

Chapter 2

Biomass Energy

A. K. Kurchania

2.1 Introduction

Biomass energy or “bioenergy” includes any solid, liquid or gaseous fuel, or any electric power or useful chemical product derived from organic matter, whether directly from plants or indirectly from plant-derived industrial, commercial or urban wastes, or agricultural and forestry residues. Thus bioenergy can be derived from a wide range of raw materials and produced in a variety of ways. Because of the wide range of potential feedstocks and the variety of technologies to produce them and process them, bioenergy is usually considered as a series of many different feedstock/technology combinations. In practice, we tend to use different terms for different end uses—e.g., electric power or transportation.

The term “biopower” describe biomass power systems that use biomass feedstocks instead of the usual fossil fuels (natural gas or coal) to produce electricity, and the term “biofuel” is used mostly for liquid transportation fuels which substitute for petroleum products such as gasoline or diesel. “Biofuel” is short for biomass fuel.

The term “biomass” generally refers to renewable organic matter generated by plants through photosynthesis. During photosynthesis, plants combine carbon dioxide from the air and water from the ground to form carbohydrates, which form the biochemical “building blocks” of biomass. The solar energy that drives photosynthesis is stored in the chemical bonds of the carbohydrates and other molecules contained in the biomass. If biomass is cultivated and harvested in a way that allows further growth without depleting nutrient and water resources, it is

A. K. Kurchania (✉)
Renewable Energy Sources Department, College of Technology and Engineering,
Maharana Pratap University of Agriculture and Technology, Udaipur, India
e-mail: kurchania@rediffmail.com

a renewable resource that can be used to generate energy on demand, with little net additional contributions to global greenhouse gas emissions [1].

Materials having organic combustible matter are also referred under biomass. Biomass can be directly utilized as fuel or can be converted through different routes into useful forms of fuel. Biomass is a scientific term for living matter, but the word biomass is also used to denote products derived from living organisms—wood from trees, harvested grasses, plant parts and residues such as twigs, stems and leaves, as well as aquatic plants and animal wastes.

Burning biomass efficiently results in little or no net emission of carbon dioxide to the atmosphere, since the bioenergy crop plants actually took up an equal amount of carbon dioxide from the air when they grew. However, burning conventional fossil fuels such as gasoline, oil, coal or natural gas results in an increase in carbon dioxide in the atmosphere, the major greenhouse gas which is thought to be responsible for global climate change. Some nitrogen oxides inevitably result from biomass burning (as with all combustion processes) but these are comparable to emissions from natural wildfires, and generally lower than those from burning fossil fuels. Other greenhouse gas emissions are associated with the use of fossil fuels by farm equipment, and with the application of inorganic fertilizers to the bioenergy crop. However, these may be offset by the increase in carbon storage in soil organic matter compared with conventional crops. Utilization of biomass residues which would otherwise have been dumped in landfills (e.g. urban and industrial residues) greatly reduces greenhouse gas emissions by preventing the formation of methane.

All the Earth's biomass exists in a thin surface layer called the biosphere. This represents only a tiny fraction of the total mass of the Earth, but in human terms it is an enormous store of energy—as fuel and as food. More importantly, it is a store which is being replenished continually. The source which supplies the energy is of course the Sun, and although only a tiny fraction of the solar energy reaching the Earth each year is converted into biomass, it is nevertheless equivalent to over five times the total world. The annual world of biomass is estimated at 146 billion metric tons, mostly from uncontrolled plant growth. The current world demand for oil and gas can be met with about 6% of the global production of biomass. Biomass is significant as heating fuel, and in some parts of the world the fuel is most widely used for cooking [2]. An advantage of this source of energy is that use of biomass for fuel would not add any net carbon dioxide to the atmosphere.

The Earth's land-based production which is used by the human population worldwide ranges from a low figure of about 5% to a high of over 30% (including food, animal fodder, timber and other products, as well as bioenergy). The higher estimates include a lot of wasted material and inefficient activities such as forest clearance, as well as losses of productivity due to human activity. Globally biomass energy use has been independently estimated at about 55 exajoules per year, or about 2% of annual biomass production on land.

Biomass has the following advantages:

- It is widely available.
- Its technology for production and conversion is well understood.
- It is suitable for small or large applications.
- Its production and utilization requires only low light intensity and low temperature (535°C).
- It incorporates advantage of storage and transportation.
- Comparatively, it is associated with low or negligible pollution.

Biomass can be classified as:

- *Agricultural and forestry residues*. They include silvicultural crops.
- *Herbaceous crops*. Include weeds, Napier grass.
- *Aquatic and marine biomass*. This category include algae, water hyacinth, aquatic weeds, plants, sea grass beds, kelp and coral reep, etc.
- *Wastes*. Various wastes such as municipal solid waste, municipal sewage sludge, animal waste and industrial waste, etc.

Worldwide, biomass is the fourth largest energy resource after coal, oil and natural gas—estimated at about 14% of global primary energy (and much higher in many developing countries). In the US, biomass today provides about 3–4% of primary energy (depending on the method of calculation). Biomass is used for *heating* (such as wood stoves in homes and for process heat in bioprocess industries), *cooking* (especially in many parts of the developing world), *transportation* (fuels such as ethanol) and, increasingly, for *electric power production*. The installed capacity of biomass power generation worldwide is about 35,000 MW, with about 7,000 MW in the US derived from forest-product-industry and agricultural residues (plus an additional 2,500 MW of municipal solid waste-fired capacity, which is often not counted as part of biomass power, and 500 MW of landfill gas-fired and other capacity). Much of this 7,000 MW capacity is presently found in the pulp and paper industry, in combined heat and power (cogeneration) systems.

2.2 Energy Plantation

This term refers to an area that is used to grow biomass for energy purposes. The idea behind energy plantation programme is to grow selected strains of tree and plant species on a short rotation system on waste or arable land. The sources of energy plantation depend on the availability of land and water and careful management of the plants. Energy crops, also called “bioenergy crops”, are fast-growing crops that are grown for the specific purpose of producing energy (electricity or liquid fuels) from all or part of the resulting plant. They are selected for their advantageous environmental qualities such as erosion control, soil organic

matter build-up and reduced fertilizer and pesticide requirements. As far as suitability of land for energy plantation is concerned the following criterion is used:

(1) It should have a minimum of 60-cm annual precipitation and (2) arable land having slope equal to or less than 30% is suitable for energy plantation.

The economics of energy plantation depends on the cost of planting and availability of market for fuel. Whereas these two factors are location specific, they vary from place to place. Further productivity of this programme depends on the microclimate of the locality, the choice of the species, the planting spacing, the inputs available and the age of harvest. There are many suitable species for energy plantation, for example, *Acacia nilotica*. There are many other perennial plant species which could be used for energy crops. In addition, some parts of traditional agricultural crops such as the stems or stalks of alfalfa, corn or sorghum may be used for energy production.

2.3 Biomass Production Techniques

Careful planning is required for biomass production, which consists of integration of different techniques and improved methods. The general sequence for biomass production is the integration of different techniques and improved methods starting from site survey, nursery techniques, transplanting techniques and maintenance of the plantation. The production techniques include:

- Site survey
- Planting site selection
- Species selection
- Preparation of the planting site
- Preparation of the soil mixture
- Sowing of seed
- Method of sowing
- Transplanting of seedling into containers
- Transport of seedlings to the planting site
- Maintenance of the plantations

After successful plantation of biomass it is harvested by various methods such as:

- Coppicing

It is one of the most widely used harvesting methods in which the tree is cut at the base, usually between 15 and 75 cm above the ground level. New shoots develop from the stump or root. These shoots are sometimes referred to as sucker or sprouts. Management of sprouts should be carried out according to use. For fuel wood the number of sprouts allowed to grow, should depend on the desired sizes of fuel wood. If many sprouts are allowed to grow for a long period, the weight of the sprouts may cause the sprouts to tear away from the

main trunk. Several rotations of coppicing are usually possible with many species. The length of the rotation period depends on the required tree products from the plantation. It is a suitable method for production of fuel wood. Most eucalyptus species and many species of the leguminous family, mainly naturally accessing shrubs can be harvested by coppicing.

- **Pollarding**

It is the harvesting system in which the branches including the top of the tree are cut, at a height of about 2 m above the ground and the main trunk is allowed to stand. The new shoots emerge from the main stem to develop a new crown. This results into a continuous increase in the diameter of the main stem although not in height. Finally, when the tree loses its sprouting vigor, the main stem is also cut for use as large diameter poles. An advantage of this method over coppicing is that the new shoots are high enough off the ground so that they are out of reach of most grazing animals. The neem tree (*Azadirachta indica*) is usually harvested in this manner. The branches may be used for poles and fuel wood.

