td>
<td>Pellet stoves and boilers</td>
<td>0.002 - 0.025</td>
<td>Wood pellets</td>
<td>&lt; 2</td>
<td>8 - 10</td>
</tr>
<tr>
<td></td>
<td>Understoker furnaces</td>
<td>0.02 - 2.5</td>
<td>Wood chips, wood residues</td>
<td>&lt; 2</td>
<td>5 - 50</td>
</tr>
<tr>
<td></td>
<td>Moving grate furnaces</td>
<td>0.15 - 15</td>
<td>All wood fuels and most biomass</td>
<td>&lt; 50</td>
<td>5 - 60</td>
</tr>
<tr>
<td></td>
<td>Pre-oven with grate</td>
<td>0.02 - 1.5</td>
<td>Dry wood (residues)</td>
<td>&lt; 5</td>
<td>5 - 35</td>
</tr>
<tr>
<td></td>
<td>Understoker with rotating grate</td>
<td>2 - 5</td>
<td>Wood chips, high water content</td>
<td>&lt; 50</td>
<td>40 - 65</td>
</tr>
<tr>
<td>Automatic</td>
<td>Cigar burner</td>
<td>3 - 5</td>
<td>Straw bales</td>
<td>&lt; 5</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Whole bale furnaces</td>
<td>3 - 5</td>
<td>Whole bales</td>
<td>&lt; 5</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Straw furnaces</td>
<td>0.1 - 5</td>
<td>Straw bales with bale cutter</td>
<td>&lt; 5</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Stationary fluidized bed</td>
<td>5 - 15</td>
<td>Various biomass, d &lt; 10mm</td>
<td>&lt; 50</td>
<td>5 - 60</td>
</tr>
<tr>
<td></td>
<td>Circulating fluidized bed</td>
<td>15 - 100</td>
<td>Various biomass, d &lt; 10mm</td>
<td>&lt; 50</td>
<td>5 - 60</td>
</tr>
<tr>
<td></td>
<td>Dust combustor, entrained flow</td>
<td>5 - 10</td>
<td>Various biomass, d &lt; 5mm</td>
<td>&lt; 5</td>
<td>&lt; 20</td>
</tr>
<tr>
<td>Co-firing*</td>
<td>Stationary fluidized bed</td>
<td>total 50 - 150</td>
<td>Various biomass, d &lt; 10mm</td>
<td>&lt; 50</td>
<td>5 - 60</td>
</tr>
<tr>
<td></td>
<td>Circulating fluidized bed</td>
<td>total 100 - 300</td>
<td>Various biomass, d &lt; 10mm</td>
<td>&lt; 50</td>
<td>5 - 60</td>
</tr>
<tr>
<td></td>
<td>Cigar burner straw</td>
<td>straw 5 - 20</td>
<td>Straw bales</td>
<td>&lt; 5</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Dust combustor in coal boilers</td>
<td>total 100 - 1000</td>
<td>Various biomass, d &lt; 2-5mm</td>
<td>&lt; 5</td>
<td>&lt; 20</td>
</tr>
</tbody>
</table>

* Biomass covers typically less than 10% of the total fuel input

Finally, Table 4.7 presents performance comparison of the main types of biomass combustion technologies: Pile burning, Stoker burning, Suspension burning and Fluidized bed burning [57].
Table 4.7: Comparison of different types of biomass conversion technologies

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Pile Combustion</th>
<th>Stoker Combustion</th>
<th>Suspension Combustion</th>
<th>Fluidized Bed Combustion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grate</td>
<td>Fixed / Stationary Grate</td>
<td>Fixed or moving grate</td>
<td>No grate or moving grate</td>
<td>No grate</td>
</tr>
<tr>
<td>Fuel Size</td>
<td>Uniform size of the fuel in the range of 60 - 75 mm is desired &amp; % fines should not be more than 20%</td>
<td>Uneven fuel size can be used</td>
<td>Preferable for high % of fines in the fuel</td>
<td>Uniform size fuel in the range of 1 - 10mm</td>
</tr>
<tr>
<td>Combustion</td>
<td>Difficult to maintain good combustion due to: – Air fuel mixing is not proper, – Bed height is in stationary condition resulting in clinker formation, – Difficult to avoid air channeling – Due to intermittent ash removal system it is difficult to maintain good combustion.</td>
<td>The combustion is better &amp; an improved version of pile combustion. Since most of the fuel is burnt in suspension the heavier size mass falls on the grate. If the system has a moving grate the ash is removed on a continuous basis &amp; therefore the chances of clinker formation are less.</td>
<td>It is similar to stoker combustion, but since the fuel sizes is small &amp; even the combustion efficiency is improved as maximum amount of fuel is combusted during suspension.</td>
<td>Best combustion takes place in comparison with the other types since the fuel particles are in fluidized state &amp; there is adequate mixing of fuel &amp; air.</td>
</tr>
<tr>
<td>Bed temperature</td>
<td>1250 - 1350 °C</td>
<td>1000 - 1200 °C</td>
<td>1250 - 1350 °C</td>
<td>800 - 850 °C</td>
</tr>
<tr>
<td>Moisture</td>
<td>High moisture leads to bed choking &amp; difficult combustion conditions</td>
<td>Combustion condition not very much disturbed with 4-5 % increase in moisture</td>
<td>Same as Stoker Combustion</td>
<td>It can handle fuels with high moisture condition up to 45 - 50% but high moisture in the fuels is not desirable, &amp; adequate precautions are to be taken up in the design stage itself.</td>
</tr>
<tr>
<td>Draft Conditions</td>
<td>Natural Draft / Forced Draft/ Balance Draft</td>
<td>Forced Draft / Balance draft</td>
<td>Balance draft</td>
<td>Balance draft</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Not much maintenance problems</td>
<td>Frequent problems due to moving grate</td>
<td>Variation in fines in fuel leads to delayed combustion thereby affecting the boiler tubes</td>
<td>Erosion of boiler tubes embedded in the bed is quite often</td>
</tr>
</tbody>
</table>
4.3 GASIFICATION

4.3.1 Overview

- The Concept

The gasification is a thermo-chemical process that converts any carbon-containing material into a combustible gas by supplying a restricted amount of oxygen. In case of biomass feedstock, this gas is also known as wood gas, which composed primarily of carbon monoxide and hydrogen as fuels, together with small amount of methane. It will also contain other compounds, such as sulfur and nitrogen, depending on the chemical composition of the fuel. Under typical gasification conditions, oxygen levels are restricted to less than 30% of that required for complete combustion. Raw syngas is not an end product, but requires further processing. Gasification adds value to low- or negative-value feedstocks by converting them to marketable fuels and products [58].

With respect to the utilization of gases from biomass gasification, it is important to understand that gas specifications are different for the various applications. Furthermore, the composition of the gasification gas is very dependent on the type of gasification process, gasification agent and the gasification temperature. Based on the general composition and the typical applications, two main types of gasification gas can be distinguished as producer gas and syngas, as illustrated in Figure 4.24 [59].

![Figure 4.24: Difference between syngas and producer gas](image)

Producer gas is generated in the low temperature gasification process (below 1000°C) and contains CO, H\textsubscript{2}, CH\textsubscript{4}, C\textsubscript{x}H\textsubscript{y}, aliphatic hydrocarbons, benzene, toluene, and tars (besides CO\textsubscript{2}, H\textsubscript{2}O, and N\textsubscript{2} in case of gasification in air). The syngas components H\textsubscript{2} and CO typically
contain only \( \sim 50\% \) of the energy in the gas, while the remainder is contained in \( \text{CH}_4 \) and higher (aromatic) hydrocarbons.

Syngas is produced by high temperature (above 1200°C) or catalytic gasification. Under these conditions the biomass is completely converted into \( \text{H}_2 \) and \( \text{CO} \) (besides \( \text{CO}_2 \), \( \text{H}_2\text{O} \), and \( \text{N}_2 \) in case of gasification in air). Syngas is chemically similar to that derived from fossil sources and can replace its fossil equivalent in all applications. This gas can also be made from producer gas by heating the thermal cracking or catalytic reforming.

The oxidant for the gasification process can be either atmospheric air or pure oxygen. Air gasification of biomass produces a low calorific value (or Low Mega-Joule) gas, which contains about 50% nitrogen and can fuel engines and furnaces. Gasification of biomass with pure oxygen results in a medium calorific value (or Medium Mega-Joule) gas, free of nitrogen. These systems also offer faster reaction rates than air gasification, but have the disadvantage of additional capital costs associated with the oxygen plant.

- **Gasifier End Uses**

    Syngas or producer gas can be burned to create heat, steam, or electricity. It can be converted to methane and fed into a natural gas distribution system. Syngas can also be converted to methanol, ethanol, and other chemicals or liquid fuels. Methanol produced through gasification can be further refined into biodiesel with addition of vegetable oils or animal fats (see Figure 4.25 for use of gasification for generation of fuels, chemicals and power) [58]. The most important end uses practiced commercially or under research, can be summarized as follows:

    - Close-coupled combustion (stoves, kilns, ovens, furnaces, dryers, boiler firing),
    - External combustion for power: externally fired turbines, Stirling engines, steam engines, Thermo-photovoltaic cells, catalytic oxidation, and thermo-electric systems,
    - Internal combustion (IC) diesel and Otto engines,
    - Compressors,
    - Hydrogen fuel production,
    - Gas turbine internal combustion,
    - Fuel cells: molten carbonate, solid oxide, proton exchange membrane, phosphoric acid,
    - Chemical synthesis: methanol, ammonia, methane, Fischer-Tropsch liquids, other oxygenates.
Advantages of Biomass Gasification

Biomass-to-electricity systems based on gasification have a number of potential advantages. Projected process efficiencies are higher than the direct combustion systems in commercial use today. Process efficiencies are comparable to high efficiency coal-based systems, but can be achieved at a smaller scale of operation. Thus, not only does biomass close the carbon cycle, but gasification based systems, due to their high efficiency, reduce CO₂ emissions per MW of power generated over conventional biomass power plants.

Biomass is also lower in sulfur than is most coal. A typical biomass contains 0.05 to 0.20 weight % sulfur on a dry basis and has a higher heating value of about 30 MJ/kg. This compares with coal at up to 2-3 dry weight %. The biomass sulfur content translates to about 51 to 214 mg SO₂/MJ. The higher sulfur level is still less than the regulated limit set in the current New Source Performance Standards (NSPS). Controlled NOₓ levels from biomass plants will also be less than the NSPS standards.
Other advantages of biomass gasification include:

- Gasification produces a more convenient easily controllable form of cleaner fuel for energy generation equipment (for both thermal and electricity generation), and provides a mean to reduce or remove conventional fossil fuels.
- Gasification gives biomass the flexibility to fuel a wide range of electricity generation systems: gas turbines, fuel cells, and reciprocating engines.
- A wide variety of biomass materials can be gasified, many of which would be difficult to burn otherwise.
- Gasification offers one means of processing waste fuels, many of which can be problematic.
- Gasification has the potential of reducing emission of pollutants and greenhouse gases per unit energy output.
- A gaseous fuel allows biomass to leverage the high efficiency power generation capabilities of combined gas and steam cycle plants and fuel cells.

Due to the above potential benefits associated with the gasification technology, considerable technological advancements in several applications could be seen in practice, even in case of small scale applications such as domestic cooking.

- **Main Classification of Gasifiers**

As in case of the direct combustion processes described in the previous section, two principal types of gasifiers have emerged: fixed bed and fluidized bed. As illustrated in Figure 4.26, fixed bed gasifiers are further classified into three types as updraft, downdraft and cross draft, depending on the flow of gas through the fuel bed. The fluidized bed gasifiers are categorized into two types as bubbling fluidized bed and circulating fluidized bed (see Figure 4.27). Fixed bed gasifiers are typically simpler, less expensive, and produce a lower heat content syngas. Fluidized bed gasifiers are more complicated, more expensive, and produce a syngas with a higher heating value.

Fixed bed gasification technology is more than century old and use of such gasifiers for operating engines was established by 1900. During World War II, more than one million gasifiers were in use for operating trucks, buses, taxis, boats, trains etc., in different parts of the world. Fluidized bed biomass gasification technology is however a relatively recent development. More details of these gasifiers are presented in Section 4.3.3 and Section 4.3.4.
4.3.2 Gasification Process

- **Main Stages of Gasification Process**

Most gasification processes include several overlapping steps. Figure 4.28 illustrates the basic process mechanisms in gasification, as an application for power generation through gas turbine technology. Among these steps, main two stages could be recognized as endothermic (heat absorbing) process in which a solid biomass fuel is thermo-chemically converted into a Low- or Medium-Mega Joule gas. In the first reaction, pyrolysis, the volatile components of the fuel are vaporized at temperatures below 600°C by a set of complex reactions. The volatile vapors include hydrocarbon gases, \( \text{H}_2 \), \( \text{CO} \), \( \text{CO}_2 \), tar, and water vapor. Because biomass fuels tend to have more volatile components (70-85% on a dry basis) than coal...
pyrolysis plays a larger role in biomass gasification than in coal gasification. Char (fixed carbon) and ash are the pyrolysis by-products which are not vaporized.

Figure 4.28: Biomass Gasification Process

In the second stage of the gasification process, char conversion, the carbon remaining after pyrolysis undergoes the classic gasification reaction (i.e. steam + carbon) and/or combustion (carbon + oxygen). It is this latter combustion reaction that provides the heat energy required to drive the pyrolysis and char gasification reactions. Due to its high reactivity (as compared to coal and other solid fuels), all of the biomass feed, including char, is normally converted to gasification products in a single pass through a gasifier system.

- **Reactor Zones**

A fixed bed gasifier can be regarded as consisting of four different zones: Drying zone, Pyrolysis zone, Reduction zone and Combustion zone in which different chemical and physical processes take place (see Figure 4.26). The processes taking place in the drying, pyrolysis and reduction zones are driven by heat transferred from the combustion zone (which is also called as the oxidation or hearth zone). In the drying zone, the moisture in biomass evaporates. In case of updraft gasifier this moisture leaves along with gas at the top. In case of downdraft gasifier the moisture passes thorough the reduction and combustion zones and participates in certain chemical reactions.

Essentially dry biomass enters the pyrolysis zone from the drying zone. Pyrolysis converts the dried biomass into char, tar vapour, water vapour and non-condensible gases. The vapours and non-condensible gases leave the gasifier at the top in case of updraft gasifier. In case of downdraft gasifiers these pass through the combustion zone and undergo further reactions.
The char produced in the pyrolysis zone is around 20% of the original biomass by weight and passes through combustion and reduction zones.

In the combustion zone, oxygen supplied for gasification first comes in contact with the fuel. In case of updraft gasifier this fuel is carbonized biomass, which can be regarded as consisting of mostly carbon and ash. In case of downdraft biomass gasifiers, the fuels oxidized are carbonized biomass plus vapours and gases formed in the pyrolysis zone; some non-condensible gases are also formed as a result of thermal cracking of tar vapours (coming from pyrolysis zone). In the reduction zone the products of complete oxidation (i.e., CO₂, H₂O, etc.) undergo reduction by the carbonized biomass. These reactions are similar to those taking place in the reduction zone of a charcoal gasifier.

In fluidized bed gasifiers, because of very good particle mixing, separate reaction zones do not exist (see Figure 4.27). Thus all the processes of drying, pyrolysis, reduction and combustion can be regarded as taking place simultaneously throughout the reactor volume although intensity of any particular processes may vary depending on the location (e.g. combustion is more intensive near the distributor, and drying is more intensive near the fuel inlet).

- **Chemical Reactions**

The overall combustion reaction taking place in the combustion zone can be written as

\[
C + O₂ = CO₂ + 393,800 \text{ kJ/kg mole Carbon}
\]

The air introduced contains, besides oxygen, water vapour and inert gases such as nitrogen and argon. The inert gases are normally assumed to be non-reactive with the fuel constituents. However, the water vapour reacts with the hot carbon according to the heterogeneous water gas reaction

\[
C + H₂O = H₂ + CO - 131,400 \text{ kJ/kg mole}
\]

CO₂ produced in the oxidation zone is reduced to CO according to the Boudouard reaction

\[
CO₂ + C = 2CO - 172,600 \text{ kJ/kg mole Carbon}
\]

Another important reaction taking place in the reduction zone is the water shift reaction

\[
CO + H₂O = CO₂ + H₂ + 41,200 \text{ kJ/kg mole}
\]
Some methane formation also takes place in the gasifier. This can be represented by the simple overall reaction

\[ C + 2H_2 = CH_4 + 75,000 \text{ kJ/kg mole Carbon} \]

### Gasifier Efficiency

Performance of a gasifier is often expressed in terms of its efficiency, which can be defined in two different ways: cold gas efficiency and hot gas efficiency. The cold gas efficiency is used if the gas is used for running an internal combustion engine in which case it is cooled down to ambient temperature and tar vapors are removed from the gas. The cold gas efficiency is defined as

\[ \eta_{\text{cold}} = \frac{V_g C_g}{M_b C_b} \]

where
- \( V_g \) = gas generation rate (m³/s)
- \( C_g \) = heating value of the gas (kJ/m³)
- \( M_b \) = biomass consumption rate (kg/s)
- \( C_b \) = calorific value of biomass (kJ/m³)

For thermal applications, the gas is not cooled before combustion and the sensible heat of the gas is also useful. The hot gas efficiency is used for such applications; which is defined as

\[ \eta_{\text{hot}} = \frac{V_g C_g + H_{\text{sensible}}}{M_b C_b} \]

where
- \( H_{\text{sensible}} = C_p V_g (T_g - T_a) \)
- \( T_g \) = gas temperature
- \( T_a \) = ambient temperature

The value of cold gas efficiency and hot gas efficiency are approximately 70% and 75%, respectively.

### Factors Affecting Rate of Gasification

Apart from the basic technology and design aspects of gasifiers, the rate of gasification is affected by several factors including the following [45]:

- The size of the feeding material particles (small; large) and its distribution
- The shape of the particulates (powdery ↔ lump)
- The structure of the material (porous ↔ non-porous)
- Environment (Reactive: Air/Oxygen ↔ Inert: Nitrogen/Argon)
- Flow of medium (Static ↔ Continuous)
- Heating rate (Slow ↔ Fast)
- Temperature (Low: < 500 °C ↔ High: > 500 °C)
- Ash (Catalytic ↔ Non-catalytic)

- Properties of Producer gas

Since the producer gas generation process is affected by various factors technical and process environment as outlined above, variations in the composition of gas produced from various biomass sources could be expected. The gas composition is also a function of gasifier design and thus, the same fuel may give different heating value as when used in two different gasifiers. Table 4.8 lists the composition of gas produced from various sources [60].

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Gasification method</th>
<th>Composition (% Volume)</th>
<th>Heating Value (MJ/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charcoal</td>
<td>Downdraft</td>
<td>CO 28 - 31 H₂ 5 - 10 CH₄ 1 - 2 CO₂ 1 - 2 N₂ 55 - 60</td>
<td>4.60-5.65</td>
</tr>
<tr>
<td>Charcoal</td>
<td>Updraft</td>
<td>CO 30 H₂ 19.7 CH₄ - CO₂ 3.6 N₂ 46</td>
<td>5.98</td>
</tr>
<tr>
<td>Wood (10-20% MC)</td>
<td>Downdraft</td>
<td>CO 17 - 22 H₂ 16 - 20 CH₄ 2 - 3 CO₂ 10 - 15 N₂ 55 - 60</td>
<td>5.00 - 5.86</td>
</tr>
<tr>
<td>Wheat straw pellets</td>
<td>Downdraft</td>
<td>CO 14 - 17 H₂ 17 - 19 CH₄ - CO₂ 11 - 14 N₂ -</td>
<td>4.50</td>
</tr>
<tr>
<td>Coconut husks</td>
<td>Downdraft</td>
<td>CO 16 - 20 H₂ 17 - 19.5 CH₄ - CO₂ 10 - 15 N₂ -</td>
<td>5.80</td>
</tr>
<tr>
<td>Coconut shells</td>
<td>Downdraft</td>
<td>CO 19 - 24 H₂ 10 - 15 CH₄ - CO₂ 11 - 15 N₂ -</td>
<td>7.20</td>
</tr>
<tr>
<td>Pressed sugarcane</td>
<td>Downdraft</td>
<td>CO 15 - 18 H₂ 15 - 18 CH₄ - CO₂ 12 - 14 N₂ -</td>
<td>5.30</td>
</tr>
<tr>
<td>Corn cobs</td>
<td>Downdraft</td>
<td>CO 18.6 H₂ 16.5 CH₄ 6.4 - CO₂ - N₂ -</td>
<td>6.29</td>
</tr>
<tr>
<td>Paddy husks pellets</td>
<td>Downdraft</td>
<td>CO 16.1 H₂ 9.6 CH₄ 0.95 - CO₂ - N₂ -</td>
<td>3.25</td>
</tr>
<tr>
<td>Cotton stalks cubed</td>
<td>Downdraft</td>
<td>CO 15.7 H₂ 11.7 CH₄ 3.4 - CO₂ - N₂ -</td>
<td>4.32</td>
</tr>
</tbody>
</table>

Note that when gasification is performed in air, the maximum dilution of producer gas occurs due to the presence of nitrogen. About 50% of gas by volume is composed of noncombustible nitrogen. The heating value of producer gas is in the range of 4.5 to 5.5 MJ/m³ (note that the heating value of methane is about 20 MJ/m³). Therefore it may be beneficial to use pure oxygen instead of air for gasification. However the cost and availability of oxygen may be a
limiting factor in this regard. Nevertheless if a high energy quality item such as methanol is derived as the end product, then the cost and use of oxygen can be justified.

