INTRODUCTION

- Any material that can be burned to release thermal energy is called a conventional fuel, which consists primarily of hydrogen (H) and carbon (C). They are referred to as hydrocarbon fuels.
- They are denoted by the general formula CnHm. Hydrocarbon fuels exist in all phases, namely coal, petrol and natural gas. The main constituent of coal is carbon. Coal also contains oxygen, hydrogen, nitrogen, sulfur, moisture and ash.
- Most liquid hydrocarbon fuels are a mixture of various hydrocarbons namely petrol, kerosene, diesel fuel, fuel oil, etc. These are obtained from crude oil by distillation.
- The liquid hydrocarbon fuels are mixtures of different hydrocarbons, which are usually considered to be a single hydrocarbon. For example, petrol and diesel fuels are treated as octane (C8H18) and dodecane (C12H26), respectively.
- The gaseous hydrocarbon fuel, which is a natural gas, is a mixture of methane (CH4) and smaller amounts of other gases. It is produced from gas/oil wells.
- Liquefied petroleum gas (LPG) is a byproduct of natural gas processing or crude oil refining. LPG consists of mainly propane (over 90%). Thus, it is usually referred to as propane. However, it also contains various amounts of butane, propylene and butylenes.

- All petroleum-based fuels are the major sources of air pollutants such as nitric oxides (NO), carbon monoxide (CO) and the greenhouse gas (GHG), carbon dioxide (CO2), when they are used in vehicles.
- Hence, there is currently a shift in the transportation industry from commercial petroleum-based conventional fuels (petrol and diesel) to the cleaner burning alternative fuels (natural gas, alcohols, ethanol and methanol) which are friendly to the environment.
- Due to the limited sources of natural gas, researchers have to explore the appropriate renewable source of energy as the fuel for sustainability and pollution-free characteristics with the natural ecology.
- One such natural resource is biomass. Biofuels are produced through the chemical or biological processes from biomass.
- The term biomass generally refers to renewable organic matter generated by plants through photosynthesis. The solar energy combines the carbon dioxide and water to form carbohydrate and oxygen in photosynthesis.
- Materials having combustible organic matter are also referred to as biomass. It contains C, H and O. It is the oxygenated hydrocarbon.
- Biomass includes forest and mill residues, agricultural crops and wastes, wood and wood wastes, animal wastes, livestock operation residues, aquatic plants, municipal and industrial wastes.
- Fossil fuels can also be referred to as biomass, since they are the fossilised remains of plants.

- Wood was initially the primary biomass fuel for humans. The goal of many biomass conversion processes is to convert solid fuel into more useful forms, i.e. gaseous or liquid fuels. Examples are

(i) conversion of biomass to gaseous fuels include anaerobic digestion of wet biomass to produce methane gas

(ii) high-temperature gasification of dry biomass to produce a flammable gas mixture of hydrogen, carbon monoxide and methane