- **Lopping**

In this method most of the branches of the tree are cut. The fresh foliage starts sprouting from the bottom to the top of the denuded stem in spite of severe defoliation, surprisingly quickly. The crown also re-grows and after a few years, the tree is lopped again. The lopped trunk continues to grow and increases in height, unless this is deliberately prevented by pruning it at the top.

- **Pruning**

It is a very common harvesting method. It involves the cutting of smaller branches and stems. The clipped materials constitute a major source of biomass for fuel and other purposes, such as fodder mulching between tree rows. It is also often required for the maintenance of fruit and forage trees, alley cropping and live fences. The process of pruning also increases the business of trees and shrubs for bio fencing. Root pruning at a required distance from the hole is effective to reduce border tree competition with crops for water and nutrients.

- **Thinning**

It is a traditional forestry practice and in fuel wood plantation, it can also be of importance. The primary objectives of thinning are to enhance diametric growth of some specific trees through early removal of poor and diseased trees to improve the plantation by reducing the competition for light and nutrients. Depending on initial plant density, initial thinning can be used for fuel wood or pole production.

2.4 Biomass Conversion Processes

There are a number of technological options available to make use of a wide variety of biomass types as a renewable energy source. Conversion technologies may release the energy directly, in the form of heat or electricity, or may convert it

into another form, such as liquid biofuel or combustible biogas. Various methods of conversion of biomass into useful energy gain can be explained as follows:

2.4.1 Direct Combustion Processes

Feedstocks used are often residues such as woodchips, sawdust, bark, bagasse, straw, municipal solid waste (MSW) and wastes from the food industry. Direct combustion furnaces can be divided into two broad categories and are used for producing either direct heat or steam. Dutch ovens, spreader-stoker and fuel cell furnaces employ two stages. The first stage is for drying and possible partial gasification, and the second is for complete combustion. More advanced versions of these systems use rotating or vibrating grates to facilitate ash removal, with some requiring water cooling.

2.4.1.1 Co-Firing

A modern practice which has allowed biomass feedstocks an early and cheap entry point into the energy market is the practice of co-firing a fossil fuel (usually coal) with a biomass feedstock. It refers to the blending of biomass with coal in the furnace of a conventional coal-fired steam cycle electric power plant. This is currently one of the simplest ways of utilizing biomass to displace fossil fuels, requiring no new investment or specialized technology. Between 5 and 15% biomass (by heat content) may be used in such facilities at an additional cost estimated at <0.5 cents/kWh (compared with coal-firing alone). Co-firing is known to reduce carbon dioxide emissions, sulfur dioxide (SO_x) emissions, and potentially some emissions of nitrogen oxides (NO_x) as well. Many electric utilities around the US have experimented successfully with co-firing, using wood chips, urban waste wood and forestry residues.

Co-firing has a number of advantages, especially where electricity production is an output. First, where the conversion facility is situated near an agro-industrial or forestry product processing plant, large quantities of low-cost biomass residues are available. These residues can represent a low-cost fuel feedstock although there may be other opportunity costs. Second, it is now widely accepted that fossil-fuel power plants are usually highly polluting in terms of sulfur, CO₂ and other GHGs. Using the existing equipment, perhaps with some modifications, and co-firing with biomass may represent a cost-effective means for meeting more stringent emissions targets. Biomass fuel's low sulfur and nitrogen (relative to coal) content and nearly zero net CO₂ emission levels allows biomass to offset the higher sulfur and carbon contents of the fossil fuel. Third, if an agro-industrial or forestry processing plant wishes to make more efficient use of the residues generated by co-producing electricity, but has a highly seasonal component to its operating schedule, co-firing with a fossil fuel may allow the economic generation of electricity all the year round.

Agro-industrial processors such as the sugarcane sugar industry can produce large amounts of electricity during the harvesting and processing season; however, during the off-season the plant will remain idle. This has two drawbacks, first, it is an inefficient use of equipment which has a limited lifetime, and second, electrical distribution utilities will not pay the full premium for electrical supplies which cannot be relied on for year-round production. In other words the distribution utility needs to guarantee year-round supply and may therefore have to invest in its own production capacity to cover the off-season gap in supply with associated costs in equipment and fuel. If however, the agro-processor can guarantee electrical supply year-round through the burning of alternative fuel supplies, then it will make efficient use of its equipment and will receive premium payments for its electricity by the distribution facility.

2.4.2 Thermochemical Process

2.4.2.1 Pyrolysis

Pyrolysis is a thermochemical decomposition of organic material at elevated temperatures in the absence of oxygen. Pyrolysis typically occurs under pressure and at operating temperatures above 430°C (800°F). In general, pyrolysis of organic substances produces gas and liquid products and leaves a solid residue richer in carbon content. Extreme pyrolysis, which leaves mostly carbon as the residue, is called carbonization.

The biomass feedstock is subjected to high temperatures at low oxygen levels, thus inhibiting complete combustion, and may be carried out under pressure. Biomass is degraded to single carbon molecules (CH_4 and CO) and H_2 producing a gaseous mixture called “producer gas”. Carbon dioxide may be produced as well, but under the pyrolytic conditions of the reactor it is reduced back to CO and H_2O ; this water further aids the reaction. Liquid-phase products result from temperatures which are too low to crack all the long chain carbon molecules thus resulting in the production of tars, oils, methanol, acetone, etc. Once all the volatiles have been driven off, the residual biomass is in the form of char which is virtually pure carbon. Pyrolysis has received attention recently for the production of liquid fuels from cellulosic feedstocks by “fast” and “flash” pyrolysis in which the biomass has a short residence time in the reactor. A more detailed understanding of the physical and chemical properties governing the pyrolytic reactions has allowed the optimization of reactor conditions necessary for these types of pyrolysis. Further work is now concentrating on the use of high-pressure reactor conditions to produce hydrogen and on low-pressure catalytic techniques (requiring zeolites) for alcohol production from the pyrolytic oil [3].

The pyrolysis process is used heavily in the chemical industry, for example, to produce charcoal, activated carbon, methanol and other chemicals from wood, to convert ethylene dichloride into vinyl chloride to make PVC, to produce coke from

coal, to convert biomass into syngas, to turn waste into safely disposable substances, and for transforming medium-weight hydrocarbons from oil into lighter ones like gasoline. These specialized uses of pyrolysis are called by various names, such as dry distillation, destructive distillation or cracking.

Pyrolysis differs from other high-temperature processes like combustion and hydrolysis in that it does not involve reactions with oxygen, water or any other reagents. In practice, it is not possible to achieve a completely oxygen-free atmosphere. Because some oxygen is present in any pyrolysis system, a small amount of oxidation occurs. The term has also been applied to the decomposition of organic material in the presence of superheated water or steam (hydrous pyrolysis), for example, in the steam cracking of oil. Pyrolysis is the basis of several methods that are being developed for producing fuel from biomass, which may include either crops grown for the purpose or biological waste products from other industries. Fuel bio-oil resembling light crude oil can also be produced by hydrous pyrolysis from many kinds of feedstock by a process called thermal depolymerization (which may however include other reactions besides pyrolysis).

2.4.2.2 Torrefaction

Biomass can be an important energy source to create a more sustainable society. However, nature has created a large diversity of biomass with varying specifications. In order to create highly efficient biomass-to-energy chains, torrefaction of biomass in combination with densification (pelletization/briquetting), is a promising step to overcome logistic economics in large scale green energy solutions. Torrefaction of biomass can be described as a mild form of pyrolysis at temperatures typically ranging between 200 and 320°C. During torrefaction the biomass properties are changed to obtain a much better fuel quality for combustion and gasification applications. Torrefaction combined with densification leads to a very energy dense fuel carrier of 20–25 GJ/ton [4].

Torrefaction is a thermochemical treatment of biomass at 200–320°C. It is carried out under atmospheric conditions and in the absence of oxygen. During the process, the water contained in the biomass as well as superfluous volatiles are removed, and the biopolymers (cellulose, hemicellulose and lignin) partly decompose giving off various types of volatiles. The final product is the remaining solid, dry, blackened material which is referred to as “torrefied biomass” or “bio-coal”.

During the process, the biomass loses typically 20% of its mass (dry bone basis), while only 10% of the energy content in the biomass is lost. This energy (the volatiles) can be used as a heating fuel for the torrefaction process. After the biomass is torrefied it can be densified, usually into briquettes or pellets using conventional densification equipment, to further increase the density of the material and to improve its hydrophobic properties. With regard to brewing and food products, torrefication occurs when a cereal (barley, maize, oats, wheat, etc.) is cooked at high temperature to gelatinize the starch endosperm creating the

expansion of the grain and creating a puffed appearance. The cereal can then be used whole or flaked. In brewing, the use of small quantities of torrefied wheat or barley in the mashing process aids in head retention and clings to the glass. Additionally, torrefied cereals are generally less expensive than equal amounts of malted products.