The chemical reaction of gasification could be rewritten for a general biomass fuel with a composition represented by $C_xH_yO_z$ (neglecting nitrogen and sulfur) as

$$C_xH_yO_z + p(O_2 + 3.76N_2) \rightarrow [xCO + \beta H_2 + \gamma CH_4] + \delta CO_2 + \varepsilon H_2O + 3.76p N_2 + \text{Heat}$$

In the above equation, the first three terms of the products of combustion (in the square bracket) represent fuel components in gaseous form. In this equation, the terms $x$, $y$ and $z$ are known for a given biomass material. The other coefficients (including the parameter $p$, which represents the amount of air used) are variable parameters that depend on the other properties of the fuel, gasifier technology employed, the operational conditions, etc. In the system design, the task is to identify the optimum air requirement (i.e. $p$) and set the operational conditions such that the fuel elements in the producer gas (i.e. $\alpha$, $\beta$, and $\gamma$) become maximum (accordingly $\delta$ and $\varepsilon$ become minimum).

On an average 1 kg of biomass produces about 2.5 $m^3$ of producer gas (at standard conditions) [60]. Therefore, in this process, it consumes about 1.5 $m^3$ of air for combustion. As estimated in Section 4.2.1, about 5.7 $m^3$ of air is required for complete combustion of waste agricultural biomass. Thus biomass gasification consumes about 26% of theoretical stoichiometric ratio for wood burning. If the heating value of 5 MJ/$m^3$ is assumed for the producer gas generated from a biomass having a heating value 18 MJ/kg, the conversion efficiency of biomass gasifiers becomes $\eta = \frac{5 \text{ MJ} / m^3 \times 2.5 \text{ m}^3 / \text{kg}}{18 \text{ MJ/kg}} = 69.4\%$.

**Tar Cleaning**

The main contaminant in the producer gases of biomass gasification is tar, which is considered to be the most cumbersome and problematic parameter in any gasification commercialization effort. Tar is undesirable as the various problems associated with condensation, formation of tar aerosols and polymerization to form more complex structure, which causes problems in the process equipment as well as engines and turbines used in the application of the fuel gas. The minimum allowable limit for tar is highly dependent on the type of process and the end use application.
Tar is formed during the pyrolysis process of gasification, which initiate at about 230°C, where the complex polymers in the biomass are broken down (resulting in a gas consisting mainly of CO₂, H₂O, CH₄, CO, H₂, tar and char). The tar consists of various heavy organics that can condense and break down subsequent processes. The level of tar concentration in the producer gas depends mainly on two factors: the type of gasification process employed and the type of feedstock used. In general, highest tar contamination in producer gas occurs in updraft gasifiers and the lowest in downdraft gasifiers, which in fluid bed gasifiers intermediate levels are experienced. A very rough generalization would places updraft at 100 g/Nm³, fluid beds at 10 g/Nm³ and downdraft at 1 g/Nm³ in tar level [58].

Several types of cleaning methods have been evolved for producer gas generated in biomass gasification processes. Figure 4.29 present the various gas cleaning strategies and available technologies [58].

![Figure 4.29: Producer gas cleaning technologies](image-url)
4.3.3 Biomass Gasification in Fixed Beds

- **Updraft Gasifiers**

The updraft (or counter-current) fixed bed gasifier is the simplest and oldest gasifier type; and also the most successful of the fixed-bed designs. In this case, the biomass is fed from the top of the gasifier and successively undergoes drying, pyrolysis, char gasification, and char combustion as it settles to the bottom of the gasifier. The product gas is removed from the top of the gasifier and the ash from the bottom. Its advantages include

- Suitability for most biomass types,
- Simplicity of fuel preparation,
- High efficiency (because of low exit gas temperature due to utilization of the sensible heat of the produced gas for pyrolysis and drying),
- General simplicity of installation.

The main disadvantage of updraft gasifiers is the high tar production since the tar vapours produced in the pyrolysis zone do not pass through the combustion zone (i.e. no thermal cracking takes place). Gas of lower tar content is obtained in some updraft gasifier designs, by drawing off the gas right above the reduction zone. In some updraft gas producers, moisture is added to the incoming air stream. This has a beneficial effect on the gas quality due to the water gas reaction taking place in the combustion and reduction zones.

- **Downdraft Gasifiers**

In downdraft gasifiers, the tar vapours given off in the distillation zones pass through the combustion zone where it is largely cracked and reduced to non-condensible gases. Downdraft gasifiers have a reduced cross-sectional area above which the air is introduced. The constriction is called throat and ensures a homogeneous layer of hot carbon through which the pyrolytic gases must pass. The more pronounced the cross sectional reduction, the greater is the temperature increase, within certain limits. A small throat on the other hand creates a greater pressure drop, which decreases the efficiency of an engine during full speed. A small throat may also sometimes interfere with flow of fuel through it.

In downdraft gasifier designs, it has been found that slight changes in the diameter of the throat or choke plate and position of the air inlet can change drastically the gas composition and the tar yield. The best configuration will depend on physical parameters of the fuel and the load factor and consequently must be found by trial and error. A large hearth diameter
may require a high nozzle velocity or other means to penetrate the deep fuel bed. This may led to high pressure drop for large hearths, placing an upper size limit to nozzle-fed downdraft gasifiers. The metal material of the hearth should be protected from thermal stress as much as possible since the temperature in the hottest part of the combustion zone is normally over 1300°C.

Downdraft gasifiers are in general not well suited for high ash fuels. Any slag formed in the oxidation zone will flow downward, quickly cool and solidify in the reduction zone and finally obstruct the gas and fuel flow. A well-designed rotating grate and operation below the ash melting point are therefore essential if fuels with high ash contents are to be used. Additional steam or water injection is uncommon in downdraft gasifiers. The combined moisture in the fuel and humidity of air are sufficient for the generation of hydrogen by the water gas reaction.

- **Cross-draft Gasifiers**

  In the cross-draft gasifiers, air enters through a nozzle and the gas flow is nearly normal to the axis of the fuel bed. Use of these gasifiers is not very common although these have been used for small scale charcoal gasification for running engines. Charcoal gasification results in very high temperatures of about 1500°C in the combustion zone. In cross-draft gasifiers, the gasifier body is insulated against high temperatures by the fuel itself.

  All the above systems are referred to as direct combustion gasifiers, in which the char is burned in the vessel where thermochemical reactions occur. There is an alternative method for transferring the heat from char combustion to the gasifier feedstock, which is referred to as indirect combustion gasifier system. Such systems utilize a separate reactor for char combustion from which heat is transferred to the gasifier reactor. With the latter system, nitrogen from the atmosphere and the combustion process is kept from combining with, and subsequently diluting, the product gas.

4.3.4 **Fluidized Bed Gasification**

  In general, fluidized bed gasifiers need solid fuel in the form of small particles; these are however not much sensitive to the biomass fuel type and thus are suitable for multi-fuel
operation. In a fluidized-bed gasifier, a continuous feed of biomass and inert heat-distributing material is fluidized by an oxidant and/or steam.

There are two options for the way in which heat is supplied to the gasifier. In a directly heated fluidized-bed gasifier, heat required for gasification comes from char combustion in the gasifier reactor. In an indirectly heated fluidized bed gasifier, char is removed from the gasifier and burned in a separate vessel. The resulting heat is transferred to the gasifier by either in-bed heat exchangers or by recirculating the inert bed material heated in the char combustor. The advantage of indirect heating is that gasification product is not diluted with the char combustion by-products.

Product gas composition, carbon efficiency, and hot gas efficiency for the fluidized-bed process are comparable to those found in the fixed-bed designs. Fluidized-bed designs, however, are capable of handling much smaller, less dense, and less uniform feedstocks. In fact, the fuel and fuel handling systems are more likely to set the lower limits for the acceptable bulk density. A shortcoming of the fluidized-bed design is the high particulate level in the raw producer gas.

4.3.5 Other Categories of Gasifiers
Several other categories of gasifier design have been immerged over the time to cater for different requirements. Figure 4.30 presents three of such designs: Entrained flow (EF) gasifiers, Duel fluidized bed (Duel FB) gasifiers and Plasma gasifiers. A brief description of these designs is given in this section [61].

![Diagram of EF, Duel FB, and Plasma gasifiers](image)

**Figure 4.30: Advanced gasification systems**
Entrained Flow Gasifiers

In EF gasifiers, powdered biomass materials is fed into the system with pressurized oxygen and/or steam. A turbulent flame at the top of the gasifier burns some of the biomass, providing large amounts of heat, at high temperature in the range of 1200 – 1500 °C, for fast conversion of biomass into very high quality syngas. Entrained flow gasifiers have high gas velocities and high material throughput. Consequently, time for reaction (residence time) is short which requires the feedstock to be of very small particle size, a liquid or liquid slurry.

Two types of EF gasifiers can be distinguished: slagging and non-slagging. In a slagging gasifier, the ash forming components melt in the gasifier, flow down the walls of the reactor and finally leave the reactor as a liquid slag. Generally, the slag mass flow should be at least 6% of the fuel flow to ensure proper operation. In a non-slagging gasifier, the walls are kept free of slag. This type of gasifiers is suitable for fuels with only little ash.

Dual Fluidized Bed Gasifiers

Dual FB gasifiers have two chambers; a gasifier and a combustor. The biomass materials is fed into the circulating fluidized bed (CFB) / bubbling fluidized bed (BFB) gasification chamber, and converted to nitrogen-free syngas and char using steam. Due to steam gasification the producer gas contains virtually no nitrogen and has a high hydrogen content. The char is burnt in air in the CFB / BFB combustion chamber, heating the accompanying bed particles. This hot bed material is then fed back into the gasification chamber, providing the indirect reaction heat. The system operates at temperatures below 900 °C to avoid ash melting and sticking. The average heating value of the syngas is about 12-14 MJ/Nm³.

Plasma Gasifiers

In plasma gasifier systems, untreated biomass materials is dropped into the gasifier, coming into contact with an electrically generated plasma, usually at atmospheric pressure and temperatures of 1,500 - 5,000 °C. Organic matter is converted into very high quality syngas, and inorganic matter is vitrified into inert slag. Note that plasma gasification uses plasma torches. It is also possible to use plasma arcs in a subsequent process step for syngas cleanup.

Plasma technologies have been used for over 30 years in a variety of industries, including the chemical and metals industries. Historically, the primary use of this technology has been to
decompose and destroy hazardous wastes, as well as to melt ash from mass-burn incinerators into a safe, non-leachable slag. Use of the technology as part of the waste-to-energy industry is much newer.

Finally, a rough comparison of gasifier types with respect to their capacity ranges is presented in Figure 4.31 [61]. The capacity is in oven dry tons per day (pdt/day).

![Figure 4.31: Capacity ranges of gasifier technologies](image)

### 4.3.6 Gasification of Different Types of Biomass

- **Charcoal Gasification**

In general fuels having higher carbon content are better fuel for gasification, particularly for internal combustion (IC) engine applications. Therefore charcoal is a better fuel than uncarbonized biomass, such as wood and waste agricultural biomass. Charcoal gasification produces a gas which has little moisture and practically no tar so that the gas cleaning system required is simple. Air gasification of charcoal has been claimed to be a relatively simple option for small energy systems. Units of capacity 5-10 kW\textsubscript{e} have been successfully operated in different parts of the world. The power generation system in this case consists of (i) a gasifier, (ii) a gas conditioning device to separate particles and cool the gas, and (iii) an IC engine - generator unit fueled by the gas. A major drawback of the charcoal gasification is that about 50 - 80\% of energy of the original wood is lost in the charcoal making process (unless the volatile matter escaped is recovered and used for energy). Thus, considering the
energy of the wood used for charcoal making, the power output of charcoal gasifier-engine systems is very low.

Although charcoal gasification presents no particular operational problem, the actual acceptance of the technology by potential users is rather insignificant at present mostly because of low return on investment. Also, producer gas is less convenient as engine fuel compared with gasoline or diesel and the user requires to have time and skill for maintaining the gasifier-engine systems. However in situations of severe scarcity of liquid fuels, charcoal gasifier-engine systems appear to be acceptable for generating power for vital applications. Thus in Vietnam, several gasoline-fueled passenger buses converted to operate with charcoal gasifier are in use. A number of commercial charcoal gasifier-engine systems have been installed since the early eighties in South American countries.

- **Gasification of uncarbonized biomass**

  In case of gasification of uncarbonized biomass such as wood or biomass residues, tar, a complex and corrosive mixture of condensed liquid vapours, is produced along with the gas. Therefore use of producer gas obtained from uncarbonized biomass for power generation using an internal combustion engine requires elaborate gas cleaning for removing tar. Projects on such power generation have often been abandoned because of a variety of reasons, the most important being the problem created by the tar in the gas. Worldwide, there are, however a number of units each of which has accumulated several thousand hours of operations.

  Use of producer gas for heat production is relatively simpler and better established throughout the world. The gas in this case does not require tar removal or cooling before combustion. Compared with the fixed bed power gasifiers, heat gasifier systems are normally of bigger size and have capacity above 50 kW\textsubscript{th}. In the developing countries, heat from combustion of producer gas has found limited use for a variety of applications e.g. drying, industrial furnaces etc. In the developing countries efforts to introduce biomass gasification during the last two decades met more failures than success so far. For instance, up to 1990, a total of 50 gasifiers were installed in Indonesia. Of these, 37 were field units. The sizes of the power gasifiers were in the range 10-120 kW\textsubscript{e}, while the sizes of the heat gasifiers were 400-900 kW\textsubscript{th}. All the eight heat gasifiers were commercial, out of which seven were operational.
On the other hand, none of the power gasifiers was fully commercialized and faced a number of problems, particularly because of tar; also, the gasifiers were mostly not operational,

- **Wood Gasification**
  Wood has been extensively studied / utilized as a gasifier fuel. For gasification, wood has to be dried to moisture content about 20% and reduced in size to small blocks. Wood gasification for industrial heat applications, although not practiced widely, is normally commercially viable. On the other hand, wood gasifier-engine systems normally face a wide range of technical problems and are often not commercially viable. At present, only a small number of wood gasifier-engine systems appear to be operating in the developing countries, particularly in India. Research and development efforts of recent years have been directed towards developing reliable gasifier-engine systems.

- **Gasification of Agricultural Residues**
  Compared to wood, residues are more difficult to gasify. Except some residues (e.g. coconut shell), the residues have low bulk density and would present a problem of flow in gasifiers having throat. Also some important residues (e.g. rice husk) have much higher ash content compared to wood (the highest ash content normally necessitates use of rotating grates). Gasification of rice husk, which is generated in rice mills where a demand for mechanical/electrical power also exists, has attracted a great deal of interest in recent years. A number of open-top throatless rice husk gasifiers operate in rice mills in China. Typically the plants require a regular maintenance schedule. The husk consumption is about 2 kg/kWh. Rice husk gasification technology has been developed in a number of other Asian countries, such as Thailand, Indonesia and India.

  Coconut shell is known to be a good fuel for gasification. Because of its low bulk density, coconut husk presents a fuel bridging problem in gasifiers. In general it is not suitable for gasification in packed-bed reactors. A mixture of equal volumes of coconut husk and wood can be gasified reasonably well. Another residue, successful gasification of which has been reported by several authors is corn cob.

  Gasification characteristics of several types of waste agricultural biomass materials are presented in Table 4.9 [60].
Table 4.9. Gasification Characteristics of various fuels

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Treatment, bulk density, moisture (MC)</th>
<th>Tar produced g/m³</th>
<th>Ash content %</th>
<th>Gasifier</th>
<th>Experience</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coconut shell</td>
<td>Crushed (1-4 cm), 435 kg/m³, MC = 11.8%</td>
<td>3</td>
<td>0.8</td>
<td>downdraft</td>
<td>Excellent fuel. No slag formation</td>
</tr>
<tr>
<td>Coconut husks</td>
<td>Pieces 2 - 5 cm, 65 kg/m³, MC = 11.8%</td>
<td>Insignificant tar coconut</td>
<td>3.4</td>
<td>downdraft</td>
<td>Slag on grate but no operational problem</td>
</tr>
<tr>
<td>Com cobs</td>
<td>304 kg/m³, MC = 11%</td>
<td>7.24</td>
<td>1.5</td>
<td>downdraft</td>
<td>Excellent fuel. No slugging</td>
</tr>
<tr>
<td>Com fodder</td>
<td>Cubed, 390 kg/m³, MC = 11.9%</td>
<td>1.43</td>
<td>6.1</td>
<td>downdraft</td>
<td>Sever slagging and bridging</td>
</tr>
<tr>
<td>Cotton stalks</td>
<td>Cubed, 259 kg/m³, MC = 20.6%</td>
<td>5</td>
<td>17.2</td>
<td>downdraft</td>
<td>Severe slag formation</td>
</tr>
<tr>
<td>Peat</td>
<td>Briquettes 555 kg/m³, MC = 13%</td>
<td>–</td>
<td>–</td>
<td>downdraft</td>
<td>Severe slugging</td>
</tr>
<tr>
<td>Rice hulls</td>
<td>Pelleted, 679 kg/m³, MC = 8.6%</td>
<td>4.32</td>
<td>14.9</td>
<td>downdraft</td>
<td>Severe slugging</td>
</tr>
<tr>
<td>Sugarcane</td>
<td>Cut 2-5 cms, 52 kg/m³, 8.6%</td>
<td>Insignificant</td>
<td>1.6</td>
<td>downdraft</td>
<td>Slag on hearthring. Bridging</td>
</tr>
<tr>
<td>Walnut shell</td>
<td>Cracked, 337 kg/m³, MC = 8%</td>
<td>6.24</td>
<td>1.1</td>
<td>downdraft</td>
<td>Excellent fuel. No slacking</td>
</tr>
<tr>
<td>Walnut shell</td>
<td>Pelleted, 14.5 kg/m³, MC = 8%</td>
<td>4.32</td>
<td>10.0</td>
<td>downdraft</td>
<td>Good fuel</td>
</tr>
<tr>
<td>Wheat straw</td>
<td>Cubed, 395 kg/m³, MC = 9.6%</td>
<td>–</td>
<td>9.3</td>
<td>downdraft</td>
<td>Severe slugging, bridging. Irregular gas production</td>
</tr>
<tr>
<td>Wheat straw and corn stalks</td>
<td>Cracked, 50% mix, 199 kg/m³, MC = 15%</td>
<td>6.24</td>
<td>0.2</td>
<td>downdraft</td>
<td>Severe bridging and slugging</td>
</tr>
<tr>
<td>Wood blocks</td>
<td>5 cm cube, 256 kg/m³, MC = 5.4%</td>
<td>3.24</td>
<td>0.2</td>
<td>downdraft</td>
<td>Excellent fuel</td>
</tr>
<tr>
<td>Wood chips</td>
<td>166 kg/m³, MC = 10.8%</td>
<td>6.24</td>
<td>6.26</td>
<td>downdraft</td>
<td>Severe bridging and slugging</td>
</tr>
</tbody>
</table>
4.3.7 Fixed Bed Gasifiers for Cooking Applications

One of the important developments in gasification technology is taken place in the area of domestic cooking due to the serious concerns of indoor air pollution associated with burning of solid biomass fuels. Further, the gasification technology is being successfully used in small scale industrial thermal energy applications and electricity generation systems. Some of the gasifier cookstoves and other small scale systems are presented in this section.

Figure 4.32: CPC turbo wood gas stove

Figure 4.32 shows the CPC "Turbo Wood-Gas Stove", which combines a specially designed gasification chamber, mixer and burner to provide a 3 kWth high intensity heat with only 10 g/minute of fuel [62]. A 2 watt "micro-blower" provides a fully variable amount of air just where and when it is needed to achieve the Turbo Stove’s very high performance levels. This innovation makes it easy to adjust the cooking intensity and time for frying, boiling, or simmering a wide variety of foods for up to two hours on a single charge of fuel.

Figure 4.33 shows the Belonio rice husk gas stove developed at the Appropriate Technology Center of the Department of Agricultural Engineering and Environmental Management of the College of Agriculture, Central Philippine University in Iloilo City, Philippines [63].

Main components of the stove include the gasifier reactor, burner, char chamber, fan, safety shield and pot support. The reactor is cylindrical in shape having a diameter of 10 to 30 cm, depending on the power output needed for the stove. The height of the reactor varies from 40
cm to 1.0 m, depending on the required operating time. The cylinder is made of an ordinary galvanized iron sheet gauge no. 18 on the outside and of a stainless steel sheet gauge no. 20 in the inside. This cylinder is provided with an annular space of 2 cm, where the burned rice husks or any other materials is placed to serve as insulation in order to prevent heat loss in the gasifier. At the lower end of the reactor is a fuel grate made of stainless steel material, which is used to hold the rice husks during gasification. The operating energy conversion efficiency of the stove is reported to be about 13%.