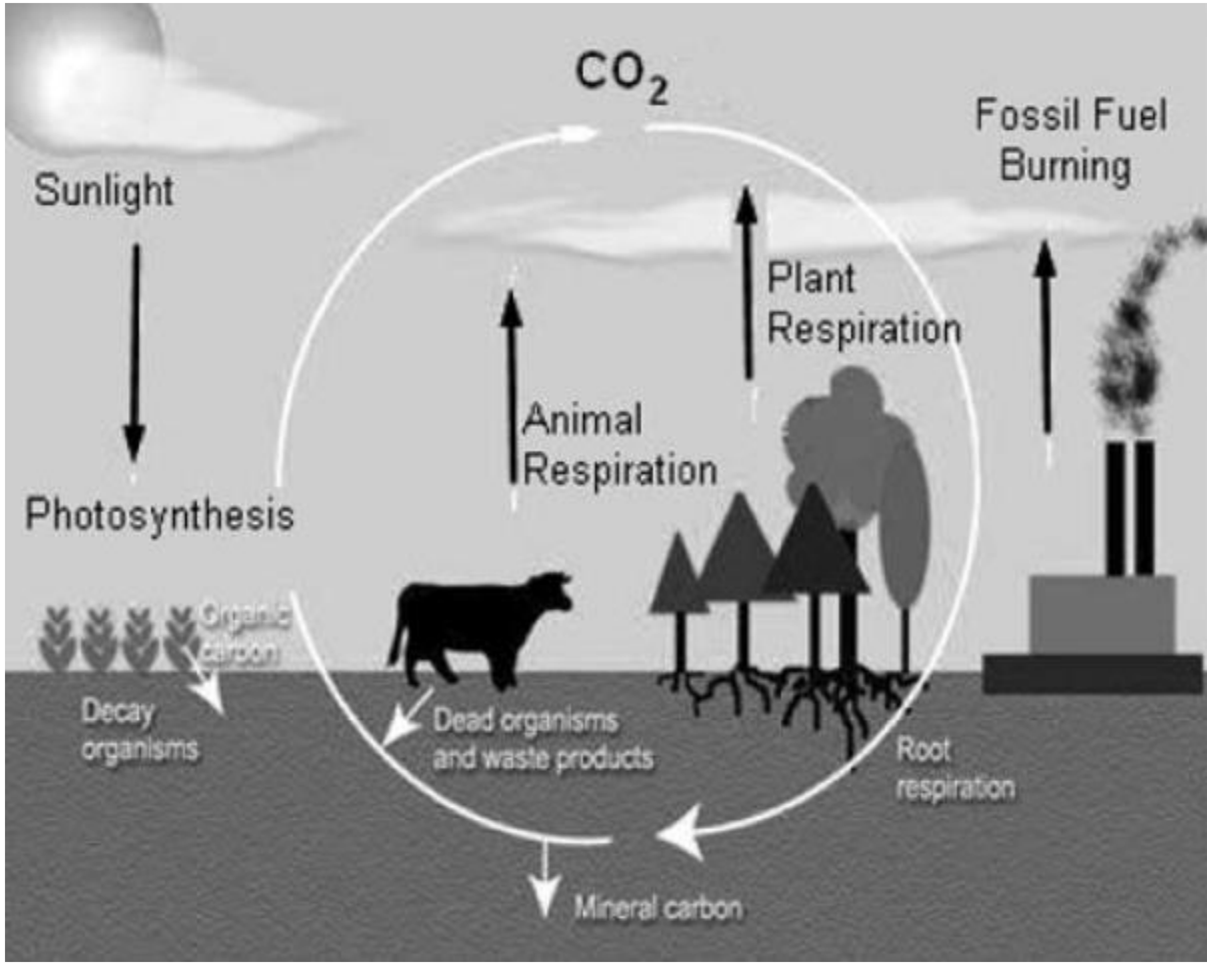
(iii) fermentation of sugars to ethanol, thermochemical conversion of biomass to pyrolysis oils

(iv) processing of vegetable oils to biodiesel

- Biomass is a versatile resource of energy that is expressed in what is termed mixed 'f ' fields, namely food, feed, fuel, feedstock, fibre and fertiliser. These form the essential ingredients for our survival.
- The broad spectrum of natural vegetation and residual deposits from human and animal activities constitute the major sources of biomass. The term "biomass" is therefore related to the quantity of all living matter from the five kingdoms in biology namely plants, animals, fungi, bacteria and algae.
- All the five kingdoms of life are in a renewable manner. Photosynthesis can occur in algae and bacteria as well as in plants.
- The term "Bio" is derived from bios (Greek word) meaning life.
- Biomass is a highly diverse and complex resource. It has to be studied in a wholly holistic context with recognition of the interdependencies in the overall system of land, water, nutrients.

BIOMASS RENEWABILITY

- The term ‘‘renewable’’ is defined as a material that can be restored when its initial stock is exhausted. In nature, biomass is formed by the process of inorganic material molecules (mainly chlorophyll) splitting water in organic cells (photolysis) in the presence of solar energy. The originating hydrogen along with carbon dioxide in the air forms the biomass (component of the carbon dioxide loop) as shown in Figure
- The energy source that causes the renewal of biomass is the Sun, which is renewable in nature.
- biomass is also considered as a form of stored solar energy.
- If the biomass is not burned, it still releases carbon into the environment by decaying.