Torrefied and densified biomass has several advantages which makes it a competitive option compared to conventional biomass (wood) pellets:

- Higher energy density.
- Energy density of 18–20 GJ/m³ compared to 10–11 GJ/m³ driving a 40–50% reduction in transportation costs.
- More homogeneous composition.

Torrefied biomass can be produced from a wide variety of raw biomass feedstocks while yielding similar product properties. The main reason for this is that about all biomass are built from the same polymers (lignocelluloses). In general (woody and herbaceous) biomass consists of three main polymeric structures: cellulose, hemicellulose and lignin. Together, these are called lignocelluloses. Torrefaction of biomass leads to improved grindability of biomass. This leads to more efficient co-firing in existing coal-fired power stations or entrained-flow gasification for the production of chemicals and transportation fuels.

Fischer–Tropsch process (or Fischer–Tropsch Synthesis) is a set of chemical reactions that convert a mixture of carbon monoxide and hydrogen into liquid hydrocarbons. The process, a key component of gas to liquids technology, produces a petroleum substitute, typically from coal, natural gas or biomass for use as synthetic lubrication oil and as synthetic fuel. The F–T process has received intermittent attention as a source of low-sulfur diesel fuel and to address the supply or cost of petroleum-derived hydrocarbons.

Generally, the Fischer–Tropsch process is operated in the temperature range of 150–300°C (302–572°F). Higher temperatures lead to faster reactions and higher conversion rates but also tend to favor methane production. As a result, the temperature is usually maintained at the low to middle part of the range. Increasing the pressure leads to higher conversion rates and also favors formation of long-chained alkanes both of which are desirable. Typical pressures range from one to several tens of atmospheres. Even higher pressures would be favorable, but the benefits may not justify the additional costs of high-pressure equipment. A variety of catalysts can be used for the Fischer–Tropsch process, but the most common are the transition metals cobalt, iron and ruthenium. Nickel can also be used, but tends to favor methane formation.

2.4.2.3 Carbonization

This is an age old pyrolytic process optimized for the production of charcoal. Traditional methods of charcoal production have centered on the use of earth mounds or covered pits into which the wood is piled. Control of the reaction

conditions is often crude and relies heavily on experience. During carbonization most of the volatile components of the wood are eliminated; this process is also called “dry wood distillation”. Carbon accumulates mainly due to a reduction in the levels of hydrogen and oxygen in the wood. The wood undergoes a number of physico-chemical changes as the temperature rises. Between 100 and 170°C most of the water is evaporated; between 170 and 270°C gases develop containing condensable vapors, CO and CO₂. These condensable vapors (long chain carbon molecules) form pyrolysis oil, which can then be used for the production of chemicals or as a fuel after cooling and scrubbing. Between 270 and 280°C an exothermic reaction develops which can be detected by the spontaneous generation of heat.

There are three basic types of charcoal-making: (a) internally heated (by controlled combustion of the raw material), (b) externally heated (using fuelwood or fossil fuels) and (c) hot circulating gas (retort or converter gas, used for the production of chemicals). Internally heated charcoal kilns are the most common form of charcoal kiln. It is estimated that 10–20% of the wood (by weight) is sacrificed; a further 60% (by weight) is lost through the conversion to, and release of, gases to the atmosphere from these kilns. Externally heated reactors allow oxygen to be completely excluded, and thus provide better quality charcoal on a larger scale. They do, however, require the use of an external fuel source, which may be provided from the “producer gas” once pyrolysis is initiated. Recirculating heated gas systems offer the potential to generate large quantities of charcoal and associated by-products, but are presently limited by high investment costs for large-scale plants.

2.4.2.4 Gasification

High temperatures and a controlled environment lead to virtually all the raw material being converted into gas. This takes place in two stages. In the first stage, the biomass is partially combusted to form producer gas and charcoal. In the second stage, the CO₂ and H₂O produced in the first stage are chemically reduced by the charcoal, forming CO and H₂. The composition of the gas is 18–20% H₂, an equal portion of CO, 2–3% CH₄, 8–10% CO₂ and the rest nitrogen. These stages are spatially separated in the gasifier, with gasifier design very much dependant on the feedstock characteristics. Gasification requires temperatures of about 800°C and is carried out in closed top or open top gasifiers. These gasifiers can be operated at atmospheric pressure or higher. The energy density of the gas is generally <5.6 MJ/m³, which is low in comparison to natural gas at 38 MJ/m³, providing only 60% of the power rating of diesel when used in a modified diesel engine. Gasification technology has existed since the turn of the century when coal was extensively gasified in the UK and elsewhere for use in power generation and in houses for cooking and lighting. Gasifiers were used extensively for transport in Europe during World War II due to shortages of oil, with a closed top design predominating.

Table 2.1 Cost analysis for biomass-fired power plants

	Steam turbine (cents/kWh)	Advanced gasification (cents/kWh)
Capital	3.0–5.0	2.63
Operating (excluding fuel)	2.2–2.8	0.4
Biomass feedstock	1.2–3.5	1.62
Total	6.4–11.3	4.65

A major future role is envisaged for electricity production from biomass plantations and agricultural residues using large-scale gasifiers with direct coupling to gas turbines. The potential gains in efficiency using such hybrid gasifier/gas turbine systems make them extremely attractive for electricity generation once commercial viability has been demonstrated. Such systems take advantage of low grade and cheap feedstocks (residues and wood produced using short rotation techniques) and the high efficiencies of modern gas turbines to produce electricity at comparable or less cost than fossil fuel-derived electricity. Net atmospheric CO₂ emissions are avoided if growth of the biomass is managed to match consumption. The use of BIG/STIG (biomass integrated gasifier steam injected gas turbine) initially and BIG/GTCC (biomass integrated gasifier gas turbine combined cycle) as the technology matures, is predicted to allow energy conversion efficiencies of 40–55%. Modern coal electrical plants have efficiencies of about 35% or less. Combined heat and power systems could eventually provide energy at efficiencies of from 50 to 80%. The use of low-grade feedstocks combined with high conversion efficiencies makes these systems economically competitive with cheap coal-based plants and energetically competitive with natural gas-based plants.

It has been observed that it takes a little under 1,000 acres (400 ha) of poplar (grown as a short-rotation crop at a usable yield of 5 dry U.S. tons/acre, or 11 metric tons/ha) to supply an electric power plant with a capacity of one megawatt (1 MW). A typical small biomass-fired power plant (25 MW) with 80% availability (i.e., actually operating 80% of the time) would produce about 175 million kWh per year, or approximately the electricity needs of 25,000 people. The required 25,000 acres of land (about 10,000 ha) would occupy about 2% of the total land area within a radius of 25 miles (40 km). These calculations are based on a 30% conversion efficiency from heat to electricity, and an energy content for dry poplar wood of 17 Btu/U.S. ton (19.7 GJ/metric ton).

The cost of electricity from two contrasting technologies (one present-day, one future), for a biomass-fired power plant from 10 to 50 MW in size are given in Table 2.1.

2.4.2.5 Catalytic Liquefaction

This technology has the potential to produce higher quality products of greater energy density. These products should also require less processing to produce

marketable products. Catalytic liquefaction is a low temperature, high pressure thermochemical conversion process carried out in the liquid phase. It requires either a catalyst or a high hydrogen partial pressure. Technical problems have so far limited the opportunities of this technology.

2.5 Types of Gasifiers

2.5.1 Updraught or Counter Current Gasifier

The oldest and simplest type of gasifier is the counter current or updraught gasifier where the air intake is at the bottom and the gas leaves at the top. The combustion reactions occur near the grate at the bottom, which are followed by reduction reactions somewhat higher up in the gasifier. In the upper part of the gasifier, heating and pyrolysis of the feedstock occur as a result of heat transfer by forced convection and radiation from the lower zones. The tars and volatiles produced during this process are carried in the gas stream. Ashes are removed from the bottom of the gasifier. The major advantages of this type of gasifier are its simplicity, high charcoal burn-out and internal heat exchange leading to low gas exit temperatures and high equipment efficiency, as well as the possibility of operation with many types of feedstock (sawdust, cereal hulls, etc.).