The two-burner rice husk gas stove technology shown in Figure 4.34 for domestic household or for institutional cooking use is another development in line with the above rice husk gasification project in Philippines. The stove has a fuel reactor that is separated from the burner. Since the stove in this model supplies gaseous fuel to the two burners, the fuel reactor is a little larger than that of the single burner stove. The stove consumes 2.5 kilogram of rice husk per load at 40 to 45 minutes continuous operation. The energy input for the blower is 44 W. The specific gasification rate is 126.2 kg/hr-m² while the fire zone rate is 1.75 cm/min. This stove is available in two models: the table-type and the table-top burner [63].
Two types of wood gas stoves, forced draft and natural draft, developed by National Engineering Research and Development (NERD) Center, Sri Lanka are shown in Figure 4.35. The forced draft wood gas stove is a single pot metal stove with ceramic liner and FD fan of capacity 2W, 12 V DC. The fuel is wood pieces dried to about 20% MC_{wb}. Cooking time is about 40 minutes per loading of 600g of wood pieces. The more popular design is the natural draft single pot metal stove with ceramic liner, which could accommodate about 650 g of wood pieces or small sticks and cooking time is about 45 minutes per loading [50].

British Petroleum India Energy Limited partnered with Bangalore based Indian Institute of Science to come up with low-cost, smokeless cooking stove named “Oorja”, which run on pellets made from agricultural waste. Oorja stove has a chamber for burning pellets and a
mini-fan, powered by rechargeable batteries and controlled by a regulator, blows air to fan the flames (see Figure 4.36). This technology increases combustion efficiency. The efficiency of the cookstove recorded in water boiling tests was around 50%, and the rated power is about 2.5 kWth [64].

![Figure 4.36. Pellet gasifier stoves: (a) the Oorja stove, (b) the ceramic combustion chamber with grate at the bottom & secondary air holes towards the top, (c) The flame](image)

The gasifier stoves shown in Figure 4.37 were developed at the Asian Institute of Technology, Thailand [65]. This stove is primarily designed for wood chunks, but agro-residue briquettes can be used as fuel.

![Figure 4.37: Gasifier stoves developed at AIT, Thailand](image)

The stove consists of a cone-shaped fuel chamber, a reaction chamber where fuel is gasified, and a combustion chamber where the gasified fuel is burned by natural convection mode.
During gasification, air passes through the layer of fuel and escapes at the other end of the reaction chamber through a producer gas outlet. Flow of air and of gases in the stove is facilitated by the draft created by the combustion chamber. Ash is discharged from the reaction chamber to the ash pit door of the stove. It was reported that the stove can be operated continuously for 24 hours, with an average thermal efficiency of 17% when using rice husk briquettes, 27% with wood chips, and 22% with wood twigs as fuel. The stove is reported to be promising for community type cooking, particularly for institutional kitchens and traditional cottage industries [66], [67].

Figure 4.38 shows the Sampada gasifier stove developed at Appropriate Rural Technology Institute (ARTI). Having an outer body of stainless steel, the stove has a fuel holder made of mild steel. Products such as wood chips, pellets, biomass briquettes, small twigs and wood chunks are used for producing the fuel required for cooking. Moreover, after cooking is complete, charcoal is left behind in the fuel holder as a by-product. It is reported that on burning 1 kg of wood leaves, around 250-300 g of charcoal is produced [68].

In the above examples of gasifier stoves, both natural draft and forced draft designs could be seen. Forced draft type gasifier stoves, which use a small battery-operated blower to supply primary and secondary air, are more recent developments. The advantages with this type are that they have higher wattage for the same stove size, easier to start and operate, and flame control is much more effective in comparison with natural-draft stoves. Some of the natural-draft wood-gas stoves were later modified as a forced-draft stove.
4.3.8 Industrial Energy Applications of Biomass Gasifiers

As illustrated in Figure 4.25 earlier, gasification represents the key conversion technology in all processes for the production of energy, fuels, and chemicals from biomass. The energy applications represent generation of electricity or heat or both heat and electricity using a combined heat and power (CHP) system. This can be either in stand-alone plants or by cofiring of the producer gas in large-scale power plants. Specifications for producer gas and syngas are defined by the final application and comprise acceptable levels for the concentration of impurities and the required gas composition. Further, for certain applications specifically a producer gas or syngas feed is preferred or required. For example [59]:

- **Heat** : Producer gas
- **Power - Combined cycle** : Producer gas
- **Power - CHP gas engine** : Producer gas, low tar content
- **Power - CHP fuel cell** : Producer gas, low hydrocarbon & organic content
- **Synthetic natural gas** : Producer gas, nitrogen-free, high methane content
- **Liquid fuel synthesis** : Syngas, nitrogen-free
- **Chemical synthesis** : Syngas, nitrogen-free
- **Hydrogen production** : Syngas, nitrogen-free
- **Ammonia production** : Syngas, containing nitrogen

Syngas can be used for the heat and power applications too, however, a producer gas is preferred because the energy efficiency from biomass to producer gas is higher than the efficiency to syngas.

In this section, some examples of gasification systems in practical usage for small scale industrial applications are presented.

Figure 4.39 presents biomass gasifier of capacity 120 kWth installed in a brass melting industry in Sri Lanka that replaced a conventional fossil fuel system. In the conventional technology, liquid fuel such as waste lubricant oil or furnace oil sludge mixed with kerosene oil is burned in a furnace using a pressure-jet atomizing burner for generation of heat. In the biomass gasifier system, producer gas is generated by burning wood chips or similar biomass residues in the gasifier and fed to the burner through a pipeline. Gas gets burnt in the furnace and is transferred to the crucible. A temperature in excess of 900 °C is attained.
Figure 4.39: 120 kWth biomass thermal gasifier in a brass melting industry

Figure 4.40 shows a downdraft gasifier - IC engine system commissioned for a rural electrification programme in Sri Lanka. Here, gliricidia wood sticks are chopped and sun dried before charging to the gasifier. The producer gas generated is cleaned and cooled, and subsequently burned in an IC engine to generate power. The system is rated at 3.5 kWe output. Typical fuel used in this system is gliricidia wood sticks of few cm diameter and chopped to a length of about 10 cm. These materials are open sun dried to reduce the moisture content up to about 20% on wet basis. The fuel feeding rate is about 5 kg/hr [69].

Figure 4.40: 3.5 kWe fuel wood gasifier - IC engine system in Sri Lanka

Similar type of rural electrification projects via biomass gasifiers could be seen in several Asian countries. For instance, in Cambodia about 90 biomass gasifiers have been installed,
majority of which are commercial/industrial scale plants and are used for generating electricity for rural electrification or use in SMEs. The major types of SMEs, which use biomass gasification, are rice mills, ice plants, rural electricity enterprises, brick factories, garment factories, and hotels. The feedstocks used for gasification mainly include rice husks or corn cobs, wood chips, coconut shells, bagasse, peanut shells, etc. [70]. Figure 4.41 presents a pilot rural electrification project implemented in the village of Anlong Tamey, in Bannan District, Cambodia. The rated installed capacity is 9 kWe, with rated biomass consumption of 12 to 14 kg/hr. The feedstocks are Leucaena wood and corn cobs [71].

Significant advancements in biomass based gasifiers have been taken place in India, supported by government funding and initiatives. Majority of these are targeted for rural energy services including home lighting, household appliances, water pumping, community cooking, rural industries, street lighting, etc. Figure 4.42 shows typical biomass gasifier systems developed in India [72].
4.4 PYROLYSIS

4.4.1 Overview

Pyrolysis is defined as irreversible chemical change (or thermal destruction) brought about to fuel materials by heat in the absence (or with a limited supply) of oxidizing agents that does not permit gasification to an appreciable extent. The destructed portions comprise of high energy content and numerous organics content, which leads to the possibility of extraction of energy and chemicals from biomass. During pyrolysis, materials undergoes a sequence of changes and normally yields products in gases, liquids and solid phases at proportions and composition dependent on feedstock characteristics and on process conditions. The solid is called charcoal (or char) while the condensable liquid is referred to as pyrolysis oil (also named by various terminologies such as pyroligneous liquid, pyroligneous liquor, or pyroligneous acid) [42]. In case of biomass pyrolysis oil is referred to as bio-oil and the charcoal is referred to as biochar. Table 4.10 presents the percentage composition of liquid, solid and gaseous products of different pyrolysis modes (adapted from [73] and [74]).

<table>
<thead>
<tr>
<th>Pyrolysis Process</th>
<th>Liquid</th>
<th>Solid</th>
<th>Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasification</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fast Pyrolysis</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moderate Pyrolysis</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slow - Carbonization</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slow - Torrefaction</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.43: Major product categories of pyrolysis modes

As given in Table 4.10, the various pyrolysis processes can also be classified based on heating rates and residence time, the two critical parameters that affects the process [75]. Generally low temperatures and slow heating rates result in high yield of char. This type of pyrolysis, in which char production is maximized, is called carbonization. In a now obsolete process for production of methanol, acetic acid and acetone, wood is heated (generally by burning the gaseous and/or solid products) in a rector (known as retort) in absence of air and the liquid vapours are condensed. This type of pyrolysis is generally called destructive.
distillation. In a relatively recent development it is found that yields of volatiles (i.e. the products in gaseous and liquid phases) increase with the rate of heating. In fact at sufficiently high heating rates all biomass can be nearly converted to volatiles, process of which is referred to as fast pyrolysis. Pyrolysis is difficult to precisely define, especially when applied to biomass. The older literature generally equates pyrolysis to carbonization, in which the principal product is a solid charcoal. Today, the term pyrolysis often describes processes in which pyrolysis oils are preferred products. Although pyrolysis (as a process for charcoal making) has been known to man since time immemorial, the complex pattern of series and parallel reactions involved in the process is not yet fully understood.

Table 4.10: Pyrolysis technology variant

<table>
<thead>
<tr>
<th>Process</th>
<th>Residence Time</th>
<th>Heating Rate</th>
<th>Temp (°C)</th>
<th>Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbonization</td>
<td>Days</td>
<td>Very low</td>
<td>400</td>
<td>Charcoal</td>
</tr>
<tr>
<td>Conventional</td>
<td>5 – 30 min</td>
<td>Low</td>
<td>600</td>
<td>Oil, Gas, Char</td>
</tr>
<tr>
<td>Fast</td>
<td>0.5 – 5 sec</td>
<td>Very high</td>
<td>650</td>
<td>Bio-oil</td>
</tr>
<tr>
<td>Flash-liquid</td>
<td>&lt; 1 sec</td>
<td>High</td>
<td>&lt;650</td>
<td>Bio-oil</td>
</tr>
<tr>
<td>Flash-gas</td>
<td>&lt; 1 sec</td>
<td>High</td>
<td>&lt;650</td>
<td>Chemicals, Gas</td>
</tr>
<tr>
<td>Ultra</td>
<td>&lt; 0.5 sec</td>
<td>Very high</td>
<td>1000</td>
<td>Chemicals, Gas</td>
</tr>
<tr>
<td>Vacuum</td>
<td>2- 30 sec</td>
<td>Medium</td>
<td>400</td>
<td>Bio-oil</td>
</tr>
<tr>
<td>Hydro-pyrolysis</td>
<td>&lt; 10 sec</td>
<td>High</td>
<td>&lt;500</td>
<td>Bio-oil</td>
</tr>
<tr>
<td>Methano-pyrolysis</td>
<td>&lt; 10 sec</td>
<td>High</td>
<td>&gt;700</td>
<td>Chemicals</td>
</tr>
</tbody>
</table>

It is important to differentiate pyrolysis from gasification. Unlike pyrolysis, gasification of solid biomass is carried out in the presence of oxygen, where the material is decomposed into producer gas or syngas by carefully controlling the amount of oxygen present. Moreover, gasification aims to produce gaseous products while pyrolysis aims to produce bio-oils and biochar.

Liquefaction can also be confused with pyrolysis. The two processes differ in operating parameters, requirement of catalyst, and final products. Liquefaction produces mainly liquid and some amounts of gaseous components at temperature and pressure ranges of 250 – 350 °C and 700 - 3000 psi, respectively, in the presence of alkali metal salts as catalyst. The liquefaction may also require supplemental CO and H₂ as reactants to facilitate the overall
process. The function of the catalysts is to hydrolyse the macromolecules of the components of biomass (i.e. cellulose, hemicelluloses, and lignin) into smaller micellar-like fragments, which are further degraded to smaller compounds via series of reactions including dehydration, dehydrogenation, deoxygenation, and decarboxylation. The liquefaction process has the potential to provide liquid fuels in line with petroleum products along with several high value chemicals. However, recent trends in biomass thermochemical conversion, liquefaction could not become commercially successful due to number of factors including the lower overall yield of oil (between 20–55% w/w), inferior oil quality (heavy tar like liquid), stricter operational parameters (higher reaction temperature and pressure), and requirements of catalysts and/or other reactants (such as CO, propanol, butanol, and glycerine) [76].

Due to the inherent heterogeneity and complexity of biomass materials, a direct conversion of the whole biomass by a particular pyrolysis mode (for example, fast pyrolysis) leads to a complex mixture of many components that originate from all the biomass fractions, and therefore becomes difficult or impossible to match with current requirements of petrochemical technologies. Isolation of individual substances from this mixture is difficult and expensive. The concept of biorefinery has been emerged in this context. Biorefinery is an overall concept of an integrated and diversified processing plant where biomass feedstocks are converted into a wide range of valuable products, using an array of processing technologies much likewise to petroleum refineries. In one such method, a low-temperature thermochemical conversion route (known as staged degasification) is employed to generate value-added chemicals, fuels and other products from biomass. Figure 4.44 illustrates the concept of staged degasification concept and its place in a thermochemical biorefinery [77].

![Staged degasification for value-added chemicals and fuels](image)

**Figure 4.44:** Staged degasification for value-added chemicals and fuels
4.4.2 Types of Pyrolysis Reactors

A pyrolysis system unit typically consists of the equipment for biomass pre-processing, the pyrolysis reactor, and equipment for downstream processing. Most pyrolysis reactors can be classified as units that produce heat and biochar (using slow pyrolysis) or units that produce biochar and bio-oils (using fast pyrolysis), as illustrated in Figure 4.45 [78].

![Figure 4.45: Options for pyrolysis reactors](image)

Different names are often used to describe some specific type of pyrolysis reactors. The term “kiln” is used for devices producing only charcoal. The terms “retort” and “converter” are used for equipments capable of recovering by-products. The term “converter” normally refers to devices used for pyrolysing biomass of small particle size and the term “retort” refers to equipment for pyrolysing log reduced in size to about 30 cm length and 18 cm diameter.

Reactors used for biomass pyrolysis is most commonly classified depending on the way the solids move through the reactor [42]. The following basic types of solid movement during pyrolysis can be identified.

- **Type A**: No solid movement through the reactor during pyrolysis (Batch reactors)
- **Type B**: Moving bed (Shaft furnaces)
- **Type C**: Movement caused by mechanical forces (e.g. rotary kiln, rotating screw etc.)
- **Type D**: Movement caused by fluid flow (e.g., fluidized bed, spouted bed, entrained bed etc.)

Pyrolysis reactor can also be classified depending the way heat is supplied to biomass as follows:
- **Type 1**: Part of the material burnt inside the reactor to provide the heat to carbonize the remainder.
- **Type 2**: Direct heat transfer from hot gases produced by combustion of one or more of the pyrolysis products or any other fuel outside the reactor.
- **Type 3**: Direct heat transfer from inert hot material (hot gases or sand introduced into the reactor).
- **Type 4**: Indirect heat transfer through the reactor walls (i.e. external heat source due to combustion of one or more pyrolysis products or any other fuel).

Although Types 2 and 3 have notable similarity, there is a basic difference between them. In Type 2, some of the hot products of combustion, e.g., CO₂ and H₂O vapour could react with charcoal produced as a result of pyrolysis and may affect the yield depending on the design of the carbonizer. Many different combinations of modes of solid movement and modes of heat transfer are possible in practice. Accordingly, the type of a pyrolysis reactor can probably be best specified by denoting it as type \(XI\) where \(X\) stands for type of solid movement and \(I\) indicates the type of heat transfer.

A number of different pyrolysis reactor designs are available. These include Fluidized bed, Circulating fluidized bed, Ablative, Rotating cone, Auger (or screw), Vacuum, Transported bed, and Entrained flow, schematic views of some of them are shown in Figure 4.46 (adapted from [76]). As pyrolysis is a precursor to gasification and combustion, the same reactors used for gasification (such as fixed bed and fluidized bed reactors) can be used for pyrolysis. Bubbling fluidized bed reactors are simpler to design and construct than other reactor designs, and have good gas to solids contact, good heat transfer, good temperature control, and a large heat storage capacity. High liquid yields (around 70% weight of wood on a dry basis) can be typically achieved. Small fuel particle sizes are needed (< 2 - 3 mm) to ensure high heat rates. The rate of particle heating is the rate limiting factor.

Circulating fluidized bed pyrolysis reactors are similar to bubbling fluidized bed reactors but have shorter residence times for chars and vapors which results in higher gas velocities, faster vapor and char escape, and higher char content in the bio-oil. They have higher processing capacity, better gas-solid contact, and improved ability to handle solids that are difficult to fluidize than bubbling fluidized bed reactors, but are less commonly used. The heat supply typically comes from a secondary char combustor.
Figure 4.46: Pyrolysis reactors
Ablative pyrolysis reactors function on the principle that, while under pressure, heat transferred from a hot reactor wall will soften feedstock in contact with it allowing the pyrolysis reaction to move through the biomass in one direction. The feedstock is mechanically pushed through the reactor. High rates of pressure significantly affect the rate of the reaction and the velocity of the feedstock on the heat exchange surface. Rather than limited by the rate of heat transfer through the biomass particle, the reaction rate is limited by the rate of heat supply to the reactor and thus larger particles can be pyrolyzed. Inert gases are not required resulting in smaller processing equipment and more intense reactions. However, the process is dependent on surface area so scaling to larger facilities is costly and the use of mechanical drivers is more complex.

In a rotating cone pyrolysis reactor, room temperature biomass particles and hot sand are introduced near the bottom of the cone, mixed, and transported upwards by the rotation of the cone. Pressures are slightly above atmospheric levels. Rapid heating and short gas phase residence times can be achieved.

### 4.4.3 Parameters Influencing Pyrolysis Process

The basic phenomena that take place during pyrolysis are:

- heat transfer from a heat source, leading to an increase in temperature inside the fuel;
- initiation of pyrolysis reactions due to this increased temperature, leading to the release of volatiles and the formation of char;
- outflow of volatiles, resulting in heat transfer between the hot volatiles and cooler unpyrolysed fuel;
- condensation of some of the volatiles in the cooler parts of the fuel to produce tar; and
- autocatalytic secondary pyrolysis reactions due to these interactions.

Important pyrolysis process control parameters include the heat rate (length of heating and intensity), the prevailing temperature, pressure, the presence of ambient atmosphere, the chemical composition of the fuel (e.g., the biomass resource), physical properties of the fuel (e.g. particle size, density), residence time and the existence of catalysts. These parameters can be regulated by selection among different reactor types and heat transfer modes, such as gas–solid convective heat transfer and solid–solid conductive heat transfer. The heat transfer modes and features of various reactors are listed in Table 4.11[79].
### Table 4.11: The heat transfer modes and typical features of various reactors

<table>
<thead>
<tr>
<th>Reactor type</th>
<th>Mode of heat transfer</th>
<th>Typical features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluidized bed</td>
<td>90% conduction;</td>
<td>High heat transfer rates; Heat supply to fluidizing gas or to bed directly; Limited char abrasion;</td>
</tr>
<tr>
<td></td>
<td>9% convection;</td>
<td>Very good solids mixing; Particle size limit &lt; 2 mm in smallest dimension; Simple reactor configuration</td>
</tr>
<tr>
<td></td>
<td>1% radiation</td>
<td></td>
</tr>
<tr>
<td>Circulating fluidized</td>
<td>80% conduction;</td>
<td>High heat transfer rates; High char abrasion from biomass and char erosion; Leading to high char in</td>
</tr>
<tr>
<td>fluidized bed</td>
<td>19% convection;</td>
<td>product; Char/solid heat carrier separation required; Solids recycle required; Increased complexity</td>
</tr>
<tr>
<td></td>
<td>1% radiation</td>
<td>of system; Maximum particle sizes up to 6 mm; Possible liquids cracking by hot solids; Possible</td>
</tr>
<tr>
<td></td>
<td></td>
<td>catalytic activity from hot char; Greater reactor wear possible</td>
</tr>
<tr>
<td>Entrained flow</td>
<td>4% conduction;</td>
<td>Low heat transfer rates; Particle size limit &lt; 2 mm; Limited gas/solid mixing</td>
</tr>
<tr>
<td></td>
<td>95% convection;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1% radiation</td>
<td></td>
</tr>
<tr>
<td>Ablative</td>
<td>95% conduction;</td>
<td>Accepts large size feedstocks; Very high mechanical char abrasion from biomass; Compact design;</td>
</tr>
<tr>
<td></td>
<td>4% convection;</td>
<td>Heat supply problematical; Heat transfer gas not required; Particulate transport gas not always</td>
</tr>
<tr>
<td></td>
<td>1% radiation</td>
<td>required</td>
</tr>
</tbody>
</table>

### 4.4.4 Mechanism and Products of Biomass Pyrolysis

On heating, the constituents of biomass materials decompose following different pathways and yielding a variety of products, each of which has its own kinetic characteristics. In addition, secondary reaction products result from cross-reactions of primary pyrolysis products and between pyrolysis products and the original feedstock molecules. Pyrolysis of each constituent is itself a complex process that is dependent on many factors. The overall mechanism of biomass pyrolysis can be represented by the general scheme shown in Figure 4.46. The biomass is decomposed by a number of parallel primary reactions into primary products, which are acted upon by a number of secondary reactions. As illustrated in Figure 4.47, char is formed as a product of the primary reactions and as solid material deposited due to the secondary reactions.
To understand pyrolysis of wood, it is interesting to consider first the pyrolysis of the main wood constituents: cellulose, hemicellulose and lignin. Cellulose and hemicellulose are the major sources of volatiles and tar while lignin is the major source of char. The rate of thermal breakdown and the product line up is determined by the order of thermochemical stability of the individual biomass constituents, which is illustrated in Figure 4.48 (adapted from [80]).