BIOMASS SUSTAINABILITY

- About 2/3 of the Earth's population is virtually dependent on biomass for their cooking and heating. Most of these people live in rural areas. Therefore, it is a fuel used in domestic sector in nearly every corner of the developing world as a source of heat.
- Biomass energy includes energy from all plant matter (trees, shrubs, and crops) and animal dung.
- It balances the environment, the economy and the social equality. Developing countries as a whole derive 35% of their energy from biomass.
- To make the biomass more sustainable, it must at least keep pace with use. The dry mass of biological material cycling is about 250×10^9 t/year in the biosphere, which includes about 100×10^9 t /year of carbon. The associated energy bound in photosynthesis is 2×10^21 J/year (0.7×10^14 W).
- Of this, about 0.5% by weight is biomass that is used for human food. The remaining biomass needs to be used efficiently and effectively for sustainable production of energy in the form of biofuels to meet the global energy requirements.
- It needs to be efficiently and cost effectively converted into modern energy carriers to play a major part in the global energy economy.

- Bioenergy sources such as producer-gas system do not require electricity storage and offer an opportunity for sustainable (as biomass can be grown sustainably), self reliant and equitable development.
- The word ‘‘sustain’’ is derived from the Latin sustinere (sus – from below and tenere – to hold). It defines to keep in existence or to maintain and implies long-term support or permanence.
- As the word ‘‘sustainability’’ pertains to biomass, it describes biomass or bioenergy systems that are capable of maintaining their productivity and usefulness to the society indefinitely. It should be environmentally sound.
- The word ‘‘sustainability’’ is also the characteristic of a process or state that can be maintained indefinitely. Hence, biomass is referred as the sustainable energy that can be replenished within a human lifetime.

ORIGIN OF BIOMASS: THE PHOTOSYNTHETIC PROCESS

- Photosynthesis refers to a chemical reaction occurring on the Earth between sunlight and green plants within the plants in the form of chemical energy. Photo means light and synthesis means the making. In the photosynthesis process, solar energy is absorbed by green plants and some microorganisms to synthesize organic compounds from low energy carbon dioxide (CO2) and water (H2O). The organic compounds formed are simply

(i) the biomass, which is a renewable energy source due to its natural and repeated occurrence in the environment in the presence of sunlight

(ii) It is this same photosynthesis that converted the Sun's energy into living organisms millions of years ago to provide the fossil fuels that we are using today

- The Sun is the primary source of energy for all living organisms on the Earth. This energy reaching the Earth from the Sun is electromagnetic radiation with a spectrum from about 0.3 to 3 μm in wavelength. This corresponds to the radiation from the near ultraviolet (UV) through the visible and into the infrared (IR). The energy association with a quantum of light (photon) is *hv* where h is Planck's constant and *v is* the frequency of the light. The photons driving the process are mostly from the red end of the visible spectrum where the energy per photon is 1.7 eV.

The energy of a photon (*hv*) in the ultraviolet portion of the solar spectrum is sufficient to break a chemical bond. A photon in the visible portion of the spectrum has sufficient energy to raise an atom to an excited state. The excited atomic state may make it possible for bonding to take place with a neighbouring atom. This is the way that photochemical reactions precede. In photosynthetic process sunlight interacts with the molecules of water and carbon dioxide to form carbohydrates as shown in the following equations

$$CO_2 + 2H_2\dot{O} \xrightarrow{light} CH_2O + H_2O + CO_2 + \dot{O}_2 \qquad (4.4)$$

In the above equation, 112 kcal of light energy is needed per mole of CH_2O formed. A mole (1 gram molecular weight) is the weight in grams equal to the molecular weight. For example, the mass number of oxygen (O) is 16, so the mass number of the oxygen molecule (O_2) is 32 (16 times 2). Hence, 1 mole of O_2 is 32 g. It also contains Avogadro's number (6.023×10^{23}) of molecules. The oxygen atoms initially in CO_2 and H_2O are to be distinguished.

The general formulae of the organic material produced during photosynthesis process is $(CH_2O)_n$ which is mainly carbohydrate. Some of the simple carbohydrates involved in this process are glucose ($C_6H_{12}O_6$) and sucrose ($C_{12}H_{22}O_{11}$). The sugars, glucose and fructose are simple carbohydrates. The photosynthetic reaction leading to glucose is

$$6CO_2 + 6H_2\dot{O} \xrightarrow{light} C_6H_{12}O_6 + 6CO_2 + 6\dot{O}_2 \tag{4.5}$$

In the above equation, 672 kcal of light energy is needed to form a mole of glucose. This reaction does not occur in a single step but requires several steps in which the various components of the sugar molecule enter into the reaction.