Major drawbacks result from the possibility of “channeling” in the equipment, which can lead to oxygen breakthrough and dangerous, explosive situations and the necessity to install automatic moving grates, as well as from the problems associated with disposal of the tar-containing condensates that result from the gas cleaning operations. The latter is of minor importance if the gas is used for direct heat applications, in which case the tars are simply burnt.

2.5.2 Downdraught or Co-Current Gasifiers

A solution to the problem of tar entrainment in the gas stream has been found by designing co-current or downdraught gasifiers, in which primary gasification air is introduced at or above the oxidation zone in the gasifier. The producer gas is removed at the bottom of the apparatus, so that fuel and gas move in the same direction.

On their way down the acid and tarry distillation products from the fuel must pass through a glowing bed of charcoal and therefore are converted into permanent gases hydrogen, carbon dioxide, carbon monoxide and methane. Depending on the temperature of the hot zone and the residence time of the tarry vapors, a more or less complete breakdown of the tars is achieved. The main advantage of down-draught gasifiers lies in the possibility of producing a tar-free gas suitable for

engine applications. In practice, however, a tar-free gas is seldom if ever achieved over the whole operating range of the equipment: tar-free operating turn-down ratios of a factor 3 are considered standard; a factor 5–6 is considered excellent. Because of the lower level of organic components in the condensate, downdraught gasifiers suffer less from environmental objections than updraught gasifiers.

A major drawback of downdraught equipment lies in its inability to operate on a number of unprocessed fuels. In particular, fluffy, low density materials give rise to flow problems and excessive pressure drop, and the solid fuel must be pelletized or briquetted before use. Downdraught gasifiers also suffer from the problems associated with high ash content fuels to a larger extent than updraught gasifiers. Minor drawbacks of the downdraught system, as compared to updraught, are somewhat of lower efficiency resulting from the lack of internal heat exchange as well as the lower heating value of the gas. Besides this, the necessity to maintain uniform high temperatures over a given cross-sectional area makes impractical the use of downdraught gasifiers in a power range above about 350 kW (shaft power).

2.5.3 Cross-Draught Gasifier

Cross-draught gasifiers are an adaptation for the use of charcoal. Charcoal gasification results in very high temperatures (1500 °C and higher) in the oxidation zone which can lead to material problems. In cross-draught gasifiers insulation against these high temperatures is provided by the fuel (charcoal) itself. Advantages of the system lie in the very small scale at which it can be operated. Installations below 10 kW (shaft power) can under certain conditions be economically feasible. The reason is the very simple gas-cleaning train (only a cyclone and a hot filter) which can be employed when using this type of a gasifier in conjunction with small engines.

A disadvantage of cross-draught gasifiers is their minimal tar-converting capabilities and the consequent need for high quality (low volatile content) charcoal. It is because of the uncertainty of charcoal quality that a number of charcoal gasifiers employ the downdraught principle, in order to maintain at least a minimal tar-cracking capability.

2.5.4 Fluidized Bed Gasifier

The operation of both up- and downdraught gasifiers is influenced by the morphological, physical and chemical properties of the fuel. Problems commonly encountered are: lack of bunker flow, slagging and extreme pressure drop over the gasifier. Air is blown through a bed of solid particles at a sufficient velocity to keep these in a state of suspension. The bed is originally externally heated and the feedstock is introduced as soon as a sufficiently high temperature is reached.

The fuel particles are introduced at the bottom of the reactor, very quickly mixed with the bed material and almost instantaneously heated up to the bed temperature. As a result of this treatment the fuel is pyrolyzed very fast, resulting in a component mix with a relatively large amount of gaseous materials. Further gasification and tar-conversion reactions occur in the gas phase. Most systems are equipped with an internal cyclone in order to minimize char blow-out as much as possible. Ash particles are also carried over the top of the reactor and have to be removed from the gas stream if the gas is used in engine applications [5].

2.5.5 Other Types of Gasifiers

A number of other biomass gasifier systems (double fired, entrained bed, molten bath), which are partly spin-offs from the coal gasification technology, are currently under development. In some cases these systems incorporate unnecessary refinements and complications, in others both the size and sophistication of the equipment make near-term application in developing countries unlikely.

2.6 Briquetting

2.6.1 Screw Press and Piston Press Technologies

High compaction technology or binderless technology consists of the piston press and the screw press. Most of the units currently installed, are the reciprocating type, where the biomass is pressed in a die by a reciprocating ram at a very high pressure. In a screw extruder press, the biomass is extruded continuously by a screw through a heated taper die. In a piston press the wear of the contact parts e.g., the ram and die is less compared to the wear of the screw and die in a screw extruder press. The power consumption in the former is less than that of the latter. But in terms of briquette quality and production procedure screw press is definitely superior to the piston press technology. The central hole incorporated into the briquettes produced by a screw extruder helps to achieve uniform and efficient combustion and, also, these briquettes can be carbonized. Table 2.2 shows a comparison between a screw extruder and a piston press.

2.6.1.1 Piston Press

The piston presses which are currently in operation, are also known as ram and die technology. In this case the biomass is punched into a die by a reciprocating ram with a very high pressure thereby compressing the mass to obtain a briquette.

Table 2.2 Comparison of a screw extruder and a piston press

	Piston press	Screw extruder
Optimum moisture content of raw material	10–15%	8–9%
Wear of contact parts	Low in case of ram and die	High in case of screw
Output from the machine	In strokes	Continuous
Power consumption	50 kWh/ton	60 kWh/ton
Density of briquette	1–1.2 gm/cm ³	1–1.4 gm/cm ³
Maintenance	High	Low
Combustion performance of briquettes	Not so good	Very good
Carbonization to charcoal	Not possible	Makes good charcoal
Suitability in gasifiers	Not suitable	Suitable
Homogeneity of briquettes	Non-homogeneous	Homogeneous

The briquette produced is 60 mm in external diameter. This machine has a 700 kg/h capacity and the power requirement is 25 kW. The ram moves approximately 270 times/min in this process.

Merits and Demerits of Piston Press Technology

1. There is less relative motion between the ram and the biomass hence, the wear of the ram is considerably reduced.
2. It is the most cost-effective technology currently offered.
3. Some operational experience has now been gained using different types of biomass.
4. The moisture content of the raw material should be less than 12% for the best results.
5. The quality of the briquettes goes down with an increase in production for the same power.
6. Carbonization of the outer layer is not possible. Briquettes are somewhat brittle.

2.6.1.2 Screw Press Technology

In the screw press technology, the biomass is extruded continuously by a screw through a taper die which is heated externally to reduce the friction.

Merits and Demerits of this Technology

1. The output is continuous and the briquette is uniform in size.
2. The outer surface of the briquette is partially carbonized facilitating easy ignition and combustion. This also protects the briquettes from ambient moisture.

3. A concentric hole in the briquette helps in combustion because of sufficient circulation of air.
4. The machine runs very smoothly without any shock load.
5. The machine is lightweight compared to the piston press because of the absence of reciprocating parts and flywheel. The machine parts and the oil used in the machine are free from dust or raw material contamination.
6. The power requirement of the machine is high compared to that of piston press.

At present, screw press and piston press technologies are becoming more important commercially. As the piston press technology is comparatively older than the screw press technology, more piston presses are operating today. However, the screw press technology is also rapidly gaining in importance. The lack of basic research to improve the piston press and the manufacturers' inability to understand the technology are the two prime reasons that these presses are not performing satisfactorily on a commercial basis [6]. Entrepreneurs face many problems due to frequent wear in the ram and the die. The life of the ram has been observed from 33 to 300 h. This is the most frequently used briquetting equipment and is manufactured throughout the world. It consists of a flywheel that operates a piston, which presses the material through a tapered die where the briquette is formed. But piston presses have not been successful due to a lack of understanding of the characteristics of raw material which in turn affects machine design parameters like flywheel size and speed, crank shaft size and piston stroke length. The feeding mechanism also needs to be perfected, in this case according to the bulk density of the raw material.

2.6.1.3 Other Briquetting Technologies

Another type of briquetting machine is the hydraulic piston press. This is different from the mechanical piston press in that the energy to the piston is transmitted from an electric motor via a high pressure hydraulic oil system. This machine is compact and light. Because of the slower press cylinder compared to that of the mechanical machine, it results in lower outputs. The briquettes produced have a bulk density lower than $1,000 \text{ kg/m}^3$ due to the fact that pressure is limited to 40–135 kg/h. This machine can tolerate higher moisture content than the usually accepted 15% moisture content for mechanical piston presses. Pelletizing is closely related to briquetting except that it uses smaller dies (approximately 30 mm) so that the smaller products produced are called pellets. The pelletizer has a number of dies arranged as holes bored on a thick steel disk or ring and the material is forced into the dies by means of two or three rollers. The two main types of pellet presses are: flat and ring types.