Upon heating to temperatures below 250°C cellulose undergoes a drop in the degree of polymerization and pyrolysis takes place slowly, the major products being H₂O, CO₂, CO and a carbonaceous residue. At temperatures above 250°C cellulose begins to pyrolyse rapidly producing condensable “tar” along with gases and leaves a charred residue. The pyrolysis of cellulose proceeds very rapidly at around 350°C and above 500°C the volatile products begin to undergo gas-phase pyrolysis. Figure 4.49 provides a simplified reaction scheme of cellulose pyrolysis. Compared to cellulose, hemicellulose pyrolysis begins at a lower temperature but takes place over a much wider temperature range and produces less char.
Finally, lignin is regarded as the most stable of the major biomass components. Below 200°C its rate of thermal degradation is very slow. Lignin decomposes between 280°C and 500°C and produces more char compared to cellulose. At low heating rates the char yield from lignin exceeds 50% by weight. Figure 4.50 presents a schematic overview of the thermal fractionation of biomass by a step-wise pyrolysis approach.
The chemistry and products of biomass pyrolysis are summarized in Table 4.12 [81].

Table 4.12: Characterization of chemistry and products of biomass pyrolysis

<table>
<thead>
<tr>
<th>Type</th>
<th>Feature and Process</th>
<th>Products and their characterizations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyrolysis of lignin</td>
<td><em>Conventional (Carbonization):</em> At 100 – 175 °C endothermic reaction; From 400°C exothermic reaction; Maximum rate occurring between 350 °C and 450 °C</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Fast and Flash pyrolysis:</em> High temperature of 475 °C, rapid heating rate, finely ground material, less than 10% moisture content, rapid cooling and condensation of gases, yields in 80% range, char and gas used for fuel</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Char: Approximately 55%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Distillates: 20%, methanol, methoxyl groups, acetone, acetic acid</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tar: 15%, phenolic compounds and carboxylic acid</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gases: CO, methane, CO2, ethane</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bio-oil: Will not mix with hydrocarbon liquids, cannot be distilled, substitute for fuel oil and diesel in boilers, furnaces, engines, turbines.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Phenols: Utilizes a solvent extraction process to recover phenolics and neutrals, 18-20% of wood weight, secondary processing of phenol formaldehyde resins, adhesives, injection molded plastics.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Other chemicals, extraction process: Chemical for stabilizing the brightness regression of thermochemical pulp (TMP) when exposed to light, food flavorings, resins, fertilizers, etc.</td>
</tr>
</tbody>
</table>
### Table 4.12: Characterization of chemistry and products of biomass pyrolysis (Cont…)

<table>
<thead>
<tr>
<th>Type</th>
<th>Feature and Process</th>
<th>Products and their characterizations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyrolysis of holocellulose</td>
<td>General effects:</td>
<td>Volatile products:</td>
</tr>
<tr>
<td></td>
<td>Colour changes from brown to black;</td>
<td>Readily escape during pyrolysis process, 59 compounds are produced out of which 37 have been identified</td>
</tr>
<tr>
<td></td>
<td>Flexibility and mechanical strength are lost, size reduced, weight reduced</td>
<td>CO, CO₂, H₂O, acetal, furfural, aldehydes, ketones.</td>
</tr>
<tr>
<td></td>
<td>Processes:</td>
<td>Tar:</td>
</tr>
<tr>
<td></td>
<td>Dehydration – also known as char forming reactions produces volatile products and char;</td>
<td>Levoglucosan is principal component.</td>
</tr>
<tr>
<td></td>
<td>Depolymerization – produces tar</td>
<td>Char:</td>
</tr>
<tr>
<td></td>
<td>Effect of temperature:</td>
<td>As heating continues there is 80% loss of weight and remaining cellulose is converted to char, prolonged heating or exposure to higher temperature (625 °C) reduces char formation to 9%.</td>
</tr>
<tr>
<td></td>
<td>At low temperatures dehydration predominates, at 355 K</td>
<td></td>
</tr>
<tr>
<td></td>
<td>depolymerization with production of levoglucosan dominates. Between 375 °C and 400 °C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>products formed are independent of temperature.</td>
<td></td>
</tr>
</tbody>
</table>

Bio-oil derived from pyrolysis comprised of complex mixtures of chemical compounds. The properties of bio-oil could vary substantially with respect to biomass feedstock. Its color varies from light brownish yellow to dark brown for various fractions during condensation phases with pungent-smoky odor and acidic pH. It contains water up to about 40% by weight, presence of which is a critical factor affecting the heating value and physiochemical properties such as pH, viscosity, and phase separation. Bio-oils can also contain aerosols.

When considering the handling, transportation and storage aspects, bio-oils are the most preferred pyrolysis fuel types. This is due to the fact bio-oil is compatibility with many existing equipments and processes. However, further processing is required before usage due to certain undesirable properties of raw products including contamination of water, aerosol and ash. Table 4.13 represents some physical and chemical characteristics of bio-oils obtained from different pyrolysis process conditions and biomass sources including waste agricultural biomass materials, animal manure and wood [76].
Table 4.13: Characteristics of bio-oil derived from pyrolysis of biomass materials

<table>
<thead>
<tr>
<th>Biomass source</th>
<th>Pyrolysis temperature (°C)</th>
<th>Bio-oil yield (wt%)</th>
<th>Moisture content (wt%)</th>
<th>Ultimate Analysis (wt %)</th>
<th>HHV (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed Sawdust</td>
<td>500</td>
<td>33-45</td>
<td>39</td>
<td>C 30.7, H 6.7, O 61.5, N 1.1, Ash -</td>
<td>10.9</td>
</tr>
<tr>
<td>Wheat straw</td>
<td>600</td>
<td>19</td>
<td>-</td>
<td>C 71.1, H 8.5, O 19.8, N 0.5, Ash -</td>
<td>16 – 19</td>
</tr>
<tr>
<td>Corn cob</td>
<td>470</td>
<td>56.7</td>
<td>32.2</td>
<td>C 38.1, H 8.0, O 53.2, N 0.7, Ash -</td>
<td>15.8</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>480</td>
<td>60.7</td>
<td>23.0</td>
<td>C 40.8, H 7.0, O 47.3, N 0.3, Ash 0.01</td>
<td>16.0</td>
</tr>
<tr>
<td>Pine wood pellets</td>
<td>450</td>
<td>57.7</td>
<td>10.0</td>
<td>C 64.9, H 7.1, O 27.8, N 0.2, Ash -</td>
<td>27.6</td>
</tr>
<tr>
<td>Barley husk</td>
<td>500</td>
<td>42-50</td>
<td>13.8</td>
<td>C 54.7, H 5.3, O 38.5, N 1.8, Ash -</td>
<td>24.1</td>
</tr>
<tr>
<td>Microalgae</td>
<td>450</td>
<td>57.2</td>
<td>-</td>
<td>C 76.2, H 11.6, O 11.2, N 0.9, Ash -</td>
<td>41.0</td>
</tr>
<tr>
<td>Swine manure</td>
<td>500</td>
<td>24.2</td>
<td>2.4</td>
<td>C 72.6, H 9.8, O 13.2, N 4.5, Ash 0.13</td>
<td>36.1</td>
</tr>
<tr>
<td>Cattle manure</td>
<td>310</td>
<td>48.7</td>
<td>2.4</td>
<td>C 73.7, H 8.1, O 16.8, N 1.4, Ash -</td>
<td>35.5</td>
</tr>
<tr>
<td>Softwood</td>
<td>500</td>
<td>45-54</td>
<td>-</td>
<td>C 62.6, H 7.0, O 29.0, N 1.1, Ash 0.25</td>
<td>27.9</td>
</tr>
</tbody>
</table>

The other significant output of pyrolysis, biochar received relatively less preference over bio-oil as a fuel source (except for charcoal produced from the carbonization process for heating application). However, there are many useful non-energy applications of biochar including that in agricultural sector. In general, the potential applications of biochar include soil enhancer, bulking agent for composting, activated carbon, remediation of water and soil, energy, and carbon sequestration. Table 4.14 represents some physical and chemical characteristics of bio-oils obtained from different pyrolysis process conditions and biomass sources including waste agricultural biomass materials and wood [76].

The gaseous fraction of pyrolysis product is, in general, referred to as pyrolysis gas or noncondensable pyrolysis gas. It is mainly composed of CO₂ and CO, while small quantities of various other gases such as NOₓ, SOₓ, H₂S, H₂, aldehydes, ketones, volatile carboxylic acids and gaseous hydrocarbons (methane - CH₄, ethylene - C₂H₄) could also be present. In general, pyrolysis gas is not a desired product of a pyrolysis process as it contains air pollutants, notably NOₓ, SOₓ an aerosol, and its heating value is relatively low (in the range of 1 MJ/kg). The presence of these pollutants depends upon the type of biomass material used. The pyrolysis gas can be used to directly or indirectly preheat the biomass followed by burning via combustors to generate heat requirements for pyrolysis process.
### Table 4.14: Characteristics of biochar derived from pyrolysis of biomass materials

<table>
<thead>
<tr>
<th>Biomass source</th>
<th>Pyrolysis temperature (°C)</th>
<th>Bio-oil yield (wt%)</th>
<th>Moisture content (wt%)</th>
<th>Ultimate Analysis (wt %)</th>
<th>HHV (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed Sawdust</td>
<td>500</td>
<td>20-27</td>
<td>-</td>
<td>C: 83.1, H: 3.7, O: 13.0, N: 0.2, Ash: -</td>
<td>30.1</td>
</tr>
<tr>
<td>Wheat straw</td>
<td>500</td>
<td>32</td>
<td>4.6</td>
<td>C: 73.6, H: 2.3, O: 8.0, N: 2.6, Ash: 13.3</td>
<td>28.1</td>
</tr>
<tr>
<td>Corn cob</td>
<td>500</td>
<td>18.9</td>
<td>-</td>
<td>C: 77.6, H: 3.1, O: 5.1, N: 0.9, Ash: 13.3</td>
<td>30.0</td>
</tr>
<tr>
<td>Corn straw</td>
<td>500</td>
<td>17.0</td>
<td>-</td>
<td>C: 57.3, H: 2.9, O: 5.5, N: 1.5, Ash: 32.8</td>
<td>21.0</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>500</td>
<td>12.9</td>
<td>3.8</td>
<td>C: 60.7, H: 4.0, O: 8.7, N: 0.8, Ash: 25.9</td>
<td>19.4</td>
</tr>
<tr>
<td>Pine wood</td>
<td>400</td>
<td>17-27</td>
<td>2.7</td>
<td>C: 83.5, H: 3.0, O: 8.3, N: 0.3, Ash: 2.3</td>
<td>31.7</td>
</tr>
<tr>
<td>Pine bark</td>
<td>450</td>
<td>17-27</td>
<td>2.3</td>
<td>C: 68.3, H: 2.5, O: 10.8, N: 0.3, Ash: 15.8</td>
<td>25.3</td>
</tr>
</tbody>
</table>

### 4.4.5 Modeling of Biomass Pyrolysis Process

Mathematical modeling of biomass pyrolysis process is a complicated task, particularly for large particles of biomass materials. Small particles offer negligible resistance to internal heat transfer and their temperature can be assumed to be uniform during pyrolysis. Further, in the case of rapid heating (e.g. in fluidized beds), the biomass particles are rapidly heated to the temperature of the reactor, which remains essentially constant during pyrolysis. However, pyrolysis of large biomass is a complicated process and involves following steps:

- Transfer of heat to the surface of the particle from its surrounding usually by convection and radiation
- Conduction of heat through the carbonized layer of the particle
- Carbonization of the virgin biomass over a range of temperature inside the particle
- Diffusion of the volatile products from inside to the surface of the particles and
- Transfer of the volatile products from the surface of the particle to the surrounding inert gas.

Thus the rate of expression for pyrolysis in this case will incorporate heat and mass transfer terms in addition to kinetics terms of biomass decomposition reactions. The overall pyrolysis process is further complicated by secondary pyrolysis of the volatile products while diffusing out through the particle, heat transfer by convection to the volatile products while diffusing out through the particle, shrinkage of the biomass particle as it undergoes pyrolysis, etc. Figure 4.51 illustrate the main stages and products of the reactions of biomass pyrolysis [82].
There are numerous studies attempting to model pyrolysis of different biomass materials under a variety of environmental and operational conditions. In one such study, pyrolysis product composition was modeled at low heating rates (< 100 °C/min) for woody biomass materials to predict char yield, simplified composition of volatile species and heat of pyrolysis [83]. The thermal decomposition of biomass has been described on the basis of decomposition of its three main constituents, viz., cellulose, hemicelluloses and lignin. The process of pyrolytic decomposition of biomass material is represented by the reaction

\[ C_{6}H_{y}O_{x} \rightarrow \alpha C + [\beta CO + \gamma H_{2} + \delta CO_{2} + \varepsilon H_{2}O] + \lambda C_{1.16}H_{4} + \mu C_{6}H_{62}O_{0.2} \pm \text{Heat} \]

In the above equation, the term in the left side represents the chemical formula of the dry and ash-free biomass, in which the terms \( x \) and \( y \) are known for a given biomass material. The products of pyrolysis consist of char and volatile matter, which composed of six species viz., \( CO, CO_{2}, H_{2}, H_{2}O, \) light hydrocarbons and heavy hydrocarbons (i.e. tar). Char is assumed to be pure carbon and the light hydrocarbons modeled as methane and ethylene in the mass ratio 3:1 giving rise to an equivalent empirical formula of \( C_{1.16}H_{4} \). The chemical formula of tar is taken as \( C_{6}H_{62}O_{0.2} \). Complete elemental balance along with experimental data has been used for determining the product composition as a function of temperature. Model predictions show that the pyrolysis process changes from endothermic to exothermic with increase in temperature, with the reversal in heat of pyrolysis occurring when the tar yield falls to zero.
4.4.6 Charcoal Making Process

Charcoal is an important household fuel and to a lesser extent, industrial fuel in many developing countries. It is mainly used in the urban areas where its ease of storage, higher energy content (30 MJ/kg as compared with 15 MJ/kg few woodfuel), lower levels of smoke emissions, and, resistance to insect attacks make it more attractive than woodfuel. The production of charcoal spans a wide range of technologies from simple and rudimentary earth kilos to complex, large-capacity charcoal retorts. The production and distribution of charcoal consist of seven major stages:

- Preparation of wood
- Drying - reduction of moisture content
- Pre-carbonization - reduction of volatiles content
- Carbonization - further reduction of volatiles content
- End of carbonization - increasing the carbon content
- Cooling and stabilization of charcoal
- Storing, packing, transport, distribution and sale

The various production techniques produce charcoal of varying quality. However, the basic steps by which wood is transformed to charcoal are the same. Three distinct phases can be distinguished: drying, pyrolysis, and cooling. In practice, and particularly when the charcoal is made in large kilns, there is often a considerable overlap between these. Thus, pyrolysis may be well advanced in one area of the kiln before drying is complete in another.

- The Drying Phase

Before wood can be carbonized, the water it contains must be driven off. This happens in two distinct stages. The first is when the water in the pores of the wood, sometimes called the free water, is expelled. While this is happening, the temperature of the charge of wood remains at about 110 °C. The wetter the wood, the longer this process takes and the greater is the amount of energy consumed during it. When all the water in the pores has been driven off, the temperature rises. When it reaches about 150 °C, water which is more tightly bound or absorbed into the cellular structure of the wood (bond water) begins to be released. This continues as the temperature rises to around 200 °C. When the charcoal is made in a kiln, the water is released to the air in the form of water vapour. This is the principal constituent of the white smoke characteristic of the early stages of carbonization.
The Pyrolysis Phase
With the continued application of heat, the temperature of the wood rises further. Around 280°C, the pyrolysis reaction begins to occur. The breakdown of the cellulose, hemicellulose, and lignin during pyrolysis results in the evolution of a complex series of chemical substances referred to as the pyrolysis products. Because most of these are driven off in the form of gas or vapour, they are often described as the volatiles. The presence of the volatiles causes the colour of the smoke coming from a charcoal kiln to darken thus indicating that pyrolysis is under way. It also gives rise to the characteristic heavy smell of wood-tar normally associated with charcoal making.

Once the pyrolysis is under way, the need for a heat supply to maintain the reaction is very much less than that needed to drive off the water during the drying phase. When using a kiln, the need to continue burning part of the charge is reduced and the air supply is usually restricted at this stage. The temperature reached during pyrolysis depends on the size of the charge of wood being carbonized, the geometry of the kiln, the degree to which the manufacturing process is insulated against heat loss, the ambient temperature, the original moisture content of the wood, and a variety of other factors. In most small-scale traditional methods of manufacture, the maximum temperature reached tends to be about 400-500°C. But in some types of kilns, temperatures of up to 600-700°C are attained. Higher temperatures normally require the use of retorts.

During pyrolysis, there is a considerable loss of volume in the wood. Across the grain this can be as much as 30-40%, though it is much less along the grain. A kiln in which the wood has been laid horizontally thus tends to collapse downwards during charcoal making, whereas on in which the wood has been stacked vertically has a much smaller change in volume.

The Cooling Phase
As the pyrolysis reaction draws to its completion, the temperature in the charge of wood begins to fall. The amount of smoke given off from a charcoal kiln drops substantially and its colour changes to a pale blue and in some cases the smoke emission stops completely. The kiln or retort must be kept tightly sealed at this stage. If air is admitted before the charcoal has fallen below its ignition temperature, there is a danger of the whole load bursting into flame. Even when it has been allowed to cool thoroughly, care must always be taken as the
charcoal is being unloaded from the kiln. High temperature pockets often remain and these can ignite spontaneously as they come into contact with air. Once it has been released to the open air, charcoal is usually left for a period of about 24 hours for ‘seasoning’ to occur. During this time, the charcoal cools to air temperature and some of the remaining volatiles escape. Some moisture and a small amount of oxygen are also absorbed.

4.4.7 Factors Influencing Charcoal Yield

A number of factors affect the yield of charcoal obtained from a particular manufacturing method. Two of the most important of these are the maximum temperature reached during carbonization and the moisture content of the wood.

- **Carbonization Temperature**

The effects of the carbonization temperature on the yield and fixed carbon content when charcoal is made in a retort are shown in Table 4.15. The extreme case is where the carbonization temperature is 200°C. This is sufficient to produce little more than a through drying and light charring of the wood. In this case, the yield is 92% of the oven dry weight of the original wood. This ‘charcoal’, however, has a high volatile content and would not be acceptable to most charcoal users.

<table>
<thead>
<tr>
<th>Carbonization Temperature °C</th>
<th>Yield of charcoal as % of oven dry weight of original wood</th>
<th>Fixed carbon as % of dry weight of charcoal</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>91.8</td>
<td>52.3</td>
</tr>
<tr>
<td>250</td>
<td>65.2</td>
<td>70.6</td>
</tr>
<tr>
<td>300</td>
<td>51.4</td>
<td>73.2</td>
</tr>
<tr>
<td>500</td>
<td>31.0</td>
<td>89.2</td>
</tr>
<tr>
<td>600</td>
<td>29.1</td>
<td>92.2</td>
</tr>
<tr>
<td>700</td>
<td>27.8</td>
<td>92.8</td>
</tr>
<tr>
<td>800</td>
<td>26.7</td>
<td>95.7</td>
</tr>
<tr>
<td>900</td>
<td>26.6</td>
<td>96.1</td>
</tr>
<tr>
<td>1000</td>
<td>26.3</td>
<td>96.6</td>
</tr>
<tr>
<td>1100</td>
<td>26.1</td>
<td>96.4</td>
</tr>
</tbody>
</table>
As the manufacturing temperature is raised, the total yield of charcoal decreases because a greater proportion of the volatiles is being driven off. As a result, the charcoal produced has a higher fixed carbon content. At 300°C the yield is 51%, and the fixed carbon content is 73%. At 600°C the yield is 29%, and the fixed carbon content is 92%. These figures, being based on laboratory tests using a retort, cannot be used to predict the exact yields obtainable in practice. In general, the yields from kilns operated under practical conditions will be considerably lower than those shown. Nevertheless, the figures illustrate the general nature of the choice which has to be made between quantity and quality in charcoal making.