Photosynthesis is a two-stage process:

(i) **Light reactions:** The first step in the light dependent process requires the direct energy of light to make energy-carrier molecules that are used in the second phase (Eqs. (4.4) and (4.5)). In light reactions, light strikes chlorophyll in such a way as to excite electrons to a higher energy state. In a series of reactions, the energy is converted (along an electron transport process) into energy rich adenosine triphosphate (ATP) and a strong reducing agent nicotinamide adenine dinucleotide phosphate (NADPH). Water is split in the process, releasing oxygen as a byproduct of the reaction.

(ii) **Dark reactions:** The light independent process occurs when the products of the light reactions are used to form C–C covalent bonds of carbohydrates. This usually occurs in the dark if the energy carriers from the light reaction process are present. These reactions take place in the stroma of the chloroplasts. The ATP and NADPH are used to make C–C bonds in dark reactions. In dark reactions, carbon dioxide from the atmosphere is captured and modified by the addition of hydrogen to form carbohydrate. The incorporation of inorganic carbon dioxide into organic compounds is known as carbon fixation. The energy for this comes from the first phase of the photosynthesis process.

Human beings depend on the chemical energy (food) formed by the plants (biomass) during the photosynthesis process. When we eat food, our body oxidises or burns the carbohydrate with oxygen from the air. One of the carbohydrates resulting from photosynthesis is cellulose, which makes up the bulk of wood and other plant materials. When wood is burnt, the cellulose is converted into carbon dioxide and stored energy is released as heat. Thus, biomass is referred to as biofuels. Burning fuel is basically the same oxidation process that occurs in our body, Hence, the stored solar energy is released in the form of chemical energy in a useful form and releases carbon dioxide to the atmosphere.

The amount of biomass that can be grown certainly depends on the availability of sunlight to drive the conversion of CO_2 and H_2O into carbohydrates ((CH_2O), Eqs. (4.4) and (4.5)). In addition to limitations of sunlight, there is a limit placed by the availability of appropriate land, temperature, climate and nutrients namely nitrogen, phosphorus and trace minerals in the soil. Plant diseases and insects also affect photosynthesis.

Let us examine the overall efficiency with which biomass can be produced from sunlight. The average solar energy per unit horizontal area and time in extraterrestrial region is about 0.5 cal/min cm^2 (Example 4.2). For the purposes of evaluating plant production, it is easier to determine the number of calories in a day per square centimeter. It is assumed that 47% of the solar energy incident on the atmosphere (Figure 4.2) reaches the ground.

The energy available for food production (biomass)

$$= 0.5\frac{\text{cal}}{\text{min}\cdot\text{cm}^2} \times (0.47) \times \frac{60\text{ min}}{1\text{ hr}} \times \frac{24\text{ hr}}{1\text{ day}} = 338\frac{\text{cal}}{\text{cm}^2\text{day}}(1420\text{ J/cm}^2\text{day}) \tag{4.6}$$