Large capacity pelletizers are available in the range of 200 kg/h–8 ton/h. Thus, pellet press capacity is not restricted by the density of the raw material as in the case of piston or screw presses. Power consumption falls within the range of 15–40 kWh/ton.

2.6.2 Compaction Characteristics of Biomass and Their Significance

In order to produce good quality briquettes, feed preparation is very important. For densification of biomass, it is important to know the feed parameters that influence the extrusion process. For different briquetting machines, the required parameters of raw materials like their particle size, moisture content, temperature are different. These are discussed below.

2.6.2.1 Effect of Particle Size

Particle size and shape are of great importance for densification. It is generally agreed that biomass material of 6–8 mm size with 10–20% powdery component (<4 mesh) gives the best results. Although the screw extruder which employs high pressure (1,000–1,500 bar), is capable of briquetting material of oversized particles, the briquetting will not be smooth and clogging might take place at the entrance of the die resulting in jamming of the machine. The larger particles which are not conveyed through the screw start accumulating at the entry point and the steam produced due to high temperature (due to rotation of screw, heat conducted from the die and also if the material is preheated) inside the barrel of the machine starts condensing afresh. Cold feed results in the formation of lumps and leads to jamming. That is why the processing conditions should be changed to suit the requirements of each particular biomass. Therefore, it is desirable to crush larger particles to get a random distribution of particle size so that an adequate amount of sufficiently small particles is present for embedding into the larger particles.

The presence of different size particles improves the packing dynamics and also contributes to high static strength. Only fine and powdered particles of size <1 mm are not suitable for a screw extruder because they are less dense, more cohesive, non-free flowing entities.

2.6.2.2 Effect of Moisture

The percentage of moisture in the feed biomass to extruder machine is a very critical factor. In general, it has been found that when the feed moisture content is 8–10%, the briquettes will have 6–8% moisture. At this moisture content, the briquettes are strong and free of cracks and the briquetting process is smooth. But when the moisture content is more than 10%, the briquettes are poor and weak and the briquetting operation is erratic. Excess steam is produced at higher moisture content leading to the blockage of incoming feed from the hopper, and sometimes it shoots out the briquettes from the die. Therefore, it is necessary to maintain optimum moisture content.

In the briquetting process water also acts as a film type binder by strengthening the bonding in briquettes. In the case of organic and cellular products, water helps in promoting bonding by van der Waals' forces by increasing the true area of contact of the particles. In fact, the surface effects of water are so pronounced that the success or failure of the compaction process depends solely upon the moisture content of the material. The right amount of moisture develops self-bonding properties in ligno-cellulose substances at elevated temperatures and pressures prevalent in briquetting machines. It is important to establish the initial moisture content of the biomass feed so that the briquettes produced have moisture content greater than the equilibrium value, otherwise the briquettes may swell during storage and transportation and disintegrate when exposed to humid atmospheric conditions.

2.6.2.3 Effect of Temperature of Biomass

By varying the temperature of biomass the briquette density, briquette crushing strength and moisture stability can be varied. In a screw extruder, the temperature does not remain constant in the axial direction of the press but gradually increases. Internal and external friction causes local heating and the material develops self-bonding properties at elevated temperatures. It can also be assumed that the moisture present in the material forms steam under high pressure conditions which then hydrolyses the hemicellulose and lignin portions of biomass into lower molecular carbohydrates, lignin products, sugar polymers and other derivatives. These products, when subjected to heat and pressure in the die, act as adhesive binders and provide a bonding effect "in situ". The addition of heat also relaxes the inherent fibers in biomass and apparently softens its structure, thereby reducing their resistance to briquetting which in turn results in decreased specific power consumption and a corresponding increase in production rate and reduction in wear of the contact parts. However, the temperature should not be increased beyond the decomposition temperature of biomass which is around 300°C.

2.6.2.4 Effect of Temperature of the Die

The distinctive feature of a screw type briquetting machine is that heat is applied to the die 'bush' section of the cylinder. This brings about two important operational advantages. The machine can be operated with less power and the life of the die is prolonged. Further, the surface of the briquette is partially carbonized/torrified to a dark brown color making the briquette resistant to atmospheric moisture during storage. The temperature of the die should be kept at about 280–290°C. If the die temperature is more than the required one, the friction between the raw material and the die wall decreases such that compaction occurs at lower pressure which results in poor densification and inferior strength. Conversely, low temperature will result in higher pressure and power consumption and lower production rate.

2.6.2.5 Effect of External Additives

The briquetting process does not add to the calorific value of the base biomass. In order to upgrade the specific heating value and combustibility of the briquette, certain additives like charcoal and coal in very fine form can be added. About 10–20% char fines can be employed in briquetting without impairing their quality. Further, only screw pressed briquettes can be carbonized. When carbonized with additives in the briquette to make dense charcoal, the yield is remarkably increased. However, depending upon the quality of charcoal and coal powder, various formulations can be evolved for optimal results.

In piston press technology the effect of particle size and moisture content is similar to that of the screw press. But in this case preheating of raw material is not employed and the die is not heated. In fact the die needs cooling for smooth briquetting.

2.6.2.6 Unit Operations

The above factors illustrate that biomass feed preparation is very important and forms an integral part of the briquetting process. The unit operations of the piston press and the screw press are similar except where the latest development in screw press technology has been adopted, i.e., where a preheating system has been incorporated to preheat the raw material for briquetting to give better performance commercially and economically to suit local conditions. In the present piston press operating briquetting plants, the biomass is briquetted after pre-processing the raw material but no preheating is carried out. Depending upon the type of biomass, three processes are generally required involving the following steps:

- A. Sieving—Drying—Preheating—Densification—Cooling—Packing
- B. Sieving—Crushing—Preheating—Densification—Cooling—Packing
- C. Drying—Crushing—Preheating—Densification—Cooling—Packing

When sawdust is used, process A is adopted. Process B is for agro- and mill-residues which are normally dry. These materials are coffee husk, rice husk, groundnut shells, etc. Process C is for materials like bagasse, coir pith (which needs sieving), mustard and other cereal stalks.

2.7 Anaerobic Digestion

Anaerobic reactors are generally used for the production of methane-rich biogas from manure (human and animal) and crop residues. Anaerobic digestion is a series of processes in which microorganisms break down biodegradable material in the absence of oxygen, used for industrial or domestic purposes to manage waste and/or to release energy.

They utilize mixed methanogenic bacterial cultures which are characterized by defined optimal temperature ranges for growth. These mixed cultures allow digesters to be operated over a wide temperature range, i.e., above 0°C up to 60°C. When functioning well, the bacteria convert about 90% of the feedstock energy content into biogas (containing about 55% methane), which is a readily useable energy source for cooking and lighting. The sludge produced after the manure has passed through the digester is non-toxic and odorless. Also, it has lost relatively little of its nitrogen or other nutrients during the digestion process thus, making a good fertilizer. In fact, compared to cattle manure left to dry in the field the digester sludge has higher nitrogen content; many of the nitrogen compounds in fresh manure become volatilized while drying in the sun. On the other hand, in the digested sludge little of the nitrogen is volatilized, and the nitrogen is more readily accessible by plants than many of the nitrogen compounds found in dung, and thus the fertilizer value of the sludge may actually be higher than that of fresh dung.

Pressure from environmentally related legislation on solid waste disposal methods in developed countries has increased the application of anaerobic digestion as a process for reducing waste volumes and generating useful by-products. Anaerobic digestion may either be used to process the source separated fraction of municipal waste, or alternatively combined with mechanical sorting systems, to process residual mixed municipal waste. These facilities are called mechanical biological treatment plants.

Utilizing anaerobic digestion technologies can help to reduce the emission of greenhouse gases in a number of key ways:

- Replacement of fossil fuels.
- Reducing or eliminating the energy footprint of waste treatment plants.
- Reducing methane emission from landfills.
- Displacing industrially produced chemical fertilizers.
- Reducing vehicle movements.
- Reducing electric grid transportation losses.

If the putrescible waste processed in anaerobic digesters was disposed of in a landfill, it would break down naturally and often anaerobically. In this case the gas will eventually escape into the atmosphere. As methane is about 20 times more potent as a greenhouse gas than carbon dioxide this has significant negative environmental effects.