When charcoal with high fixed carbon content is required, a relatively high-temperature method of charcoal making has to be used in order to drive off the requisite proportion of volatiles. This inevitably reduces the total yield. Where a higher volatile content is acceptable, as it is when the charcoal is intended to be used for domestic consumption, a lower manufacturing temperature can be used with a corresponding increase in the yield.

**Water Content**

The water content of the wood also affects the final yield because it determines the proportion of the charge which has to be burned during the drying phase. For example, for green wood with a moisture content of 56% on a wet basis, 17.4% of the original dry weight of the wood is lost in driving off the water. If the wood is pre-dried to a moisture content of 17%, then the proportion required to drive off the water falls to 2.7%. This means that 14.3% of the original wood charge, which would otherwise have been burned to drive off the water, is available for turning into charcoal; there should therefore be a corresponding increase in the final yield of charcoal. High initial water content also reduces the maximum temperature reached during carbonization. In addition, it extends the carbonization time.

The influence of moisture content on the final yield is therefore very complex. There is no doubt that when charcoal with high fixed carbon content is required, the use of dry wood leads to a higher yield. It also reduces the time needed for carbonization, which is a particularly important factor when charcoal making equipment with a high capital cost is being used. In such cases, it usually makes considerable technical and economic sense to reduce the water content of wood before making it into charcoal.
But the same reasoning does not necessarily apply when traditional methods are being used to produce charcoal for the domestic market. In this case, the charcoal can have a reasonably high volatile content which means that low temperature manufacturing methods are acceptable. The use of wet wood is one way of keeping the kiln temperature relatively low.

### 4.4.8 Types of Charcoal Kiln

Figure 4.52 presents a broad classification of systems for carbonization of biomass.

![Diagram: Classification of biomass carbonization systems](image)

Traditionally, charcoal is made in earth kilns. These may consist of pits built in flat terrain or into a slope, or of mounds of rectangular shape or circular shape. Instead of earth, sawdust and rice husks may also be used to cover and seal kilns. Pit or mound kilns can be improved by the use of chimneys in order to control and accelerate carbonization. Past efforts to improve charcoal production have largely focused on enhancing the efficiency of the combustion stages through the design of new charcoal kilns.
The improved charcoal kilns can be broadly classified into five categories:

- Earth kilns
- Metal kilns
- Brick kilns
- Cement or masonry kilns
- Retort kilns

Figure 4.53 presents schematic diagram of few charcoal kilns.

![Figure 4.53: Charcoal kilns](image)

There exist various types of metal kilns which have the advantage of being portable and of accelerating carbonization. They can be made from simple 200 litre drums used in the horizontal position or in the vertical position as single or double drum. For professional operations, larger steel kilns are preferable consisting of one or two rings, a cover, special air inlets/smoke outlets and pipes.

Fixed kilns are built in localities used over several years or permanently for carbonization. They are built from mud, bricks, or concrete. Mud kilns of beehive shape are usually of simple construction, small and not very durable. For professional and longer-term use brick
kilns fitted with chimneys are more common. They are normally of the beehive type but may also be built as a ring with a metal cover or be of rectangular shape. Industrial charcoal production facilities normally employ large brick beehive kilns in batteries of several kilns, or the Missouri kiln, made of reinforced concrete, which allows mechanical loading and unloading. Retorts produce higher charcoal yields, permit by-product recovery and reduce air pollution.

The brick kilns are virtually proof against damage due to local overheating unlike the steel kilns. The only maintenance normally required is pouring on of mud slurry to seal cracks. Furthermore, when the kilns must be moved to a new site; a few kilometers away, they are simply dismantled and the bricks re-erected into kilns at the new site; however, brick kilns are normally used in cases where frequent relocations are not to be expected and where wood can be transported to the kiln. The brick kiln is generally much larger than the steel one and hence produces ten to twenty times more charcoal at a single burn. The brick kiln has doors and this makes loading and unloading simple.

Loading of wood and unloading of charcoal in case of metal kilns are labourious processes. The still kiln requires wood to be reduced to a size typically not bigger than 30×10×10 cm so that wood preparation needed is significant. On the other hand, brick kilns can use logs up to 50 cm diameter and 2 m long.

The steel kiln is prone to two special problems. First, since air leaks occur easily at the ground line, hot spots can occur during a burn, which lead to buckling and collapse of sections of the steel. The second problem is due to low insulation value of the steel kiln. Under the action of rain and cold winds, the walls of the kiln can become too cold so that the decomposition of the wood near them slows down and results in excessive production of partly carbonized wood. Brick kilns, because of their greater size and better insulation, are less prone to this problem. The steel kilns, require back up maintenance of steel plate and welding and heavy sheet metal working capability. These may be beyond the capability of simple charcoal makers. Also the steel sheet may have to be imported.
CHAPTER 05: BIOLOGICAL CONVERSION

5.1 INTRODUCTION
Conversion of the biomass to fuel by exposing biomass to certain microorganisms is called biological conversion. The secondary fuels are produced as a result of metabolic activity of the microorganisms. Fermentation and anaerobic digestions are the two most common biological conversion processes and products of these processes are ethanol and biogas.

Today, ethanol is widely used as an alternative source of liquid fuels for the transport sector in countries and regions like USA, Brazil, EU and China. Ethanol as a fuel offers many advantages such as lower thermal energy content, high octane number (99) than petrol (80–100), low emission. As well as there are some small problems, like: difficult cold start of the engine due to difficult vaporization, might be aggressive to certain steels and rubbers, energy per mass/volume ratio lower as that of gasoline. Biogas originates from the bio-degradation of organic material under anaerobic conditions. Today biogas has several applications such as industrial and household cooking, lighting, radiant heaters and incubators for agricultural purposes and absorption refrigerators. Biogas system provides a whole range of benefits for their users, the society and the environment in general:
- production of energy (heat, light, electricity),
- transformation of organic waste into high quality fertilizer,
- improvement of hygienic conditions via reduction of pathogens, worm eggs and flies,
- increase of productivity, mainly for women, in firewood collection and cooking,
- environmental advantages through protection of soil, water, air and woody vegetation,
- micro-economical benefits through energy and fertilizer substitution,
- additional income sources and increasing yields of animal husbandry and agriculture,
- macro-economical benefits through decentralized energy generation, import substitution and environmental protection.

5.2 FERMENTATION

5.2.1 Overview
Fermentation is a natural process initiated by microorganisms of the saccharomyces type, similar to common yeast cultures under anaerobic conditions. Ethanol can derive from any material which contains sugar. In the Fermentation process, Hexose/pentose sugars such as
glucose, fructose and sucrose are converted into ethanol and carbon dioxide as metabolic waste products. The net chemical equation for the production of ethanol from glucose is:

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$$

The raw materials used in the production of ethanol via fermentation are mainly classified into three types as sugars, starches, and cellulose materials. Sugars (extracted from from sugarcane, sugar beets, molasses, and fruits) can be converted into ethanol directly. But starches (from corn, cassava, potatoes, and root crops) and cellulose (from wood, agricultural residues, waste sulfite liquor from pulp, and paper mills) are needed to pre-treat prior the fermentation. Starches must first be hydrolyzed to fermentable sugars by the action of enzymes from malt or molds. Mainly three pre processing methods, viz. enzymatic hydrolysis, acidic hydrolysis and gasification, are used for preprocessing of cellulose biomass (see Figure 5.1). The final product, ethanol (C₂H₅OH) mixed with small amounts of methanol or higher alcohols and diluted in water. It should be distilled out from the water mixture.

Figure 5.1: Flow diagram of bioethanol production
5.2.2 Sugar Fermentation

Sugar Fermentation method is the simplest way to make ethanol. Raw materials for this process include high sugar plant sources such as sugar cane, molasses and fruits are crushed and pressed to release sugar water. Then this sugar water is directly fermented with yeast to produce ethanol. The bagasse generated in the process as a byproduct can be burned, gasified, or used in the cellulosic/fermentation process. Essentially, almost all of the plant can be used to produce energy (see Section 2.3.6). It is economically possible for individual farmers to produce ethanol on the farm. One of the disadvantages of this method is that the collected sugar water is unstable and must be processed fairly quickly after being pressed from the plant.

5.2.3 Starch Fermentation

In this chemical process, starchy grains such as corn, cassava, potatoes and root crops, are crushed and mixed with water. Then enzymes are added to break down the long starch molecules into smaller sugar molecules. Then the smaller sugar molecules are fermented with means of yeast. The advantage of starch fermentation is that it is a relatively simple and well understood process. A disadvantage is the use of edible foods to produce vehicle fuels, potentially driving up the price of certain foods. Another potential disadvantage is that the energy output contained in the ethanol may not be significantly higher than the required energy input (e.g., equipment and fertilizer energy).

5.2.4 Cellulosic Ethanol Production

Cellulosic ethanol production is more difficult than sugar or starch fermentation, as cellulose is so rigid and strong, pretreatment is required in order to break into the strong exterior to fermentable molecules. There are several ways to make ethanol from cellulosic material and three are discussed below.

- **Enzymatic Hydrolysis**

  Enzymes are added to cellulose, which decompose the biomass to simple sugars. The reaction occurs around 50°C and at a pH of about 5. Drawback of the enzymatic hydrolysis is the inhibition of glucose for the process. The hydrolysis products (such as glucose and cellulose chains) inhibit the ability for enzymes to convert cellulose to glucose. As more products are formed, the enzymes become more inhibited by the excess glucose present. This ultimately slows down the hydrolysis process.
Acid Hydrolysis

In acid hydrolysis, acids are used to decompose the biomass. The acid reacts with the cellulosic material to produce glucose molecules and short chains. Two qualities of acids namely dilute or concentrated are used. Dilute acid hydrolysis occurs under high temperature and high pressure while concentrated acid hydrolysis occurs at low temperatures and atmospheric pressure. Dilute acid hydrolysis process is costly to run and produces a low yield of usable glucose. Concentrated acid hydrolysis process is more efficient although the process is time consuming, taking up to 120 hours to complete [84]. Acidic hydrolysis is expensive because the process requires an acid recovery system. Otherwise any excess concentrated acid would kill yeast introduced to the product glucose in the fermentation.

Gasification-Syngas-Fermentation

Initially biomass is gasified to produce synthesis gas. Gasification is the incomplete burning of carbon-based materials in a high temperature but low oxygen atmosphere. The products of gasification are synthesis gas, heat, tars, and ash. The synthesis gas is composed mainly of CO, CO$_2$ and H$_2$. Approximate stoichiometric reaction of the process is given by

$$8\text{CH}_2\text{O} + (4\text{N}_2) \rightarrow 6\text{CO} + 2\text{CO}_2 + 8\text{H}_2 + (4\text{N}_2)$$

Then the synthesis gas is cooled and bubbled through the fermenter. Microorganisms use the gases as a food source and produce ethanol. Stoichiometric reaction can be written as;

$$6\text{CO} + 3\text{H}_2\text{O} \rightarrow \text{CH}_3\text{CH}_2\text{OH} + 4\text{CO}_2$$
$$6\text{H}_2 + 2\text{CO}_2 \rightarrow \text{CH}_3\text{CH}_2\text{OH} + 3\text{H}_2\text{O}$$

By combining the above equations, one can obtain

$$8\text{CH}_2\text{O} + (4\text{N}_2) \rightarrow 6\text{CO} + 2\text{CO}_2 + 8\text{H}_2 + (4\text{N}_2)$$

5.2.5 Factors that influence the ethanol fermentation

Production of ethanol is mainly depending on the rate of growth of microorganisms. Following factors can influence to the microbial growth:

- Temperature
- Water
- pH
- Nutrients
- **Temperature**
  The specific temperatures required for optimal operation of fermentation and enzymatic hydrolysis are 25 °C and 47 °C, respectively. Any extreme of temperature during fermentation, either high or low, directly affects to the growth of the microorganisms and produces minimal concentrations of ethanol. Yeast does not grow well in temperatures much lower than 20 °C or much higher than 40 °C. The hydrolysis process, if the temperature drops too low, the enzymes will not digest material [84].

- **Water**
  Microorganisms require optimum amounts of water to maintain their metabolism and produce required products. The main drawback of the ethanol fermentation is the inhibition of the ethanol produced to the fermentation reaction. As the concentration in ethanol increases, the ethanol attacks the various microorganisms in the system.

- **pH**
  Optimum pH for bacteria is in the range of 6.5 - 7.5, yeasts 4 - 5, molds 4 - 7. The pH of the medium should be maintained at optimum level for the microorganism being employed to ensure better product yield.

- **Nutrients**
  Microorganisms require optimum concentrations of nutrients like amino acids, nitrogen, vitamins, phosphorus and minerals for optimal fermentation. This will be different for each of the different types.

### 5.3 ANAEROBIC DIGESTION PROCESS

#### 5.3.1 Basic Process

A simplified stoichiometry for anaerobic digestion of biomass is:

\[
C_6H_{10}O_5 + H_2O \rightarrow 3CH_4 + 3CO_2
\]

The whole process of biogas production from organic wastes occurred in main three steps namely hydrolysis, acidification, and methane formation. Three types of bacteria namely fermentative, acetogenic and methanogenic are involved in hydrolysis, acidification and methane formation respectively.
Figure 5.2: The three stage anaerobic fermentation of biomass

- **Hydrolysis**
  In hydrolysis aerobic micro-organisms convert complex organic compounds (carbohydrates, proteins and lipids) into simple forms which are soluble and can be consumed by the micro-organisms. As an example, Polysaccharides are converted into monosaccharides, lipids to fatty acids, proteins to amino acids and peptides.

- **Acidification**
  In the second step, acid-producing bacteria (acetogenic bacteria), convert the intermediates of fermenting bacteria into mixture of acetic acid (CH₃COOH), hydrogen (H₂), carbon dioxide (CO₂), alcohols, organic acids, amino acids and hydrogen sulphide. These bacteria are facultatively anaerobic and can grow under acid conditions. The oxygen requirement for producing acetic acid is fulfilled by the oxygen solved in the solution or bounded-oxygen. Hereby, the acid-producing bacteria create an anaerobic condition which is essential for the methane producing microorganisms.

- **Methane formation**
  In the third step, methane-producing bacteria utilize hydrogen, carbon dioxide and acetic acid formed in acidification process to form methane and carbon dioxide.
5.3.2 Factors that influence the biogas production

- **Substrate temperature**
  
  The optimal temperature range for the biogas production is 20-28°C. It can achieve a satisfactory level only where mean annual temperatures are around 20°C or above or where the average daily temperature is at least 18°C. If the temperature of the bio-mass is below 15°C, gas production will be so low that the biogas plant is no longer economically feasible [85].

- **Changes in temperature**
  
  The process of bio-methanation is very sensitive to changes in temperature. Most of the biogas plants are built in underground in order to overcome this issue. The temperature fluctuations between day and night are no great problem for plants built underground, since the temperature of the earth below a depth of one meter is practically constant.

- **Available nutrient**
  
  In order to grow, bacteria need organic substances as a source of carbon and energy. In addition to carbon, oxygen and hydrogen, the generation of bio-mass requires an adequate supply of nitrogen, sulfur, phosphorous, potassium, calcium, magnesium and a number of trace elements such as iron, manganese, molybdenum, zinc, cobalt, selenium, tungsten, nickel etc. "Normal" substrates such as agricultural residues or municipal sewage usually contain adequate amounts of the mentioned elements. Higher concentration of any individual substance usually has an inhibitory effect, so that analyses are recommended on a case-to-case basis to determine which amount of which nutrients, if any, still needs to be added.

- **Retention time**
  
  The effective retention time may vary widely for the individual substrate constituents depending on the vessel geometry, the means of mixing, etc. Selection of a suitable retention time thus depends not only on the process temperature, but also on the type of substrate used. For liquid manure undergoing fermentation in the mesophilic temperature range, the following approximate values apply:
  
  - liquid cow manure: 20-30 days
  - liquid pig manure: 15-25 days
  - liquid chicken manure: 20-40 days
  - animal manure mixed with plant material: 50-80 days
If the retention time is not maintained properly and it is too short, the bacteria in the digester are "washed out" faster than they can reproduce, so that the fermentation practically comes to a standstill. This problem rarely occurs in agricultural biogas systems [85].

- **pH value**
The best condition for the methane-producing bacteria is neutral to slightly alkaline conditions. Once the process of fermentation has stabilized under anaerobic conditions, the pH will normally take on a value of between 7 and 8.5. If the pH value drops below 6.2, the medium will have a toxic effect on the methanogenic bacteria [85].

- **Nitrogen inhibition**
Nitrogen in the substrate inhibits the process of fermentation. Noticeable inhibition occurs at a nitrogen concentration of roughly 1700 mg ammonium-nitrogen (NH₄-N) per liter substrate. Nonetheless, given enough time, the methanogens are capable of adapting to NH₄-N concentrations in the range of 5000-7000 mg/l substrate, the main prerequisite being that the ammonia level (NH₃) does not exceed 200-300 mg NH₃-N per liter substrate. The rate of ammonia dissociation in water depends on the process temperature and pH value of the substrate slurry [85].

- **C/N ratio**
Microorganisms required both nitrogen and carbon for assimilation into their cell structures. Various experiments have shown that the metabolic activity of methanogenic bacteria can be optimized at a C/N ratio of approximately 8-20, whereby the optimum point varies depending on the nature of the substrate.

- **Substrate solids content**
Solid content of the substrate impaired the mobility of the methanogens within the substrate. Therefore the biogas yield decreases with the increase of solids content. However, reports of relatively high biogas yields from landfill material with high solids content may be found in recent literature. No generally valid guidelines can be offered with regard to specific biogas production for any particular solids percentage [85].
**Agitation**

Many substrates and various modes of fermentation require some sort of substrate agitation or mixing in order to maintain process stability within the digester. The most important objectives of agitation are:

- removal of the metabolites produced by the methanogens (gas)
- mixing of fresh substrate and bacterial population (inoculation)
- preclusion of scum formation and sedimentation
- avoidance of pronounced temperature gradients within the digester
- provision of a uniform bacterial population density
- prevention of the formation of dead spaces that would reduce the effective digester volume

Since the results of agitation and mixing are highly dependent on the substrate in use, it is not possible to achieve a sufficiently uniform comparative evaluation of various mixing systems and/or intensity levels. Thus, each such system can only be designed on the basis of empirical data.

**Inhibitory factors**

The presence of heavy metals, antibiotics (Bacitracin, Flavomycin, Lasalocid, Monensin, Spiramycin, etc.) and detergents used in livestock husbandry can have an inhibitory effect on the process of bio-methanation. The table 5.1 lists the limit concentrations (mg/l) for various inhibitors [85].

**Table 5.1: Limiting concentrations for various inhibitors of biomethanation**

<table>
<thead>
<tr>
<th>Substance</th>
<th>Limit concentration, [mg/l]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>10-250</td>
</tr>
<tr>
<td>Calcium</td>
<td>8000</td>
</tr>
<tr>
<td>Sodium</td>
<td>8000</td>
</tr>
<tr>
<td>Magnesium</td>
<td>3000</td>
</tr>
<tr>
<td>Nickel</td>
<td>100-1000</td>
</tr>
<tr>
<td>Zinc</td>
<td>350-1000</td>
</tr>
<tr>
<td>Chromium</td>
<td>200-2000</td>
</tr>
<tr>
<td>Sulfide (as Sulfur)</td>
<td>200</td>
</tr>
<tr>
<td>Cyanide</td>
<td>2</td>
</tr>
</tbody>
</table>
5.3.3 Types of plants

There are various types of biogas plants available in the world and they are classified mainly based on feeding method and construction. Concerning the feed method, three different forms can be distinguished:

- Batch plants,
- Continuous plants,
- Semi-batch plants.

Concerning the construction, two main types of simple biogas plants can be distinguished:

- Fixed-dome plants,
- Floating-drum plants.

**Batch plants**

In batch type plants, materials fed into the digester at a time and sealed only allowing the gas to exit and then emptied completely after a fixed retention time. Each design and each fermentation material is suitable for batch filling, but batch plants require high labor input. The major disadvantage of this type is unsteady gas-output. Sketch of a batch type digester is shown in Figure 5.3 [86].

![Batch type biogas digester](image)

**Continuous plants**

Once the process of the continuous type plants started, regular quantity of waste are fed continuously to the digester and regular quantity of material discharged continuously. They empty automatically through the overflow whenever new material is filled in. Therefore, the substrate must be fluid and homogeneous. This technology is suitable for both medium and
large scale waste treatment and large scale biogas production. Advantages of this type are constant and higher gas production.

- **Semibatch plants**
  
  If the two materials which have completely different digestion rates (such as straw and dung) are to be digested together, a biogas plant can be operated on a semibatch basis. The slowly digested straw-type material is fed in about twice a year as a batch load. The dung is added and removed regularly.

- **Fixed-dome plants**
  
  A fixed-dome plant comprises of a closed, dome-shaped digester with an immovable, rigid gas-holder and a displacement pit. The gas is stored in the upper part of the digester. When gas production commences, the slurry is displaced into the displacement tank. Gas pressure increases with the volume of gas stored, i.e. with the height difference between the two slurry levels. If there is little gas in the gas holder, the gas pressure is low.

![Fixed dome biogas digester - Nicarao design](image)

**Figure 5.4: Fixed dome biogas digester - Nicarao design**

The digesters of fixed-dome plants are usually masonry structures, structures of cement and ferro-cement exist. Main parameters for the choice of material are technical suitability (stability, gas- and liquid tightness), cost-effectiveness, availability in the region and transport costs and availability of local skills for working with the particular building material.