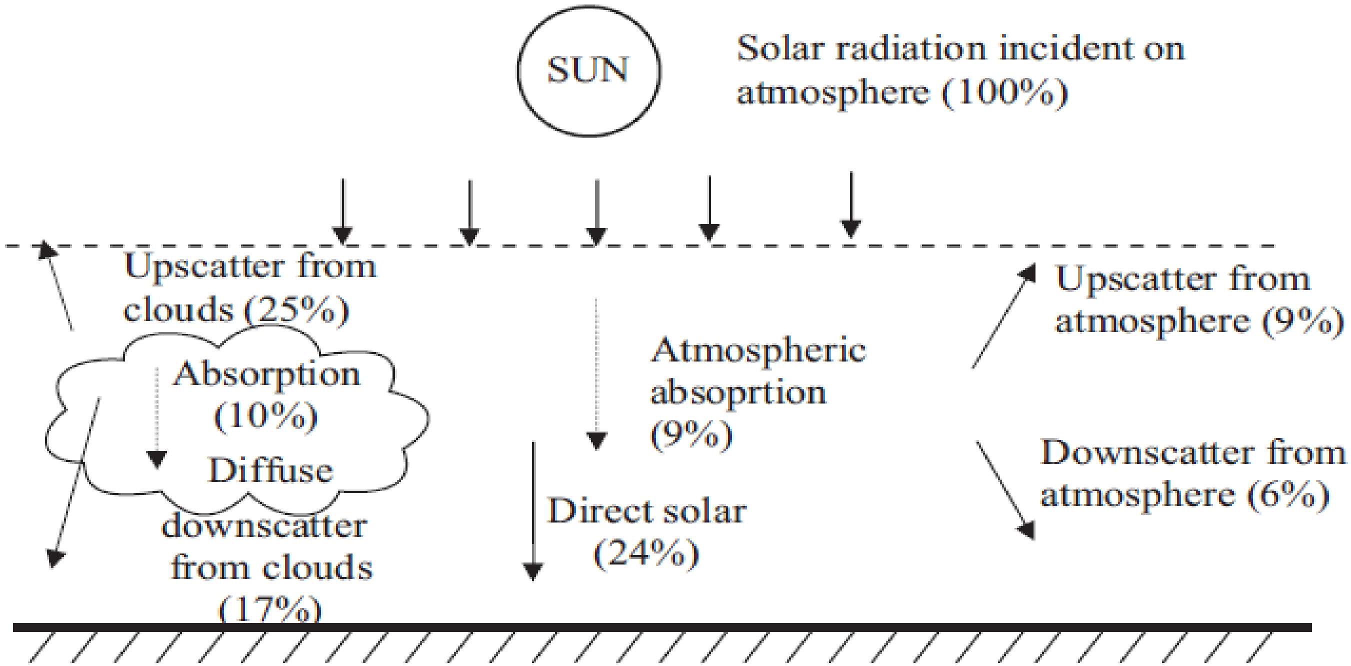
For a typical summer day, the value of solar energy = 500 to 700 cal/cm^2 day. The overall efficiency of photosynthesis is as follows:

(i) Plants use visible light (0.4–0.7 μm); 50% of the solar spectrum.
(ii) Chloroplasts absorb; 80%
(iii) Theoretical photon to glucose efficiency for absorption process; 35% (8 hf for each CO_2)
(iv) Dark respiration (metabolism) uses 50%; 50% (remaining)

By taking all of these factors into account,

$$\text{The overall efficiency} = 0.5 \times 0.8 \times 0.35 \times 0.5 \times 100 = 7\%$$

The amount of energy stored per carbohydrate unit synthesised is about 5 eV.



If an energy content of 3744 cal/g with the dry biomass production resulting from photosynthesis is assumed then

$$\text{The biomass production per year} = 120 \times 10^{12}\,\frac{\text{J}}{\text{s}} \times \frac{1\,\text{cal}}{4.18\,\text{J}} \times \frac{3.15 \times 10^{7}\,\text{s}}{\text{year}} \times \frac{1\,\text{g}}{3744\,\text{cal}}$$

$$= 24 \times \frac{10^{16}\ \text{g}}{\text{year}} \approx 250 \times 10^{19}\ ty^{-1} \qquad (4.8)$$

BIOMASS CHARACTERISTICS

- The main components of biomass material are as follows (i) lignin (ii) hemicelluloses (iii) cellulose (iv) mineral matter and (v) ash.
- Wood is a solid lignocellulosic material naturally produced in trees and some shrubs. It is made up of 40–50% cellulose, 20–30% hemicelluloses and 20–30% lignin. The percentage of the abovementioned components of biomass varies from species to species.
- Evaluation of biomass resources requires information about their composition, i.e. heating value, production yields (in the case of energy crops) and bulk density.
- Compositional information can be reported in terms of (i) biochemical analysis, (ii) proximate analysis and (iii) ultimate analysis.

1. Biochemical Analysis

- Biochemical analysis describes the kinds and amounts of plant chemicals as proteins, oils, sugar, starches and lignocelluloses (fibre).
- Engineers are particularly interested in the lignocellulosic component and how it is partitioned among cellulose, hemicellulose and lignin in the case of energy crops.
- This information is particularly useful in designing biological processes that convert plant chemicals into liquid fuels.
- Energy crops are defined as plants grown specifically as an energy resource. Cellulose is the carbohydrate and it is the principal constituent of wood. It forms the structural framework of the wood cells. It is a polymer of glucose with a repeating unit of $C6H10O5$.
- Hemicellulose consists of short, highly branched chains of sugars. In contrast to cellulose, a hemicellulose is a polymer of five different sugars.
- Lignin is the major noncarbohydrate constituent of wood. Lignocellulose refers to plant materials made up primarily of lignin, cellulose and hemicelluloses. Herbaceous plants are generally nonwoody species of vegetation, usually of low lignin content such as grasses.