The most common and popular on-farm use of biogas is to fuel an engine-generator (generator-set or genset) to produce electricity for on-farm use, or, less commonly, for off-farm sale or under a net-metered arrangement with the utility. Heat recovered from combustion of the biogas (whether in boilers or internal combustion engines) can be used to maintain the operating temperature of the anaerobic digester or for other on-farm uses. Burners and boilers used to produce heat and steam can be fueled by biogas. The direct substitution of biogas for natural gas or LPG, however, will not work for most standard commercially available burners. At the given fuel gas feed pressures, gas must flow into combustion in the right stoichiometric ratio with air. Because of its high CO₂ content, if biogas flows

through the burner orifice at the pressure intended for feeding methane or propane, the fuel-to-air ratio is insufficient to ensure flame stability.

A relatively simple option is to provide the combustion equipment with a second “as is” biogas burner that operates in parallel with the first. In this case, regardless of the fuel used, air flow is kept constant. Burner orifices for the respective burners can be set such that each burner meters the proper amount of gas to meet combustion stoichiometry. This could require other control measures such as (for simplest control) complete switchovers from pure biogas fuel to the fossil alternative, and modest (a few hours’ worth) backup biogas storage, but is otherwise straightforward [7].

Digester liquor can be used as a fertilizer supplying vital nutrients to soils. The solid, fibrous component of the digested material can be used as a soil conditioner to increase the organic content of soils. The liquor can be used instead of chemical fertilizers which require large amounts of energy to produce and transport. The use of manufactured fertilizers is therefore more carbon intensive than the use of anaerobic digester liquor fertilizer.

In countries that collect household waste, the utilization of local anaerobic digestion facilities can help to reduce the amount of waste that requires transportation to centralized landfill sites or incineration facilities. This reduced burden on transportation reduces carbon emissions from the collection vehicles. If localized anaerobic digestion facilities are embedded within an electrical distribution network, they can help in reducing the electrical losses that are associated with transporting electricity over a national grid.

There are four key biological and chemical stages of anaerobic digestion:

1. Hydrolysis
2. Acidogenesis
3. Acetogenesis
4. Methanogenesis

In most cases biomass is made up of large organic polymers. In order for the bacteria in anaerobic digesters to access the energy potential of the material, these chains must first be broken down into their smaller constituent parts. These constituent parts or monomers such as sugars are readily available by other bacteria. The process of breaking these chains and dissolving the smaller molecules into solution is called hydrolysis. Therefore, hydrolysis of these high molecular weight polymeric components is the necessary first step in anaerobic digestion. Through hydrolysis the complex organic molecules are broken down into simple sugars, amino acids and fatty acids.

Acetate and hydrogen produced in the first stages can be used directly by methanogens. Other molecules such as volatile fatty acids (VFAs) with a chain length that is greater than acetate must first be catabolized into compounds that can be directly utilized by methanogens. The biological process of acidogenesis is where there is further breakdown of the remaining components by acidogenic (fermentative) bacteria. Here, VFAs are created along with ammonia, carbon dioxide and hydrogen sulfide as well as other by-products. The process of acidogenesis is

similar to the way that milk sours. The third stage of anaerobic digestion is acetogenesis. Here, simple molecules created through the acidogenesis phase are further digested by acetogens to produce largely acetic acid as well as carbon dioxide and hydrogen [8].

The terminal stage of anaerobic digestion is the biological process of methanogenesis. Here, methanogens utilize the intermediate products of the preceding stages and convert them into methane, carbon dioxide and water. It is these components that make up the majority of the biogas emitted from the system. Methanogenesis is sensitive to both high and low pHs and occurs between pH 6.5 and 8. The remaining, non-digestible material which the microbes cannot feed upon, along with any dead bacterial remains constitutes the digestate.

The end products of biological treatment are:

- *Biogas* (methane not less than 55%, carbon dioxide not more than 45%, hydrogen sulfide not more than 2%, hydrogen not more than 1%);
- *fermented substrate as fermentation residue*, consisting of water, cellulose residues, small quantity of bacteria and organic nutrients (nitrogen, phosphorus, potassium, etc.).

Anaerobic digesters can be designed and engineered to operate using a number of different process configurations:

- Batch or continuous.
- Temperature: mesophilic or thermophilic.
- Solids content: high solids or low solids.
- Complexity: single stage or multistage.

2.7.1 Batch or Continuous

A batch system is the simplest form of digestion. Biomass is added to the reactor at the start of the process in a batch and is sealed for the duration of the process. Batch reactors suffer from odor issues that can be a severe problem when they are emptied. Typically, biogas production will be formed with a normal distribution pattern over time. The operator can use this fact to determine when they believe the process of digestion of the organic matter has completed. As the batch digestion is simple and requires less equipment and lower levels of design work it is typically a cheaper form of digestion.

In continuous digestion processes organic matter is constantly added (continuous complete mixed) or added in stages to the reactor (continuous plug flow; first in–first out). Here the end products are constantly or periodically removed, resulting in constant production of biogas. Single or multiple digesters in sequence may be used. Examples of this form of anaerobic digestion include continuous stirred-tank reactors (CSTRs), upflow anaerobic sludge blanket (UASB), expanded granular sludge bed (EGSB) and internal circulation reactors (IC).

2.7.2 Temperature

There are two conventional operational temperature levels for anaerobic digesters, which are determined by the species of methanogens in the digesters:

- Mesophilic which takes place optimally around 30–38°C or at ambient temperatures between 20 and 45°C where mesophiles are the primary microorganism present.
- Thermophilic which takes place optimally around 49–57°C at elevated temperatures up to 70°C where thermophiles are the primary microorganisms present.

There are a greater number of species of mesophiles than thermophiles. These bacteria are also more tolerant to changes in environmental conditions than thermophiles. Mesophilic systems are therefore considered to be more stable than thermophilic digestion systems.

As mentioned above, thermophilic digestion systems are considered to be less stable, the energy input is higher and more energy is removed from the organic matter. However, the increased temperatures facilitate faster reaction rates and hence faster gas yields. Operation at higher temperatures facilitates greater sterilization of the end digestate.

2.7.3 Solids

Typically, there are three different operational parameters associated with the solids content of the feedstock to the digesters:

- High-solids (dry—stackable substrate)
- High-solids (wet—pumpable substrate)
- Low-solids (wet—pumpable substrate)

High-solids (dry) digesters are designed to process materials with high-solids content between ~25 and 40%. Unlike wet digesters that process pumpable slurries, high solids (dry—stackable substrate) digesters are designed to process solid substrates deposited in tunnel-like chambers with a gas-tight door. They typically have few moving parts, require minimal or no pre-grinding or shredding, and do not use water addition. Solid state digestion of cattle dung is a suitable technology in which fresh cattle dung is anaerobically digested. Solid degradation of about 40–48% is observed in the effluent slurry that provides easy flowability to the outlet slurry [9].

Wet digesters can either be designed to operate in high solids content, with a total suspended solids (TSS) concentration greater than ~20%, or a low solids concentration less than ~15%. High-solids (wet) digesters process a thick slurry that requires more energy input to move and process the feedstock. The thickness

of the material may also lead to associated problems with abrasion. High-solids digesters will typically have a lower land requirement due to the lower volumes associated with the moisture.

Low-solids (wet) digesters can transport material through the system using standard pumps that require significantly lower energy input. Low-solids digesters require a larger amount of land than high-solids due to the increase volumes associated with the increased liquid-to-feedstock ratio of the digesters. There are benefits associated with operation in a liquid environment as it enables more thorough circulation of materials and contact between the bacteria and their food. This enables the bacteria to more readily access the substances they are feeding off and increases the speed of gas yields.

2.7.4 Number of Stages

Digestion systems can be configured with different levels of complexity:

- One-stage or single-stage
- Two-stage or multistage

A single-stage digestion system is one in which all of the biological reactions occur within a single sealed reactor or holding tank. Utilizing a single stage reduces construction costs; however, it facilitates less control of the reactions occurring within the system. Acidogenic bacteria, through the production of acids, reduce the pH of the tank. Methanogenic bacteria, as outlined earlier, operate in a strictly defined pH range. Therefore, the biological reactions of the different species in a single stage reactor can be in direct competition with each other. Another one-stage reaction system is an anaerobic lagoon. These lagoons are pond-like earthen basins used for the treatment and long-term storage of manures. Here, the anaerobic reactions are contained within the natural anaerobic sludge contained in the pool.

In a two-stage or multistage digestion system different digestion vessels are optimized to bring maximum control over the bacterial communities living within the digesters. Acidogenic bacteria produce organic acids and grow and reproduce more quickly than methanogenic bacteria. Methanogenic bacteria require stable pH and temperature in order to optimize their performance.

Typically hydrolysis, acetogenesis and acidogenesis occur within the first reaction vessel. The organic material is then heated to the required operational temperature (either mesophilic or thermophilic) prior to being pumped into a methanogenic reactor. The initial hydrolysis or acidogenesis tanks prior to the methanogenic reactor can provide a buffer to the rate at which feedstock is added. It should be noted that it is not possible to completely isolate the different reaction phases and often there is some biogas that is produced in the hydrolysis or acidogenesis tanks.