**Advantages of fixed dome plants**

- Produce just as much gas as floating-drum plants, if they are gas-tight.
- Low cost operation
Disadvantages of fixed dome plants
- Utilization of the gas is less effective as the gas pressure fluctuates substantially.
- Labor-intensive design
- Not easy to build. Difficult to achieve gas tightness.

Types of fixed-dome plants
Currently, various types of fixed dome plants are available such as Chinese fixed dome plant, Janata model, Deenbandhu and CAMARTEC model. Chinese fixed-dome plant, shown in Figure 5.5, is the archetype of all fixed dome plants and extensively use in China. The digester consists of a cylinder with round bottom and top.

![Figure 5.5: Chinese fixed dome type biogas digester](image)

Janata model was the first fixed-dome design in India, as a response to the Chinese fixed dome plant. It is not constructed anymore because the mode of construction leads to cracks in the gasholder. Deenbandhu is a improved design of the Janata plant in India. This plant is reported to be more crack-proof and consumed less building material than the Janata plant.

Figure 5.6 shows CAMARTEC model, which has a hemispherical dome shell based on a rigid foundation ring only and a calculated joint of fraction, the so-called weak / strong ring. This model was developed in the late 80s in Tanzania [87].
Floating-drum plants

Major difference between fixed dome and floating drum type plant is, a floating-drum plant consists of a floating gas-holder, or drum. This floats either directly in the fermenting slurry or in a separate water jacket. The drum in which the biogas collects has an internal and/or external guide frame that provides stability and keeps the drum upright. If biogas is produced, the drum moves up, if gas is consumed, the gasholder sinks back.

Floating-drum plants are used mainly in continuous feed mode of operation. They are used most frequently by small- to middle-sized farms (digester size: 5-15 m³) or in institutions and larger agro-industrial estates (digester size: 20-100 m³) [87].
**Advantages**
- Simple operation
- Provide gas at a constant pressure
- Stored gas-volume is immediately recognizable by the position of the drum.

**Disadvantages**
- The steel drum is relatively expensive and maintenance-intensive.
- Removing rust and painting has to be carried out regularly.
- The life-time of the drum is short (up to 15 years; in tropical coastal regions about five years).

### 5.3.4 Biogas Yield

Around 50-60% of the initial energy content in the organic material can be converted to biogas in a properly operated digester. The resultant gas mixture consists of about 60 - 65%, CH$_4$ and the rest is CO$_2$ with small amounts of water vapours, H$_2$S, NH$_3$, and some organics that give bad odour.

**Table 5.2: Biogas yield from various bio materials**

<table>
<thead>
<tr>
<th>Bio material</th>
<th>Biogas production per ton of biomass (Nm$^3$/ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milking cows</td>
<td>27</td>
</tr>
<tr>
<td>Yong stock</td>
<td>23</td>
</tr>
<tr>
<td>Porkers</td>
<td>24</td>
</tr>
<tr>
<td>Hens</td>
<td>136</td>
</tr>
<tr>
<td>Boilers</td>
<td>195</td>
</tr>
<tr>
<td>Sap from vegetable</td>
<td>17 - 34</td>
</tr>
</tbody>
</table>
CHAPTER 06: EXTRACTION OF BIODIESEL

6.1. INTRODUCTION
The use of vegetable oils for combustion in diesel engines has occurred for over 100 years. In fact, in the 1890s Rudolf Diesel tested his first prototype engine on vegetable oils. Whilst it is feasible to run diesel engines on raw vegetable oils, in general the oils must first be chemically transformed to resemble petroleum-based diesel more closely. The raw oil can be obtained from a variety of annual and perennial plant species. Research into the use of transesterified sunflower oil, and refining it to diesel fuel standards, was initiated in South Africa in 1979. An Austrian company erected the first biodiesel pilot plant in November 1987 and the first industrial-scale plant in April 1989 [88].

Biodiesel are the fuel oil extracted from the vegetable oils, animal fats, and recycled greases via transesterification reaction. These raw materials contain triglycerides, free fatty acids, and other contaminants. Examples for plants with high oil content are oil palm, sunflower, canola (rapeseed), soy, linseed, hemp, jojoba, jatropha, avocado, all kinds of nuts. Biodiesel is comprised of mono-alkyl esters of long chain fatty acids.

Biodiesel is biodegradable and can be used in diesel engines in its pure form with little or no modifications. Biodiesel is simple to use, nontoxic, and essentially free of sulfur and aromatics. It is a superior additive for petroleum diesel to reduce levels of particulates, carbon monoxide, hydrocarbons and air toxics from diesel-powered vehicles. When biodiesel used as an additive, the resulting diesel fuel is named as B5, B10 or B20, representing the percentage of the biodiesel that is blended with petroleum diesel.

6.2. PRODUCTION PROCESS OF BIODIESEL
6.2.1 Oil Extraction Process
Basically, oil crops are used for production of pure plant oil (PPO) or biodiesel. Biodiesel production process involves main three steps namely; oil extraction, oil refining and transesterification. The first step of production of both PPO and biodiesel is oil extraction. There are two process types based on the scale of the production and infrastructure known as small scale pressing and industrial. In small scale pressing process, purified seeds are mechanically pressed at maximum temperature of 40°C. Filtration or sedimentation is used
for removing suspended solids. The byproduct called press cake is used as an animal fodder. This method is not widely used because of higher production cost [89].

In industrial large scale method, pre treatments such as drying, seasoning, peeling of the organic matter is required. After that the cleaned seeds are crushed under conditioned temperature and humidity. The temperature should maintain above 80\(^{0}\)C in order to deactivate microorganisms and avoid smearing. Then oil seeds are pressed at temperature of 80\(^{0}\)C. Then the oil is filtered and dehydrated. This oil is used for further refining into PPO or for biodiesel production. In addition to that, the byproduct of the pressing process (press cake) contains about 25% of oil. Therefore initially it is crushed and then oil is extracted. For that a solvent probably hexane is used. The products of this process are miscella (mixture of oil with hexane) and extraction grist. Miscelladistillation is carried out to separate oil and the hexane [89].

Figure 6.1 illustrate the general overall process of oil extraction from seeds, highlighting main stages and intermediate products. More details of process flow related to oil extraction are illustrated in Figure 6.2 [89].
Figure 6.2: Typical flow diagram of oil extraction
6.2.2 Oil Refining Process

The oil extracted by oil extraction process is unrefined and it contains impurities such as phosphatides, free fatty acids and waxes. Therefore refining is required to use as pure plat oil (PPO) or biodiesel. The refining process is depends on the quality of the oil extracted. The simplified process flow diagram for extraction of unrefined oil is shown in Figure 6.3 [89].

![Figure 6.3: Typical flow diagram of oil refining](image)

Figure 6.3: Typical flow diagram of oil refining
6.2.3 Transesterification

Transesterification is a process of reacting a triglyceride with alcohol (methanol or ethanol) to brake the triglyceride to methyl or ethyl esters. The process is named either methanolysis or ethanolysis based on the type of alcohol used. The product of the methanolysis is fatty acid methyl ester and ethanolysis is fatty acid ethyl ester. The most common method for biodiesel production is methanolysis. This reaction is often catalyzed by the addition of base or acid. Glycerin is a byproduct of the process. Simplified form of the reaction is as follows [90]:

![Transesterification reaction diagram]

**Figure 6.4: Transesterification reaction**

In the above figure, R₁, R₂, and R₃ represent long hydrocarbon chains (fatty acid chains). There are only five chains that are most common in soybean oil and animal fats (others are present in small amounts) [90].

- **Palmitic**: \( R = -(\text{CH}_2)_{14} - \text{CH}_3 \)
  - 16 carbons, (16:0)

- **Stearic**: \( R = -(\text{CH}_2)_{16} - \text{CH}_3 \)
  - 18 carbons, 0 double bonds (18:0)

- **Oleic**: \( R = -(\text{CH}_2)_{7} \text{CH} = \text{CH} (\text{CH}_2)_{7} \text{CH}_3 \)
  - 18 carbons, 1 double bond (18:1)

- **Linoleic**: \( R = -(\text{CH}_2)_{7} \text{CH} = \text{CH} - \text{CH}_2 - \text{CH} = \text{CH} (\text{CH}_2)_{4} \text{CH}_3 \)
  - 18 carbons, 2 double bonds (18:2)

- **Linolenic**: \( R = -(\text{CH}_2)_{7} \text{CH} = \text{CH} - \text{CH}_2 - \text{CH} = \text{CH} - \text{CH}_2 - \text{CH} = \text{CH} - \text{CH}_2 - \text{CH}_3 \)
  - 18 carbons, 3 double bonds (18:3)
Biodiesel can be produced by heating a mixture of 80 – 90% oil, 10-20% methanol and small amount of catalysts. It is required to mix all ingredients well in order have a maximum efficiency of the process.

### 6.2.4 Oil Extraction Techniques

Oil can be extracted using the following methods:

- Wooden/stone sekku (mortar and pestle, which is one of the traditional methods)
- Batch type oil press
- Continuous expeller

Oil extraction can be more effectively carried out by the methods described below. There are batch type presses ranging from small, hand-driven models to power-driven commercial scale hydraulic presses. The batch press method is used for oil extraction to get high quality oil at a low temperature. The process is also known as the cold press method, and the oil (content) yield recorded is comparatively less than that reported when using a continuous screw expeller.

- **Batch type hydraulic jack operated oil expeller**

The batch Cottage level oil expeller shown in Figure 6.5 above is operated by a 10 MT hydraulic jack. The expeller unit, consists of a hollow cylinder made out of stainless steel, a piston, a handle, a pressure indicator gauge and a mounting frame to house all the above. The
amount of crushed seed kernel that the expeller can accommodate per batch is 1.5 - 2 kg. After loading a batch into the cylinder the piston (in the form of a circular disc) - which is fitting quite perfectly with the inner walls of the cylinder with minimum clearance and is attached to an arm - is pressed by a hydraulic jack. This forces the oil to be expelled from the feed through the perforated holes. The oil is then collected for filtration and further processing.

After complete expulsion, the hydraulic press is released and the residue cake is removed from the cylinder for further processing. The whole operation takes about 30 - 45 minutes per batch.

- **Continuous Screw Expeller**

  In this type of press, the first stage of oil expelling (pre-pressing) is done by using a high pressure continuous screw press called the expeller. Continuous screw expellers have a rotating screw inside a horizontal cylinder (barrel) that is made out of mild steel with 1 - 0.05 mm slots in each 25mm. The discharge end is open and clearance can be adjusted to suit different kind of raw material. The screw forces the seeds through the cylinder, gradually increasing the pressure on the crushed seed pulp, slowly moving it to the discharge end. The material gets heated due to friction and the oil escapes from the cylinder through small slots while operating the machine, and pressed residue emerges from the end of the cylinder. The pressure can be adjusted to suit different kinds of seeds in order to get the highest oil yield. Two or three passes might be required depending on the type of raw material. Extracted oil is filtered, and the material removed from the oil is fed back into the stream (new batch) along with the fresh material. The material which is finally discharged from the pressed residue is called ‘pressed cake’.

### 6.2.5 Oil Extraction from Different Seed Varieties

- **Jatropha seeds expelling**

  Jatropha fruits are mechanically / manually de-hulled. From the fruits the extracted Jatropha seeds have a thin hard shell, which can directly be fed to the continuous expeller (see Figure 6.7). The oil content in Jatropha seeds (with seed cover) is reported to be in the range of 30 - 50% by weight of the seed and ranges from 45 - 60% weight of the kernel itself.
- **Neem Seeds**

Approximately 16 - 17% w/w oil can be recovered from neem seeds without removing seed coat and a test carried out in Sri Lanka has been recorded a 38 – 39% w/w oil yields from a fresh seed sample. Due to its bitter taste, the pressed cake generated after extraction of the oil from neem seed has no value for animal feed.
• **Rubber Seeds**

All the seeds other than rubber seeds can be expelled with their seed cover. At least partial de-hulling is required before the expelling of rubber seeds. Foreign particles were removed and seeds were separated from the shells before oil expelling. A single phase, screw type expeller can be used for expelling. The best yields can be obtained with 8 - 9% moisture and 15 - 20% shell. The kernel makes up 54 - 60% of the rubber seed weight depending on the moisture content (see Table 6.1).

![Figure 6.9: Rubber roll Sheller and rubber kernel](image)

<table>
<thead>
<tr>
<th>Seed variety</th>
<th>Weight (kg)</th>
<th>Seed Cover</th>
<th>Kernel</th>
<th>Oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubber</td>
<td></td>
<td>46</td>
<td>54</td>
<td>18</td>
</tr>
<tr>
<td>Neem</td>
<td></td>
<td>44</td>
<td>56</td>
<td>18</td>
</tr>
<tr>
<td>Jatropha</td>
<td></td>
<td>44</td>
<td>56</td>
<td>19</td>
</tr>
<tr>
<td>Castor</td>
<td></td>
<td>44</td>
<td>56</td>
<td>18</td>
</tr>
</tbody>
</table>

### Table 6.1: Seed varieties and weights out of 100 kg

**6.3. MICROALGAE FOR BIODIESEL PRODUCTION**

**6.3.1 Overview**

Microalgae are prokaryotic or eukaryotic photosynthetic microorganisms that can grow rapidly and live in harsh conditions due to their unicellular or simple multicellular structure. Examples of prokaryotic microorganisms are Cyanobacteria (Cyanophyceae) and eukaryotic microalgae are for example green algae (Chlorophyta) and diatoms (Bacillariophyta) [88].
Microalgae are present in all existing earth ecosystems, not just aquatic but also terrestrial, representing a big variety of species living in a wide range of environmental conditions.

It is estimated that more than 50,000 species exist, but only a limited number, of around 30,000, have been studied and analyzed. During the past decades extensive collections of microalgae have been created by researchers in different countries. An example is the freshwater microalgae collection of University of Coimbra (Portugal) considered one of the world’s largest, having more than 4000 strains and 1000 species. This collection attests to the large variety of different microalgae available to be selected for use in a broad diversity of applications, such as value added products for pharmaceutical purposes, food crops for human consumption and as energy source. Many research reports and articles described many advantages of using microalgae for biodiesel production in comparison with other available feedstocks. From a practical point of view, they are easy to cultivate, can grow with little or even no attention, using water unsuitable for human consumption and easy to obtain nutrients. Microalgae reproduce themselves using photosynthesis to convert sun energy into chemical energy, completing an entire growth cycle every few days. Moreover they can grow almost anywhere, requiring sunlight and some simple nutrients, although the growth rates can be accelerated by the addition of specific nutrients and sufficient aeration [88].

6.3.2 Biodiesel Production Process

Figure 6.10 shows a schematic representation of the algal biodiesel value chain stages, starting with the selection of microalgae species depending on local specific conditions and the design and implementation of cultivation system for microalgae growth [88]. Then, it follows the biomass harvesting, processing and oil extraction to supply the biodiesel production unit. Figure 6.11 illustrate the unit operation of a bioreactor for microalgae biodiesel generation.

It is common to apply dehydration of biomass that also increases its shelf-life and of the final product. Several methods have been employed to dry microalgae such as Chlorella, Scenedesmus and Spirulina, where the most common include spray-drying, drum drying, freeze-drying and sun-drying. Because of the high water content of algal biomass sun-drying is not a very effective method for algal powder production and spray-drying is not economically feasible for low value products, such as biofuel or protein.
Figure 6.10: Microalgae biodiesel value chain stages

Figure 6.11: Bioreactor process
After drying it follows the cell disruption of the microalgae cells for release of the metabolites of interest. Several methods can be used depending on the microalgae wall and on the product nature to be obtained either based on mechanical action (e.g. cell homogenizers, bead mills, ultrasounds, autoclave, and spray drying) or non-mechanical action (e.g. freezing, organic solvents and osmotic shock and acid, base and enzyme reactions).

Taking the example of the astaxanthin recovery, although different methods have been studied the best results were obtained from autoclaved and mechanically disrupted biomass, with yield 3 times higher than with other methods. Lyophilization breaks up the cells and turns the algal material into a loose and fine powder, making other treatment unnecessary. Table 6.2 presents a performance comparison of microalgae with other biodiesel feedstock [88].

Table 6.2: Comparison of microalgae with other biodiesel feedstock

<table>
<thead>
<tr>
<th>Plant source</th>
<th>Seed oil content (%)</th>
<th>Oil yield (l oil/ha year)</th>
<th>Land use (m² year/kg of biodiesel)</th>
<th>Biodiesel productivity (kg biodiesel/ha year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn/Maize (Zea mays L.)</td>
<td>44</td>
<td>172</td>
<td>66</td>
<td>152</td>
</tr>
<tr>
<td>Hemp (Cannabis sativa L.)</td>
<td>33</td>
<td>363</td>
<td>31</td>
<td>321</td>
</tr>
<tr>
<td>Soybean (Glycine max L.)</td>
<td>18</td>
<td>636</td>
<td>18</td>
<td>562</td>
</tr>
<tr>
<td>Jatropha (Jatropha curcas L.)</td>
<td>28</td>
<td>741</td>
<td>15</td>
<td>656</td>
</tr>
<tr>
<td>Camelina (Camelina sativa L.)</td>
<td>42</td>
<td>915</td>
<td>12</td>
<td>809</td>
</tr>
<tr>
<td>Canola/Rapeseed (Brassica napus L.)</td>
<td>41</td>
<td>974</td>
<td>12</td>
<td>862</td>
</tr>
<tr>
<td>Sunflower (Helianthus annuus L.)</td>
<td>40</td>
<td>1070</td>
<td>11</td>
<td>946</td>
</tr>
<tr>
<td>Castor (Ricinus communis)</td>
<td>48</td>
<td>1307</td>
<td>9</td>
<td>1156</td>
</tr>
<tr>
<td>Palm oil (Elaeis guineensis)</td>
<td>36</td>
<td>5366</td>
<td>2</td>
<td>4747</td>
</tr>
<tr>
<td>Microalgae (low oil content)</td>
<td>30</td>
<td>58700</td>
<td>0.2</td>
<td>51927</td>
</tr>
<tr>
<td>Microalgae (medium oil content)</td>
<td>50</td>
<td>97800</td>
<td>0.1</td>
<td>86515</td>
</tr>
<tr>
<td>Microalgae (high oil content)</td>
<td>70</td>
<td>136900</td>
<td>0.1</td>
<td>121104</td>
</tr>
</tbody>
</table>
For biodiesel production, lipids and fatty acids have to be extracted from the micro algal biomass. For lipids a solvent extraction is normally done directly from the lyophilized biomass, being a quick and efficient extraction method that slightly reduces the degradation. Several solvents can be used such as hexane, ethanol (96%), or a hexane–ethanol (96%) mixture, being possible to obtain up to 98% quantitative extraction of purified fatty acids. Although ethanol is a very good solvent it can also extract some cellular contaminants such as sugars, amino acids, salts, hydrophobic proteins and pigments, which is not desirable if the purpose of the extraction is just the lipids.

![Figure 6.12: Production of algae and biodiesel pumping station](image)

**Table 6.3: Properties of microalgal oil, diesel fuel and ASTM bio diesel standards [91]**

<table>
<thead>
<tr>
<th>Properties</th>
<th>Biodiesel from microalgae oil</th>
<th>Diesel oil</th>
<th>ASTM biodiesel standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/L)</td>
<td>0.864</td>
<td>0.838</td>
<td>0.84 – 0.9</td>
</tr>
<tr>
<td>Viscosity (mm2/s, cSt at 40°C)</td>
<td>5.2</td>
<td>1.9 – 4.1</td>
<td>3.5 – 5.0</td>
</tr>
<tr>
<td>Flash point (°C)</td>
<td>115</td>
<td>75</td>
<td>Min 100</td>
</tr>
<tr>
<td>Solidifying point (°C)</td>
<td>-12</td>
<td>-50 to 10</td>
<td>-</td>
</tr>
<tr>
<td>Cold filter plugging point (°C)</td>
<td>-11</td>
<td>-3.0 (max -6.7)</td>
<td>Sumer max 0 Winter max -15</td>
</tr>
<tr>
<td>Acid value (mg KOH /g)</td>
<td>0.374</td>
<td>Max 0.5</td>
<td>Max 0.5</td>
</tr>
<tr>
<td>Heating value (MJ/kg)</td>
<td>41</td>
<td>40 - 45</td>
<td>-</td>
</tr>
<tr>
<td>H/C value</td>
<td>1.81</td>
<td>1.81</td>
<td>-</td>
</tr>
</tbody>
</table>

Algae concepts are still under development in an attempt to reach commercial feasibility. Through innovation, technological improvements such as increased automation, genetically
superior algae, higher oil yields, recycling of nutrients and water, and minimized light losses are to be expected, and co-production will improve the economics.

6.4 PROPERTIES OF BIOFUELS

Properties of biodiesel are very similar to fossil diesel and following table shows the comparison of fossil diesel, PPO and biodiesel.

Table 6.4: Parameters of biodiesel and PPO in comparison with fossil diesel [14]

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel</td>
<td>0.84</td>
<td>5</td>
<td>80</td>
<td>42.7</td>
<td>50</td>
<td>1</td>
</tr>
<tr>
<td>PPO (Rapeseed Oil)</td>
<td>0.92</td>
<td>74</td>
<td>317</td>
<td>37.6</td>
<td>40</td>
<td>0.96</td>
</tr>
<tr>
<td>Biodiesel</td>
<td>0.88</td>
<td>7.5</td>
<td>120</td>
<td>37.1</td>
<td>56</td>
<td>0.91</td>
</tr>
</tbody>
</table>

Table 6.5: Properties of transesterified Jatropha oil[18]

<table>
<thead>
<tr>
<th>Properties</th>
<th>Units</th>
<th>Transesterified sample</th>
<th>Standard value for Biodiesel (ASTM D 6751)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>g/cm³</td>
<td>0.9037</td>
<td>0.87 – 0.89</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>-</td>
<td>0.9074</td>
<td>0.88 – 0.90</td>
</tr>
<tr>
<td>Viscosity</td>
<td>Mm²/s</td>
<td>22.0</td>
<td>1.9 – 6.0</td>
</tr>
<tr>
<td>Flash point</td>
<td>°C</td>
<td>39.3</td>
<td>100 - 170</td>
</tr>
</tbody>
</table>

There is a large difference between the PPO and fossil diesel. Viscosity of the PPO is much higher than the fossil fuel. Therefore it is much difficult use in engines. PPO is prone to waxing, coking, freezing, aging and difficult cold start of the engine. Therefore engines need to be converted or adapted to PPO. Flashpoint of the PPO is significantly higher than the fossil diesel. Therefore it is safe in storage, transport and easy to handle. PPO can easily be produced and utilized at small scale and it is biodegradable in a short time.

Viscosity and ignition properties of the bio diesel are very similar to the fossil diesel. Therefore it is a perfect diesel substitute and can be used in all types of diesel engines. Cetane number of the biodiesel is higher than the normal diesel and it shows good lubrication properties. Therefore it avoids wear to the engine. And also alcohol component of the bio
diesel contain, which helps to complete combustion of the fuel. Biodiesel does not contain the sulphur and flue gas is free from sulphur oxides.

Some of the disadvantages of the biodiesel are it may contain residues of methanol or alkali catalyst, may require special anti-freezing precautions. And also biodiesel is readily oxidizes and long-term storage may cause problems. Biodiesel attacks to the plastic and rubber components of the vehicles because of its solvent properties.

### 6.5 BIODIESEL UTILIZATION

Biodiesel is a renewable fuel that can be manufactured from new and used vegetable oils, animal fats, and recycled restaurant grease. Biodiesel’s physical properties are similar to those of petroleum diesel, but the fuel significantly reduces greenhouse gas emissions and toxic air pollutants. It is a biodegradable and cleaner-burning alternative to petroleum diesel. Biodiesel can be blended and used in many different concentrations. They include B100 (pure biodiesel), B20 (20% biodiesel, 80% petroleum diesel), B5 (5% biodiesel, 95% petroleum diesel), and B2 (2% biodiesel, 98% petroleum diesel). The most common biodiesel blend is B20.

![Figure 6.13: B20 biodiesel is ready to use](image)

As long as the vehicle was manufactured after 1993, biodiesel can be used in diesel engines and fuel injection equipment with little impact on operating performance. If the vehicle is older than that, beware the engine could be assembled with incompatible accessories, which can break down with repetitive high-blend biodiesel usage. Regardless of the vehicle’s age, it’s a good idea to check original engine manufacturer (OEM) recommendations before using...
biodiesel. Most OEMs approve blends up to B5 in their vehicles. Some approve blends up to B20 if the fuel meets certain specifications and standards. One even approves B100 in certain types of farm equipment.

Table 6.6: Castor oil biodiesel characteristics [92]

<table>
<thead>
<tr>
<th>Properties</th>
<th>Units</th>
<th>Petroleum diesel</th>
<th>B10</th>
<th>B20</th>
<th>B100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supper grade</td>
<td></td>
<td>0.8610</td>
<td>0.8643</td>
<td>0.8703</td>
<td>0.9268</td>
</tr>
<tr>
<td>Density</td>
<td>Kg/m³</td>
<td>861.0</td>
<td>864.3</td>
<td>870.3</td>
<td>926.8</td>
</tr>
<tr>
<td>Kinematic viscosity</td>
<td>mm²/s</td>
<td>3.81</td>
<td>4.54</td>
<td>4.97</td>
<td>15.98</td>
</tr>
<tr>
<td>Flash point</td>
<td>°C</td>
<td>68.3</td>
<td>85.3</td>
<td>88.7</td>
<td>190.7</td>
</tr>
<tr>
<td>Heating value</td>
<td>MJ/kg</td>
<td>47.2</td>
<td>44.4</td>
<td>44.8</td>
<td>37.9</td>
</tr>
<tr>
<td>Carbon residue</td>
<td>% mass</td>
<td>0</td>
<td>0.009</td>
<td>0.007</td>
<td>0.037</td>
</tr>
<tr>
<td>Cloud point</td>
<td>°C</td>
<td>-6</td>
<td>-26</td>
<td>-30</td>
<td>-45</td>
</tr>
<tr>
<td>Pour point</td>
<td>°C</td>
<td>-6</td>
<td>-26</td>
<td>-30</td>
<td>-45</td>
</tr>
</tbody>
</table>

Table 6.7: Jatropha biodiesel characteristics [93]

<table>
<thead>
<tr>
<th>Properties</th>
<th>B5</th>
<th>B10</th>
<th>B100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture % by weight</td>
<td>0.0441</td>
<td>0.079</td>
<td>0.2765</td>
</tr>
<tr>
<td>Cetane number</td>
<td>45.8</td>
<td>45.6</td>
<td>43.3</td>
</tr>
<tr>
<td>Ramsbottom Carbon Residue</td>
<td>0.08</td>
<td>0.12</td>
<td>0.39</td>
</tr>
<tr>
<td>Flash Point (°C)</td>
<td>51</td>
<td>52</td>
<td>100</td>
</tr>
<tr>
<td>Pour Point (°C)</td>
<td>0</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Viscosity (cSt)</td>
<td>3.43</td>
<td>3.61</td>
<td>9.02</td>
</tr>
<tr>
<td>Sulfur Content %</td>
<td>0.0929</td>
<td>0.0887</td>
<td>0.0170</td>
</tr>
<tr>
<td>Gross Calorific Value (MJ/g)</td>
<td>45.4</td>
<td>45.4</td>
<td>44.8</td>
</tr>
<tr>
<td>Acidity</td>
<td>0.48</td>
<td>0.66</td>
<td>0.75</td>
</tr>
<tr>
<td>Initial Boiling Point/Final Boiling Point (°C)</td>
<td>141/372</td>
<td>142/373</td>
<td>290/350</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>855.2</td>
<td>858.2</td>
<td>898.1</td>
</tr>
</tbody>
</table>
FACT SHEETS
Energy Conversion Technologies for Waste Agricultural Biomass

### Technology - Gasification

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Specification of gasifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Down draft gasifier</td>
<td>Capacity: 300 kWt</td>
</tr>
<tr>
<td>Up draft gasifier</td>
<td></td>
</tr>
<tr>
<td>Cross draft gasifier</td>
<td>Gas Output: 2.5 to 3 Nm³/kg of fuel</td>
</tr>
<tr>
<td>Bubbling fluidized bed gasifier</td>
<td>Internal Consumption (kW): 3.5</td>
</tr>
<tr>
<td>Circulating fluidized bed gasifier</td>
<td>Feeding Rate (kg/hr): 80 kg/hr</td>
</tr>
</tbody>
</table>

### Fuel that can be used in gasification

1. Paddy husk
2. Briquettes
3. Pellets
4. Coconuts
5. Coconut husk

Moisture content - 15% to 20%

### Auxiliary Equipments

1. Fuel feeding system, manually or automatic feeding conveyor
2. Air blower - Induced draft (ID) or forced draft (FD)
3. Cyclone separator to remove ash particles
4. Particle filters (Bag or cloth filters) to remove fine particles. These equipments are very essential in power generation application
5. Producer gas burner with combustion air supply

### Comparison of Gasification Types

- **Down Draft Gasifier**
  - The tar vapours given off in the distillation zones pass through the combustion zone where it is largely cracked and reduced to non-condensable gases. Downdraft gasifiers are in general well suited for high ash fuels. Any slag formed in the condensation zone will flow downward, quickly cool and solidify in the reduction zone and finally obstruct the gas and fuel flow. The metal material of the hearth should be protected from thermal stress as much as possible since the temperature in the hottest part of the combustion zone is normally over 1500°C.

- **Cross Draft Gasifier**
  - In the cross draft gasifiers, air enters through a nozzle and the gas flow is near-normal to the axis of the fuel bed. Use of these gasifiers is not very common although they have been used for small scale charcoal gasification for running engines. Charcoal gasification results in very high temperatures of about 1500°C in the combustion zone. In cross draft gasifiers, the gasifier body is insulated against high temperatures by the fuel itself.

- **Up Draft Gasifier**
  - In this case, the biomass is fed from the top of the gasifier and successively undergoes drying, pyrolysis, char gasification, and char combustion as it settles to the bottom of the gasifier. The product gas is removed from the top of the gasifier and the ash from the bottom. Its advantages include:
    - Suitability for most biomass types
    - Simplicity of fuel preparation
    - High efficiency
    - General simplicity of installation

### Specification of producer gas

<table>
<thead>
<tr>
<th>Calorific value</th>
<th>Parameter</th>
<th>Composition (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000 to 1100 kCal/Nm³ or 4200 to 4800 kCal/Nm³</td>
<td>CO</td>
<td>21.4%</td>
</tr>
<tr>
<td></td>
<td>CO₂</td>
<td>12.3%</td>
</tr>
<tr>
<td></td>
<td>H₂</td>
<td>21.1%</td>
</tr>
<tr>
<td></td>
<td>CH₄</td>
<td>0.3%</td>
</tr>
<tr>
<td></td>
<td>N₂</td>
<td>41.4%</td>
</tr>
<tr>
<td></td>
<td>O₂</td>
<td>0.0%</td>
</tr>
</tbody>
</table>

### Environmental Characterization

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Solid</th>
<th>Liquid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste</td>
<td>Rice husk ash (RHA) is about 25% by weight of rice husk when burnt in gasifiers / boilers.</td>
<td></td>
</tr>
<tr>
<td>Emission</td>
<td>Producer gas consists of 15% CO by volume and ensure to operate in a close system without leaking</td>
<td></td>
</tr>
<tr>
<td>Noise</td>
<td>65 to 85 dB</td>
<td></td>
</tr>
</tbody>
</table>
Application 01 - Steam boiler

Steam generation. Both producer gas and liquid fuel can be used in a boiler simultaneously with little modification in the burner. Picture shows the modification. A 4" thick cylindrical ring insert is between burner and the front door and the gas supply line (yellow line) fits to that ring. Even though the smoke will be emitted to the environment in Agro waste direct combustion applications, producer gas does not emit any smoke and this system is better for clean environment such as hotels, hospitals etc.

Specific energy consumption
1 liter of furnace oil can replace with 4 kg of dry firewood, paddy husk, briquettes or pellets by introducing producer gas to the boilers.

Application 02 - Furnace (Brass / Aluminium melting etc.)

Brass / aluminium melting. Brass get melt at 950°C and the temperature of the producer gas burner is in the range of 900°C to 940°C. There fore it required a small quantity of secondary fuel like diesel or furnace oil to get required temperature. Considering the economy of scale producer gas can be recommended for continuous operation.

Capacity of the gasifier
- 125 kW
Fuel (Paddy husk, Briquettes or pellets) consumption
- 40 kg/hr
Specific fuel cost
- Liquid fuel - 3.35 Rs/kg of brass
- Agro waste - 1.15 Rs/kg of brass

Application 03 - Kiln (Lime, Floor / Wall Tile manufacturing etc.)

Advantage of use of producer gas in lime kiln
1. Temperature of the firing zone can be controlled with gasification technology so that over firing and under firing of lime stones can be reduced and quality of the final products can be improved.
2. Ash contamination with final products can be eliminated completely and the quality of the final products can be improved.
3. Combustion can be improved and existing firewood consumption can be reduced by 40% to 60%.
4. Production rate can be improved by 2 to 3 times with this new technology and the total production cost can be reduced by 25% to 30%.
5. Complete combustion can be achieved with gasification technology and harmful gases are not emitted to the environment.

With Traditional System
- Daily production - 1250 kg
- Firewood consumption - 750 kg/day (2.5 m²)
- Specific cost - 2.0 US$/100 kg of lime

With Producer Gas System
- Hourly production - 1000 kg
- Fuel (Paddy husk, Briquettes or pellets) consumption - 90 kg/hr
- Electricity consumption - 2 Units per hour
- Specific cost - 1.2 US$/100 kg of lime

Application 04 - Institutional Cooking

Producer gas can be used in cooking applications as an alternative fuel for LPG or firewood. The producer gas mixture is highly flammable and can be used as a fuel to generate heat at higher temperature. The gas generation rate can be regulate easily and possible to transfer it to the required location through a pipe line. Institutions like hotels, hostels, hospitals, restaurants etc. are few examples where this technology can be utilize effectively. Apart from that this technology can be utilize in small and medium industries like silk, bathik making etc. mainly for boiling and cooking applications. Details of energy consumption in a typical application (Paddy husk based gasification) in a hotel in Sri Lanka.

LPG Consumption
- 4.2 kg/hr
- Specific cost - 5.12 US$/hr

With Producer Gas (Paddy Husk)
- Paddy husk consumption - 41 kg/hr
- Specific cost - 0.66 US$/hr
- Investment - 46,400 US$
- Pay Back - 2 years

Application 05 - Power Generation

Producer gas can be used as a single fuel for petrol or gas engine (IC engine) and thereby electricity can be generated. Especially in rural electrifications (Off grid solutions) this technology is been used. Capacity can be varied from 3 to 10kW. Waste generated in the vicinity can be used as a source for electricity generation in this off grid solutions so that there is no any requirement to import energy from outside. In addition to this produce gas with IC engine is been used in grid connected electricity generation applications and the capacity of these power plants varied form 25 to 300 kW.

Specific fuel (Paddy husk, Briquettes or pellets) consumption for power generation
- 1 to 1.2 kg/kWh
Technology - Densification (Briquette and Pellets)

<table>
<thead>
<tr>
<th>Equipments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piston Press</td>
</tr>
<tr>
<td>Conical Screw Press</td>
</tr>
<tr>
<td>Screw Press with Heated Die</td>
</tr>
<tr>
<td>Pelletizing Press</td>
</tr>
</tbody>
</table>

Agro waste that can be used in densification:
1. Paddy husk
2. Straw
3. Cob
4. Stalk
5. Peanuts Shells
6. Charcoal powder

Moisture Content - 8% to 12%. Too high moisture causes steam formation and could result in an explosion.

The material is pushed by a piston press against the frictional force caused by die taper and is heated to 150-200°C during the process. The piston presses are normally provided with a relatively long channel, which serves to maintain the shape of the briquettes while they undergo cooling after emerging from the die. The cooling is necessary to condense steam formed and contained inside the briquettes; otherwise, the pressure of the steam would result in surface cracks and fragility of the briquettes. The briquettes are usually cylindrical with diameter in the range 50 to 100 mm. The capacity of commercial piston presses is in the range 40 to 1500 kg/hr.

Conical screw compresses the raw material. The screw forces the material into the compression chamber. A rotating die head extrudes the material through a perforated matrix to produce briquettes of diameter about 2.5 cm. A knife cuts the densified product to a specified length.

The material is forced by a screw having no or small taper through a slightly tapered die, which is heated from outside normally by electric heaters. The die temperature is normally maintained at about 300°C. The raw materials get heated up to about 200°C during the process, most of the heating is caused by friction. The biomass materials often get partially pyrolyzed at the surface causing significant amount of smoke generation during the process.

Pelletizing presses normally consist of a die and a roller. The die rotates in contact with the roller. The raw material is frictionally heated and forced through holes in the die. The densified material emerges from the die as strands of uniform section and cut with knives into the desired length.

Energy Conversion Technologies for Waste Agricultural Biomass
Properties of Briquettes / Pellets

<table>
<thead>
<tr>
<th>Property</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calorific value</td>
<td>4200 - 4600 Kcal/kg</td>
</tr>
<tr>
<td>Density</td>
<td>1.2 - 1 kg/m³</td>
</tr>
<tr>
<td>Moisture content</td>
<td>9 %</td>
</tr>
<tr>
<td>Ash content</td>
<td></td>
</tr>
<tr>
<td>Rice husk briquettes</td>
<td>25% weight basis</td>
</tr>
<tr>
<td>Others</td>
<td>2% weight basis</td>
</tr>
</tbody>
</table>

Advantages:
- The process increases the net calorific value of material per unit volume
- End product is easy to transport and store
- The fuel produces uniform in size and quality
- The process helps to solve the problem of residue disposal
- The process helps to reduce deforestation by providing a substitute for fuel wood.
- The process reduces/eliminates the possibility of spontaneous combustion in storage
- The process reduces biodegradation of residues

Disadvantages:
- High investment cost and energy input to the process
- Undesirable combustion characteristics often observed in the case of briquettes, e.g., poor ignitability, smoking, etc. Tendency of briquettes to loosen when exposed to water or even high humidity weather.

Application 01 - Steam boiler / Air heater

- The combustion efficiency of boilers and air heaters will improve with the use of briquettes. Briquettes are uniform in size, composition and moisture content so that the combustion can be controlled easily and thereby the energy waste can be minimized. Test results of a briquette fired air heater in a tea factory is given in the attached table.

Specific Energy Consumption
- 0.93 kg of Made Tea kg of firewood
- 0.53 kg of Made Tea kg of briquette
- Energy Saving Option: 45% savings

Application 02 - Cook Stoves

- The combustion efficiency of the stoves can be increased with the use of briquettes and pellets. Smoke will be generated depending on the raw materials such as paddy husk, straw, etc. but char coal fired stoves gives smokeless flame. In addition to that the temperature of the charcoal fired stoves is very high than the other fuels.

Application 03 - Gasification

- Briquettes and pellets are more suitable for gasification as a fuel since the energy density of these materials are very high. Size of the briquettes has to be varied depending on the design and capacity of the gasifier and also it has to be ensured to feed hard briquettes than the soft materials.

<table>
<thead>
<tr>
<th>Aggro Waste</th>
<th>Densification</th>
<th>Carbonising</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paddy husk, straw, cob, pea</td>
<td>Pellets,</td>
<td>Char Coal</td>
</tr>
<tr>
<td>nut shells, stalks etc</td>
<td>briquettes</td>
<td></td>
</tr>
<tr>
<td>Low energy density, Low</td>
<td>High energy</td>
<td>High energy density, Smokeless</td>
</tr>
<tr>
<td>efficient combustion</td>
<td>high density, High energy density, Smokeless burning</td>
<td></td>
</tr>
<tr>
<td>Briquettes, potary kilns, paddy</td>
<td>high density, burning</td>
<td></td>
</tr>
<tr>
<td>husk stoves</td>
<td>High energy density, Smokeless burning</td>
<td></td>
</tr>
<tr>
<td>Boilers, air heaters, gasifiers,</td>
<td>Smokeless</td>
<td></td>
</tr>
<tr>
<td>stoves etc</td>
<td>stoves, ovens, water purification etc.</td>
<td></td>
</tr>
</tbody>
</table>
**Technology - Carbonizing (Pyrolysis)**

Pyrolysis is defined as irreversible chemical change brought about by heat in the absence of oxygen. During pyrolysis, biomass undergoes a sequence of changes and normally yields a mixture of gases, liquids and solid. The solid is called charcoal. Generally, low temperatures and slow heating rates result in high yield of charcoal.

**Agro waste that can be used in densification**
1. Coconut shells
2. Peanut shells
3. Combi
4. Paddy husk

Sinquates and pellets made of agro wastes

**Moisture Content** - Dry materials (moisture 15% to 17%) is preferred. The yield can be improved with reduction of moisture content.

**Earth Pit**
- Volume: 30 m³
- Charge volume: 26 m³
- Production time: 20 to 30 days
- Percentage volatile evaporation: 50% to 70%
- Cooling time: 40 days

**Earth Mound**
Earth mound is an alternative to digging a pit, where the wood is stacked above the ground and covered with earth. Essentially, the process is the same as the pit - the wood to be carbonized is enclosed behind an air-tight well made from earth.

**Casamance kiln**
The mound is covered with grass and straw and then sand or loam. The chimney is placed at the edge of the pile as in the diagram, with its base opening connected to the base of the pile. The chimney improves gas circulation which reduces the amount of brands (partially carbonized wood pieces) and speeds up the carbonisation. Less brands means an improved yield of charcoal.

**Transportable metal kiln**

**Brick kiln**
Properly constructed and operated brick kilns are one of the most effective methods of charcoal production. They have proved themselves over decades of use to be low in capital cost, moderate in labour requirements and capable of giving good yields of quality charcoal suitable for all industrial and domestic uses. The ability of the brick kiln to conserve the heat of carbonisation is an important factor in its high conversion efficiency of wood to charcoal.

**Automatic kiln**
This consists of four to six circular hearths stacked one above the other inside a cylindrical refractory-lined shell, as shown in Figure A10. The raw material is fed to the uppermost hearth and falls from one hearth to the lower under the action of a rotating center shaft fitted with rubble arms at each hearth level. Normal operating temperature: 900 - 1000°C; Capacity: 4 - 10 tons of wood/residues per hr.