2.7.5 Residence

The residence time in a digester varies with the amount and type of feed material, the configuration of the digestion system and whether it be one-stage or two-stage. In the case of single-stage thermophilic digestion residence times may be in the region of 14 days, which compared to mesophilic digestion is relatively fast. The plug-flow nature of some of these systems will mean that the full degradation of the material may not have been realized in this timescale. In two-stage mesophilic digestion, residence time may vary between 15 and 40 days. In the case of mesophilic UASB digestion hydraulic residence times can be (1 h–1 day) and solid retention times can be up to 90 days. In this manner the UASB system is able to separate solid and hydraulic retention times with the utilization of a sludge blanket.

Continuous digesters have mechanical or hydraulic devices, depending on the level of solids in the material, to mix the contents enabling the bacteria and the food to be in contact. They also allow excess material to be continuously extracted to maintain a reasonably constant volume within the digestion tanks.

2.7.6 Feedstocks

The most important initial issue when considering the application of anaerobic digestion systems is the feedstock to the process. Digesters typically can accept any biodegradable material; however, if biogas production is the aim, the level of putrescibility is the key factor in its successful application. The more putrescible the material the higher the gas yields possible from the system. Substrate composition is a major factor in determining the methane yield and methane production rates from the digestion of biomass. Techniques are available to determine the compositional characteristics of the feedstock, while parameters such as solids, elemental and organic analyses are important for digester design and operation.

Anaerobes can break down material to varying degrees of success from readily in the case of short chain hydrocarbons such as sugars, to over longer periods of time in the case of cellulose and hemicellulose. Anaerobic microorganisms are unable to break down long chain woody molecules such as lignin. Anaerobic digesters were originally designed for operation using sewage sludge and manures. Sewage and manure are not, however, the material with the most potential for anaerobic digestion as the biodegradable material has already had much of the energy content taken out by the animal that produced it. Therefore, many digesters operate with *co-digestion* of two or more types of feedstock. For example, in a farm-based digester that uses dairy manure as the primary feedstock the gas production may be significantly increased by adding a second feedstock; e.g. *grass* and *corn* (typical on-site feedstock), or various organic by-products, such as *slaughterhouse waste, fats oils and grease* from restaurants, *organic household waste*, etc. (typical off-site feedstock).

A second consideration related to the feedstock is moisture content. Dryer, stackable substrates, such as food and yard wastes, are suitable for digestion in tunnel-like chambers. Tunnel style systems typically have near-zero wastewater discharge as well so this style system has advantages where the discharge of digester liquids are a liability. The wetter the material the more suitable it will be for handling with standard pumps instead of energy intensive concrete pumps and physical means of movement. Also the wetter the material, the more volume and area it takes up relative to the levels of gas that are produced. The moisture content of the target feedstock will also affect what type of system is applied to its treatment. In order to use a high solids anaerobic digester for dilute feedstocks, bulking agents such as compost should be applied to increase the solid content of the input material. Another key consideration is the carbon:nitrogen ratio of the input material. This ratio is the balance of food a microbe requires in order to grow. The optimal C:N ratio for the 'food' of a microbe is 20–30:1. Excess N can lead to ammonia inhibition of digestion.

The level of contamination of the feedstock material is a key consideration. If the feedstock to the digesters has significant levels of physical contaminants such as plastic, glass or metals, then pre-processing will be required in order for the material to be used. If it is not removed then the digesters can be blocked and will not function efficiently. It is with this that mechanical biological treatment plants are designed. The higher the level of pre-treatment a feedstock requires, the more processing machinery will be required and hence the project will have higher capital costs.

2.8 Methane Production in Landfills

Anaerobic digestion in landfills is brought about by the microbial decomposition of the organic matter in refuse. The levels of organic matter produced per capita vary considerably from developed to developing countries. Worldwide, the urban population is growing at twice the rate of the total population growth, creating unprecedented demands for goods and services as well as increasing pressure on the environment and on safe waste disposal [10]. Landfill-generated gas is on average half methane and half carbon dioxide with energy content from 18 to 19 MJ/m³. Its production does not occur under pressure, and thus recovery processes must be active. Commercial production of land-gas can also aid with the leaching problems now increasingly associated with landfill sites. Local communities neighboring landfill sites are becoming more aware of the potential for heavy metals and nutrients to leach into aquifers. Landfill processing reduces the volume of sludge to be disposed of, and the nutrient content, thus facilitating proper disposal. Methane is a powerful greenhouse gas, with substantial amounts being derived from unutilized methane production from landfill sites. Its recovery therefore, not only results in the stabilization of the landfill site, allowing faster

reuse of the land, but also serves to lessen the impact of biosphere methane emissions on global warming.

2.9 Ethanol Fermentation

Ethanol is mainly used as a substitute for imported oil in order to reduce their dependence on imported energy supplies. The substantial gains made in fermentation technologies now make the production of ethanol for use as a petroleum substitute and fuel enhancer, both economically competitive (given certain assumptions) and environmentally beneficial. The most commonly used feedstock in developing countries is sugarcane, due to its high productivity when supplied with sufficient water. Where water availability is limited, sweet sorghum or cassava may become the preferred feedstocks. Other advantages of sugarcane feedstock include the high residue energy potential and modern management practices which make sustainable and environmentally benign production possible while at the same time allowing continued production of sugar. Other feedstocks include saccharide-rich sugarbeet, and carbohydrate-rich potatoes, wheat and maize.

Ethanol fermentation, also referred to as alcoholic fermentation, is a biological process in which sugars such as glucose, fructose and sucrose are converted into cellular energy and thereby produce ethanol and carbon dioxide as metabolic waste products. Because yeasts perform this process in the absence of oxygen, ethanol fermentation is classified as anaerobic. Ethanol fermentation occurs in the production of alcoholic beverages and ethanol fuel, and in the rising of bread dough.

Typically, sugars are extracted from the biomass feedstock by crushing and washing (or in the case of starchy feedstocks like corn, by breakdown of starch to sugars). The sugar syrup is then mixed with yeast and kept warm, so that the yeast breaks down the sugars into ethanol. However, the fermented product is only about 10% ethanol, so a further stage of distillation is required to concentrate the ethanol to 95%. If the ethanol is intended for blending with gasoline, a “dehydration” phase may be required to make 100% pure ethanol. In the near future, ethanol may be made from cellulose, again by breakdown into sugars for fermentation. Cellulose is widely and cheaply available from many other biomass feedstocks, energy crops, agricultural and forestry residues [11].

One of the most promising fermentation technologies to be identified recently is the “Biostil” process which uses centrifugal yeast reclamation, and continuous evaporative removal of the ethanol. This allows the fermentation medium to be continuously sterilized and minimizes water use. The Biostil process markedly lowers the production of stillage, while the non-stop nature of the fermentation process allows substrate concentrations to be constantly kept at optimal levels and therefore fermentation efficiency is maximized. Improved varieties of yeast, produced through clonal selection techniques have also raised the tolerance levels of the yeast to alcohol concentrations, again improving efficiency.

Ethanol or ethyl alcohol, $\text{CH}_3\text{CH}_2\text{OH}$, has been described as one of the most exotic synthetic oxygen-containing organic chemicals because of its unique combination of properties as a solvent, a germicide, a beverage, an antifreeze, a fuel, a depressant and especially because of its versatility as a chemical intermediate for other organic chemicals.

A great number of bacteria are capable of ethanol formation. Many of these microorganisms, however, generate multiple end products in addition to ethyl alcohol. These include other alcohols (butanol, isopropylalcohol, 2, 3-butanediol), organic acid (acetic acid, formic acid, and lactic acids), polyols (arabitol, glycerol and xylitol), ketones (acetone) or various gases (methane, carbon dioxide, hydrogen). Many bacteria (i.e. *Enterobacteriaceae*, *Spirochaeta*, *Bacteroides*, etc.) metabolize glucose by the Embden-Meyerhof pathway. Briefly, this path utilizes 1 mol of glucose to yield 2 mol of pyruvate which are then decarboxylated to acetaldehyde and reduced to ethanol. Besides that the Entner-Doudoroff pathway is an additional means of glucose consumption in many bacteria.

The organisms of primary interest to industrial operations in fermentation of ethanol include *Saccharomyces cerevisiae*, *S. uvarum*, *Schizosaccharomyces pombe* and *Kluyveromyces sp.* Yeast, under anaerobic conditions, metabolize glucose to ethanol primarily by way of the Embden-Meyerhof pathway. The overall net reaction involves the production of 2 mol each of ethanol, but the yield attained in practical fermentations however does not usually exceed 90–95% in theory. This is partly due to the *requirement* for some nutrient to be utilized in the synthesis of new biomass and other cell maintenance related reactions.