**Pillar Rotary Carbonizer**
Part of the pyrolysis gas is recycled and burned to provide heat required for carbonization. The hot flue gases come in direct contact with the raw material slowly moving down the inclined furnace. Capacity: 200 - 1500 kg/hr.
Properties of Char Coal
- Calorific value: 32.33 MJ/kg with standard deviation 0.47 MJ/kg
- Fixed Carbon: 80 - 82% (Charcoal manufacturing temperature 700°C to 1000°C)
- Moisture content: 7.2% - 7.9%
- Ash content:
  - Peanut charcoal: 39% weight basis
  - Paddy husk charcoal: 3.5 - 7.5% weight basis

Environmental Characterization
Emission
The volatile emit to the environment during the char coal manufacturing process and the emission quantity depends on the manufacturing temperature. The emission is rich of energy and can be reuse to the manufacturing process. Improved technologies are available to reduce the emission and also to reuse the emission effectively.

Dome type brick kiln
- Kiln body volume: 60 cubic meters
- Minimum height: 25 ft
- Feeding amount of coconut shell: 80,000
- Charcoal output: 5 tons
- Operating time per batch: 8 - 10 hours
- LP gas consumption per batch: 7 kg / batch

Automatic kiln
- Charcoal output: 3 tons / day
- Operating time per batch: 8 - 10 hours
- Cooling time: 3 - 6 hrs

The volatile gas emission completely use in the combustion process and there is no any environmental pollution in this method.

Yield and Quality of Charcoal Produced at 500°C, 4 hr

<table>
<thead>
<tr>
<th>Residues</th>
<th>Yield (%)</th>
<th>Volatile Matter (%)</th>
<th>Ash (%)</th>
<th>Fixed Carbon (%)</th>
<th>Gross Calorific Value (Kcal/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bagasse</td>
<td>32.00</td>
<td>74.8</td>
<td>12.53</td>
<td>57.15</td>
<td>3588</td>
</tr>
<tr>
<td>Casava Hull</td>
<td>50.21</td>
<td>19.6</td>
<td>11.30</td>
<td>79.35</td>
<td>6580</td>
</tr>
<tr>
<td>Coconut Husk</td>
<td>37.63</td>
<td>13.9</td>
<td>5.70</td>
<td>76.43</td>
<td>7254</td>
</tr>
<tr>
<td>Coconut Shell</td>
<td>37.48</td>
<td>8.18</td>
<td>11.93</td>
<td>77.92</td>
<td>7170</td>
</tr>
<tr>
<td>Paddy Straw</td>
<td>37.58</td>
<td>12.05</td>
<td>5.42</td>
<td>73.59</td>
<td>6524</td>
</tr>
<tr>
<td>Peanut Shell</td>
<td>36.38</td>
<td>9.30</td>
<td>3.83</td>
<td>72.11</td>
<td>6710</td>
</tr>
<tr>
<td>Rice Husk</td>
<td>37.10</td>
<td>4.17</td>
<td>1.92</td>
<td>71.18</td>
<td>6443</td>
</tr>
</tbody>
</table>

Application of Char Coal
- Chemical industry
  - manufacture of carbon disulphide, sodium cyanide and carbides.
- Metallurgy
  - smelting and sintering iron ores, production of ferro-silicon and pure silicon, case-hardening of steel, purification agent in smelting non-ferrous metals, fuel in foundry cupola, electrodes
- Cement industry
  - As a fuel, since the energy content in the char coal is very high.
- Activated carbon and filter industry
  - water purification, dechlorination, gas purification, solvent recovery, waste water treatment, cigarette filters.
- Gas generator
  - Produces gas for vehicles and carbonation of soft drinks.
- Horticulture
  - Charcoal is used in different grades as as top dressing for the improvement of flavour and bowling greens. These top dressings act as mulch and also provide valuable trace elements and sweeten the soil. Pottery mixtures used in nurseries often contain fine charcoal
  - As fuel for fireplaces, chargrills and other similar devices
    - In comparison with the usual fuel (for example — fuelwood), charcoal doesn’t produce smoke and open flame (if the firing is right) but gives only necessary temperature and heat.

Composition and Quality of Pyrolysis Gas Evolved at 500°C, 4 hr

<table>
<thead>
<tr>
<th>Residues</th>
<th>Gas Composition by Volume %</th>
<th>Gross Calorific Value (Kcal/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bagasse</td>
<td>He 63.6 CO2 12.6 CH4 24.0 CO 0.8</td>
<td>897</td>
</tr>
<tr>
<td>Casava Hull</td>
<td>He 69.0 CO2 9.6 CH4 21.0 CO 0.8</td>
<td>900</td>
</tr>
<tr>
<td>Coconut Husk</td>
<td>He 62.3 CO2 17.9 CH4 19.0 CO 0.8</td>
<td>887</td>
</tr>
<tr>
<td>Coconut Shell</td>
<td>He 61.8 CO2 17.8 CH4 20.4 CO 0.8</td>
<td>890</td>
</tr>
<tr>
<td>Paddy Straw</td>
<td>He 61.7 CO2 17.8 CH4 20.5 CO 0.8</td>
<td>891</td>
</tr>
<tr>
<td>Peanut Shell</td>
<td>He 62.1 CO2 17.7 CH4 20.2 CO 0.8</td>
<td>893</td>
</tr>
<tr>
<td>Rice Husk</td>
<td>He 62.0 CO2 17.6 CH4 20.4 CO 0.8</td>
<td>892</td>
</tr>
</tbody>
</table>

Proximate Analysis of Selected Residues

<table>
<thead>
<tr>
<th>Parameters on Moisture Free Basis</th>
<th>Bagasse</th>
<th>Casava Hull</th>
<th>Coconut Husk</th>
<th>Coconut Shell</th>
<th>Paddy Straw</th>
<th>Peanut Shell</th>
<th>Rice Husk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volatile Matter (%)</td>
<td>74.8</td>
<td>76.44</td>
<td>75.49</td>
<td>74.2</td>
<td>74.65</td>
<td>73.85</td>
<td>73.34</td>
</tr>
<tr>
<td>Ash (%)</td>
<td>12.53</td>
<td>11.30</td>
<td>5.70</td>
<td>11.93</td>
<td>12.05</td>
<td>9.30</td>
<td>4.17</td>
</tr>
<tr>
<td>Fixed Carbon (%)</td>
<td>57.15</td>
<td>79.35</td>
<td>57.92</td>
<td>77.92</td>
<td>73.59</td>
<td>72.11</td>
<td>71.18</td>
</tr>
</tbody>
</table>

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**Technology - Direct Combustion**

Generation of heat through rapid chemical reactions of fuels is known as combustion:

**Incomplete combustion of hydrocarbons**

\[ C_nH_m + \left( n + \frac{m}{4} \right) (O_2 + 3.76N_2) \rightarrow \]

\[ (n - \alpha)\text{CO}_2 \left( \frac{m}{2} - \beta \right) \text{H}_2 \text{O} + 3.76 \left( n + \frac{m}{4} - \frac{\alpha}{2} \right) N_2 \]

\[ + [\alpha\text{CO} + \beta\text{H}_2 + \gamma\text{NO}_x + \text{someO}_2] \]

**Complete combustion of hydrocarbons**

\[ C_nH_m + \left( n + \frac{m}{4} \right) (O_2 + 3.76N_2) \rightarrow n\text{CO}_2 + \frac{m}{2} \text{H}_2 \text{O} + 3.76(n + \frac{m}{4}) N_2 \]

Incomplete combustion takes place due to many reasons:

1. Lack of combustion air
2. Lack of turbulence in the combustion
3. Use of wet material
4. Uneven size of the combustible fuel etc.
5. Use of different type of fuels at a time

Important factors which influence combustion:

1. Physical and chemical properties of the fuel:
2. Fuel air ratio:
3. Temperature of the flame envelope:
4. Mode of fuel supply:
5. Primary and secondary air supplies

(a) The amounts of fuel and air taking part in a combustion process are often expressed as the 'air to fuel' ratio:

\[ \text{AFR} = \frac{m_{\text{air}}}{m_{\text{fuel}}} \]

(b) In order to obtain complete combustion, supply of excess amount of air (or oxygen) is required in practice.

(c) The amount of excess air required depends on the properties of the fuel and the technology of the combustion device.

(a) During combustion, molecules undergo chemical reactions.

(b) The reactant atoms are rearranged to form new combinations (oxidized).

(c) The chemical reaction can be presented by reaction equations.

(d) However, reaction equations represent initial and final results and do not indicate the actual path of the reaction, which may involve many intermediate steps and intermediate species.

(e) This approach is similar to thermodynamics system analysis, where only end states and not path mechanism are used.

**Estimation of Heating Values**

\[ \text{CH}_4 + 2(\text{O}_2 + \frac{3}{4}\text{N}_2) \rightarrow \text{CO}_2 + 2\text{H}_2\text{O} + 15.866\text{MJ} / (\text{Gas}) / 15.866\text{MJ} / (\text{Liquid}) \]

(i) Net Calorific Value

\[ \text{NCV} = \frac{(H_{\text{products}} - H_{\text{reactants}})\text{mass of CH}_4}{(H_{\text{products}} - H_{\text{reactants}})\text{mass of CH}_4} \]

(ii) Gross Calorific Value

\[ \text{GCV} = \frac{(H_{\text{products}} - H_{\text{reactants}})\text{mass of CH}_4}{(H_{\text{products}} - H_{\text{reactants}})\text{mass of CH}_4} \]

<table>
<thead>
<tr>
<th>Fuel</th>
<th>MJ/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Producer gas</td>
<td>18.4</td>
</tr>
<tr>
<td>Biogas</td>
<td>22</td>
</tr>
<tr>
<td>Paddy husk</td>
<td>12.7</td>
</tr>
<tr>
<td>Straw</td>
<td>14.5</td>
</tr>
<tr>
<td>Coffee and oil palm husk</td>
<td>17.6</td>
</tr>
<tr>
<td>Coconut shells</td>
<td>15.9</td>
</tr>
<tr>
<td>Coconut husk</td>
<td>14.1</td>
</tr>
<tr>
<td>Cotton Stalk</td>
<td>19.7</td>
</tr>
<tr>
<td>Maze Cob</td>
<td>16.2</td>
</tr>
<tr>
<td>Maze Stalk</td>
<td>14.7</td>
</tr>
<tr>
<td>Bagasse (Dry basis)</td>
<td>18.5</td>
</tr>
<tr>
<td>Wheat Straw</td>
<td>13.9</td>
</tr>
<tr>
<td>Peanut Shells</td>
<td>16.8</td>
</tr>
<tr>
<td>Pellets (8% moisture)</td>
<td>17.5</td>
</tr>
</tbody>
</table>
Energy Conversion Technologies for Waste Agricultural Biomass

This stove is composed of a gasifier reactor, where rice husk is placed and burnt with limited amount of air (primary air), a burner which converts (with secondary air) the gas coming out from the reactor to a bluish flame, and a char chamber with a fan, component of the stove that provides the air needed by the fuel during gasification. The ratio between primary and secondary air is precise and definite by secondary air holes.

Stove type: Ez Turbo Charcoal Stove
Construction material: Made of clay and burned, 12V DC blower to supply combustion air.
Fuel type: Charcoal (Saw dust, Coconut shells or pellets as substitutes). Smokeless flame can be taken with charcoal.
Auxiliary equipment: 12V DC supply

Stove type: Wood gas stove.
Single pot metal stove with ceramic liner.
Combustion air supply: 2W, 12V DC FD fan or Natural draft
Developed by: National Engineering Research and Development Centre, Sri Lanka
Construction material: Metal, Ceramic liner.
Fuel type: Pellets or Wood pieces
Cooking time: ~ 40 mins per loading of 600g of fuel
Cost: ~ 50 US$
This is a batch type cooker. The fuel container filled with pellets or chips and place inside the stove and lights at the top. The pellets get burn from top to bottom and after finishing the combustion it has to be refill. For continuous operation, it can be utilize two stoves simultaneously.

Name of the cooker: Biomass Operated Rice Cooker
Developed by: National Engineering Research and Development Centre, Sri Lanka
Fuel type: Can cook 1 kg of rice using 02 coconut shells (Pellets or chips can be used)
Rice can keep warm for about 8 hrs and can boil 3 liters of water
Cooking time: 40 minutes
Cost: ~ 40 US$

Name of Dryer: Paddy husk operated forced draft vegetable/fruit dehydrator. The dryer is equipped with chimney and two sawdust stoves
Performance: 20 kg (fresh) veg/fruit can be dried in 8 hrs with 30kg of paddy husk.
Electricity supply: 230V, 50Hz
Developed by: National Engineering Research and Development Centre, Sri Lanka
Cost: ~ 800US$
Technology - Anaerobic Digestion

### Types of plants

- **Fixed-dome plants**
- **Floating-drum plants**

### Fuel that can be used in biogas production

1. Vegetable waste
2. Livestock waste
3. Waste water
4. Sewage sludge

### Auxiliary Equipments

1. Influent collecting tank
2. Inlet pipe
3. Digester
4. Gas holder
5. Gas pipe
6. Outlet pipe
7. Displacement tank
8. Stirrer

---

**Biogas production process** is based on the breakdown of the organic micromolecules of biomass by naturally occurring micro-organisms. Main three steps of the process are:

1. **Hydrolysis**: Polymers such as cellulose, starch, proteins and lipids are hydrolysed to soluble compounds (monomers) such as sugars by means of bacteria.
2. **Acidification**: Acid-producing bacteria convert the hydrolysed products into acetic acid, hydrogen and carbon dioxide.
3. **Methanogenesis**: Products from the acetogenesis step are reacted together to produce methane.

---

A fixed-dome plant comprises of a closed, dome-shaped digester with an immovable, rigid gas-holder and a displacement tank. The gas is stored in the upper part of the digester. When gas production commences, the slurry is displaced into the displacement tank. Gas pressure increases with the volume of gas stored, i.e. with the height difference between the two slurry levels. If there is little gas in the gas-holder, the gas pressure is low. Fixed-dome plants must be covered with earth up to the top of the gas-filled space to counteract the internal pressure (up to 0.15 bar). Due to economic parameters, the recommended minimum size of a fixed-dome plant is 5 m³. Digester volumes up to 200 m³ are known and possible.

---

A floating-drum plant consists of a cylindrical or domeshaped digester and a moving, floating gas-holder, or drum. The gas-holder floats either directly in the fermenting slurry or in a separate water jacket. The drum in which the biogas collects has an internal and/or external guide frame that provides stability and keeps the drum upright. If biogas is produced, the drum moves up, if gas is consumed, the gas-holder sinks back. Floating-drum plants are used chiefly for digesting animal and human feces on a continuous feed mode of operation, i.e. with daily input. They are used most frequently by small- to middle-sized farms (digester size: 5-15 m³) or in institutions and larger agro-industrial estates (digester size: 20-100 m³).

---

### Specification of biogas

<table>
<thead>
<tr>
<th>Calorific value</th>
<th>$6 \text{ kWh/m}^3$</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Composition (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH4</td>
<td>40 - 70%</td>
</tr>
<tr>
<td>CO2</td>
<td>30 - 60%</td>
</tr>
<tr>
<td>H2</td>
<td>0 - 1%</td>
</tr>
<tr>
<td>H2S</td>
<td>0 - 3%</td>
</tr>
<tr>
<td>Other</td>
<td>1 - 5%</td>
</tr>
</tbody>
</table>

### Application 01 - Biogas Fueled Engines

The following types of engines are well-suited for operating on biogas:

- Four-stroke diesel engines
- Four-stroke spark-ignition engines
- Converting diesel engines
- Converting spark-ignition engines
Application 02 - Gas Cookers/Stoves
Biogas cookers and stoves provide good burning properties such as a stable flame, high efficiency, easy operation, versatility, easy to clean, acceptable cost and easy repair and attractive appearance. Biogas cookers require purposeful installation with adequate protection from the wind. Before any cooker is used, the burners must be carefully adjusted, for a compact, bluish flame, the pot should be capped by the outer cone of the flame without being touched by the inner cone and the flame should be self-stabilizing.

Application 03 - Biogas Lamps
Biogas lamps are controlled by adjusting the supply of gas and primary air. The aim is to make the gas mantle burn with a uniform brightness and steady sputtering. Biogas lamps provide bright light as a result of incandescence. However, these lamps are not very energy efficient and they get very hot. If they hang directly below the roof, they cause a fire hazard. It is important that the gas and air in a biogas lamp are thoroughly mixed before they reach the gas mantle, and that the air space around the mantle is adequately warm.

Application 04 - Radiant Heaters
Infrared heaters are used in agriculture for achieving the temperatures required for raising young stock, e.g. piglets and chicken in a limited amount of space. The nursery temperature for piglets begins at 30-35 °C for the first week and then gradually drops off to an temperature of 18-23 °C in the 4th-5th week. Therefore radiant heaters built with a temperature control. Radiant heaters develop their infrared thermal radiation via a ceramic body that is heated to 600-500 °C (red-hot) by the biogas flame. Small-heater outputs range from

Application 04 - Incubators
Incubators are used to initiate and maintain optimal hatching temperatures for eggs. They are used to increase brooding efficiency. Indirectly warmed, water-heated平板-type incubators in which a burner heats water in a heating element through the incubating chamber are suitable for operating on biogas. The temperature is controlled by thermostat-regulated vents.

Application 05 - Refrigerators
Absorption-type refrigerating machines operating on ammonia and water and equipped for automatic thermo-siphon circulation can be fuelled with biogas. Since biogas is only the refrigerator’s external source of heat, just the burner itself has to be modified. Whenever a refrigerator is converted for operating on biogas, care must be taken to ensure that all safety features (safety pilot) function properly. Remote ignition via a piezoelectric element substantially increases the ease of operation.

Gas demand
- 1 kg firewood corresponds to 2001 biogas
- 1 kg dried cow dung corresponds to 100 l biogas
- 1 kg charcoal corresponds to 5001 biogas

For one liter water to be cooked 30-401 biogas, for 1.2 kg rice 120-140 l and for 1/4 kg legumes 160-190 l are required.

Luminous efficacy
- 1.2 - 2 lm/W

Gas consumption of one lamp
- 120 - 150 l/day

Biogas usage
- 200 - 300 l/h for pig or chicken rearing

Output
- 1.5 to 10 kW thermal power

Gas demand
For 100 litres refrigeration volume, about 2000 l of biogas per day, depending on outside temperatures, must be assumed. A larger household refrigerator consumes about 3000 l per day.
REFERENCES


[18] DTIE-UNEP, “EST Assessment Methodology and Implementation”, Training Kit prepared for the support of the project on Environmental Management of the Iraqi


[61] E4tech, “Review of technology for the gasification of biomass and wastes”, NNFCC project 09/008, a project funded by DECC, June 2009.


[84] M.L. Maurice, “Factors Effecting Ethanol Fermentation Via Simultaneous Saccharification and Fermentation”, A study to determine the optimal operating conditions to convert cellulosic biomass into ethanol during enzymatic hydrolysis and microbial fermentation, A Major Qualifying Project for the Degree of Bachelor Science, Worcester Polytechnic Institute, April 27, 2011.


About the UNEP Division of Technology, Industry and Economics

Set up in 1975, three years after UNEP was created, the Division of Technology, Industry and Economics (DTIE) provides solutions to policy-makers and helps change the business environment by offering platforms for dialogue and co-operation, innovative policy options, pilot projects and creative market mechanisms.

DTIE plays a leading role in three of the six UNEP strategic priorities: climate change, harmful substances and hazardous waste, resource efficiency.

DTIE is also actively contributing to the Green Economy Initiative launched by UNEP in 2008. This aims to shift national and world economies on to a new path, in which jobs and output growth are driven by increased investment in green sectors, and by a switch of consumers’ preferences towards environmentally friendly goods and services.

Moreover, DTIE is responsible for fulfilling UNEP’s mandate as an implementing agency for the Montreal Protocol Multilateral Fund and plays an executing role for a number of UNEP projects financed by the Global Environment Facility.

The Office of the Director, located in Paris, coordinates activities through:

> The International Environmental Technology Centre - IETC (Osaka), which implements integrated waste, water and disaster management programmes, focusing in particular on Asia.

> Sustainable Consumption and Production (Paris), which promotes sustainable consumption and production patterns as a contribution to human development through global markets.

> Chemicals (Geneva), which catalyses global actions to bring about the sound management of chemicals and the improvement of chemical safety worldwide.

> Energy (Paris and Nairobi), which fosters energy and transport policies for sustainable development and encourages investment in renewable energy and energy efficiency.

> OzonAction (Paris), which supports the phase-out of ozone depleting substances in developing countries and countries with economies in transition to ensure implementation of the Montreal Protocol.

> Economics and Trade (Geneva), which helps countries to integrate environmental considerations into economic and trade policies, and works with the finance sector to incorporate sustainable development policies. This branch is also charged with producing green economy reports.

DTIE works with many partners (other UN agencies and programmes, international organizations, governments, non-governmental organizations, business, industry, the media and the public) to raise awareness, improve the transfer of knowledge and information, foster technological cooperation and implement international conventions and agreements.

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