A small concentration of oxygen must be provided to the fermenting yeast as it is a necessary component in the biosynthesis of polyunsaturated fats and lipids. Typical amounts of O_2 maintained in the broth are 0.05–0.10 mm Hg oxygen tension. Yeast is highly susceptible to ethanol inhibition. Concentration of 1–2% (w/v) is sufficient to retard microbial growth and at 10% (w/v) alcohol, the growth rate of the organism is nearly halted.

Based on a capital cost of \$2.50–3.00 per U.S. gallon of annual capacity (for production plants of around 50 million gallons/year), the fixed costs are about 60 cents/gallon. Operating costs are expected to be about 35 cents/gallon and feedstock costs in the range of 30–50 cents/gallon. Assuming an electricity co-product credit equivalent to 10–15 cents/gallon, total costs could range from about \$1.10 to 1.35/gallon. Currently, ethanol is produced from corn, and sells for around \$1.20–1.50/gallon. Other options for producing ethanol, such as with thermal gasification instead of biological breakdown of cellulose, might reduce the cost further. Costs are also expected to decline over time with improvements in technology and operating experience.

The bioconversion of biomass to mixed alcohol fuels can be accomplished using the MixAlco process. Through bioconversion of biomass to a mixed alcohol, more energy from the biomass will end up as liquid fuels than in converting biomass into ethanol by yeast fermentation. The process involves a biological/chemical method for converting any biodegradable material (e.g., urban wastes, such as municipal solid waste, biodegradable, and sewage sludge, agricultural residues

such as corn stover, sugarcane bagasse, cotton gin trash, manure) into useful chemicals, such as carboxylic acids (e.g., acetic, propionic, butyric acid), ketones (e.g., acetone, methyl ethyl ketone, diethyl ketone) and biofuels, such as a mixture of primary alcohols (e.g., ethanol, propanol, *n*-butanol) and/or a mixture of secondary alcohols (e.g., isopropanol, 2-butanol, 3-pentanol). Because of the many products that can be economically produced, this process is a true biorefinery.

2.10 Biodiesel

Another form of liquid fuel from biomass is “biodiesel”, which is derived from the vegetable oils extracted by crushing oilseeds, although waste cooking oil or animal fats (tallow) can also be used. The oil is strained and usually “esterified”, by combining the fatty acid molecules in the oil with methanol or ethanol. Vegetable oil esters have been shown to make good-quality clean-burning diesel fuel.

The use of vegetable oils for combustion in diesel engines has occurred for over 100 years. In fact, Rudolf Diesel tested his first prototype on vegetable oils, which can be used, “raw”, in an emergency. While 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. Perennials include oil palms, coconut palms, physica nut and Chinese tallow tree. Annuals include sunflower, groundnut, soybean and rapeseed. Many of these plants can produce high yields of oil, with positive energy and carbon balances. Transformation of the raw oil is necessary to avoid problems associated with variations in feedstock. The oil can undergo thermal or catalytic cracking, Kolbe electrolysis, or transesterification processes in order to obtain better characteristics. Untreated oil causes problems through incomplete combustion, resulting in the buildup of sooty residues, waxes, gums, etc.

Biodiesel refers to a vegetable oil- or animal fat-based diesel fuel consisting of long-chain alkyl (methyl, propyl or ethyl) esters. Biodiesel is typically made by chemically reacting lipids (e.g., vegetable oil, animal fat (tallow)) with an alcohol. Biodiesel is meant to be used in standard diesel engines and is thus distinct from the vegetable and waste oils used to fuel *converted* diesel engines. Biodiesel can be used alone, or blended with petrodiesel.

Blends of biodiesel and conventional hydrocarbon-based diesel products are most commonly distributed for use in the retail diesel fuel marketplace. Much of the world uses a system known as the “B” factor to state the amount of biodiesel in any fuel mix:

- 100% biodiesel is referred to as **B100**, while
- 20% biodiesel is labeled **B20**
- 5% biodiesel is labeled **B5**
- 2% biodiesel is labeled **B2**.

Obviously, the higher the percentage of biodiesel, the more ecology-friendly the fuel is. Blends of 20% biodiesel with 80% petroleum diesel (B20) can generally be used in unmodified diesel engines. Biodiesel can also be used in its pure form (B100), but may require certain engine modifications to avoid maintenance and performance problems. Blending B100 with petroleum diesel may be accomplished by:

- Mixing in tanks at manufacturing point prior to delivery to tanker truck.
- Splash mixing in the tanker truck (adding specific percentages of biodiesel and petroleum diesel).
- In-line mixing, two components arrive at tanker truck simultaneously.
- Metered pump mixing, petroleum diesel and biodiesel meters are set to X total volume, transfer pump pulls from two points and mix is complete on leaving pump.

There is ongoing research into finding more suitable crops and improving oil yield. Using the current yields, vast amounts of land and fresh water would be needed to produce enough oil to completely replace fossil fuel usage. It would require twice the land area of the US to be devoted to soybean production, or two-thirds to be devoted to rapeseed production, to meet the current US heating and transportation needs. Specially bred mustard varieties can produce reasonably high oil yields and are very useful in crop rotation with cereals, and have the added benefit that the meal leftover after the oil has been pressed out can act as an effective and biodegradable pesticide.

It was experimented with using algae as a biodiesel source and it was found that these oil-rich algae can be processed into biodiesel, with the dried remainder further reprocessed to create ethanol. In addition to its projected high yield, algaculture—unlike crop-based biofuels—does not entail a decrease in food production, since it requires neither farmland nor fresh water. Many companies are pursuing algae bio-reactors for various purposes, including scaling up biodiesel production to commercial levels.

2.11 First-Generation Versus Second-Generation Technologies

First-generation technologies are well established, these include transesterification of plant oils, fermentation of plant sugars and starch for liquid biofuel production, anaerobic fermentation of organic residues to generate biogas, combustion of organic materials for heat recovery or combined heat and power (CHP) systems for the production of both heat and electrical power. Second-generation or advanced technologies often refer to the conversion of lignocellulose materials into fuels. These technologies comprise a range of alternatives such as enzymatic production of lignocellulose ethanol, syngas-based fuels, pyrolysis-oil based biofuels, gasification and others, but are not yet economically viable and technical aspects are still under development.

Much attention is currently focused on the production of liquid biofuels that are manufactured with first-generation technologies because they rely on feedstocks derived from food-crops, the so-called first-generation biofuel. Thus, this has heightened the needs to identify and work on agronomic potential of alternative bioenergy crops including non-edible oil crops such as jatropha, castor bean, jojoba, karanja that can be grown on land unsuitable for food crops and multi-purpose crops like sweet sorghum that can yield food in the form of grain, fuel in the form of ethanol from its stem juice, and fodder from its leaves and bagasse.

Deployment of second-generation technologies offers an opportunity to expand the type of feedstock and to take advantage of currently unused lignocellulose sources. It also facilitates the use of energy crops that can be grown on land unsuitable for food crops. These technologies offer a more efficient production making use of the entire plant beyond the carbohydrate component. Further research and development on bioenergy conversion technologies is required to overcome the technical barriers for them to become a viable option.

2.12 Conclusion

Various technology options are available from biomass which can serve many different energy needs from large-scale industrial applications to small-scale, rural end uses. Different types of solid, liquid or gaseous fuels exist in bioenergy. Such fuels can be utilized in transportation and also in engine and turbine electrical power generation. Chemical products can also be obtained from all organic matter produced. There are various conversion technologies that can convert biomass resources into power, heat and fuels for potential use. Biorefinery integrates biomass conversion processes and equipment to produce fuels, power and value-added chemicals from biomass.

First-generation biofuels can be derived from sources such as starch, sugar, animal fats and vegetable oil and can be produced through well-known processes such as cold pressing/extraction, transesterification, hydrolysis and fermentation, and chemical synthesis. The most popular types of first-generation biofuels are biodiesel, vegetable oil, bioethanol and biogas. Second-generation biofuels are not yet commercial on a large scale as their conversion technologies are still in the research and/or development stage. Second-generation biofuels are produced through more advanced processes, including hydro treatment, advanced hydrolysis and fermentation, and gasification and synthesis. A wide range of feedstocks can be used in the production of these biofuels, including lignocellulosic sources such as short-rotation woody crops. These produce biodiesel, bioethanol, synthetic fuels and bio-hydrogen.

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