Table 4.1a Biochemical composition of cellulosic biomass (dry basis).[1]

Feedstock	*Cellulose*	*Hemicellulose*	*Lignin*	*Others**
Bagasse	35	25	20	20
Com cobs	32	44	13	11
Wheat straw	38	36	16	10
Short-rotation woody crops	50	23	22	5
Herbaceous energy crops	45	30	15	10
Waste paper	76	13	11	0

Table 4.1b Biochemical composition of starch and sugar biomass (dry basis).[2]

Feedstock	*Protein*	*Oil*	*Starch*	*Sugar*	*Fibre*
Corn grain	10	5	20	<1	13
Wheat grain	14	<1	13	<1	5
Sugar cane	<1	<1	<1	50	50
Sweet sorghum	<1	<1	<1	50	50

2. Proximate Analysis

- Proximate analysis is important in developing thermochemical conversion processes for biomass.
- Proximate analysis reports the yields (% mass basis) of various products obtained upon heating the material under controlled conditions in presence of air.
- These products consist of moisture, volatile matter, fixed carbon and ash. The proximate analysis of biomass is commonly reported on a dry basis.
- Volatile matter is the fraction of biomass. It decomposes and escapes as gases upon heating a sample at moderate temperatures (about 400 C) in an inert environment.
- Knowledge of volatile material is important in designing burners and gasifiers for biomass. The remaining fraction is a mixture of fixed carbon and ash.
- It can be distinguished by further heating the sample in the presence of oxygen. The carbon is converted to carbon dioxide, leaving only the ash.
- It is to be noted that the relatively high volatile content of biomass, (50–75%) compared to coal (typically less than 25%) makes biomass very suitable for gasification.

3. Ultimate Analysis

- Biomass also contains negligible amounts of nitrogen and sulfur.
- The heating value is the net energy released upon reaction of a particular fuel with oxygen under isothermal conditions. If the water vapours, formed during reaction, condense at the end of the process, the latent heat of condensation is known as the higher heating value (HHV).
- If latent heat does not contribute, then the lower heating value (LHV) is considered. These measurements are typically performed in a bomb calorimeter and then higher heating values (HHV) of the biofuels are recorded.
- Heating values of biomass/biofuels are important in performing energy balances on a biomass conversion process. Bulk density is determined by weighing a known volume of biomass that is packed or baled in the form anticipated for its transportation or use.
- Clearly, solid logs have higher bulk density than the same wood chipped. Bulk density is an important determinant of transportation costs and the size of fuel storage and handling equipments.
- Volumetric energy content is also important in transportation and storage issues. The cost of collecting large quantities of biomass is significant.
- Wood or other biomass resources must generally be produced within no more than a 50-mile radius of the power plant for economical viability due to the high transportation costs and low densities of biomass.

Table 4.2 Proximate analysis of some biomass.[3]

Proximate analysis (%)	*Coal*	*Sawdust*	*Groundnut*	*Rice Husk*
Moisture	5	10–20	–	10
Volatile matter	25	50–70	73.3	55
Fixed carbon	30	20–25	22.9	15
Ash	40	1–3	3.8	20

Table 4.3 Ultimate analysis of some biomass.[3]

Feedstock	*C(%)*	*H(%)*	*N(%)*	*O(%)*	*Ash(%)*
Wood	44–52	5–7	0.5–0.9	40–48	1–3
Rice husk	37	5.5	0.5	37	20
Bagasse	47	6.5	0.0	42.5	4
Groundnut shell	34–45	2–4.6	1.1–1.4	43–60	3–5

Table 4.4 Alkali content of biomass.[4]

Feedstock	*Heating values (MJ/kg)*	*Ash in Fuel (%)*	*Alkali in ash (%)*
Hybrid poplar	19.0	1.9	19.8
Pine chips	19.9	0.7	3.0
Tree trimming	18.9	3.6	16.5
Urban wood waste	19.0	6.0	6.2
White oak	19.0	0.4	31.8
Almond shell	17.6	3.5	21.1
Bagasse (washed)	19.1	1.7	12.3
Rice straw	15.1	18.7	13.3
Switch grass	18.0	10.1	15.1
Wheat straw	18.5	5.1	31.5

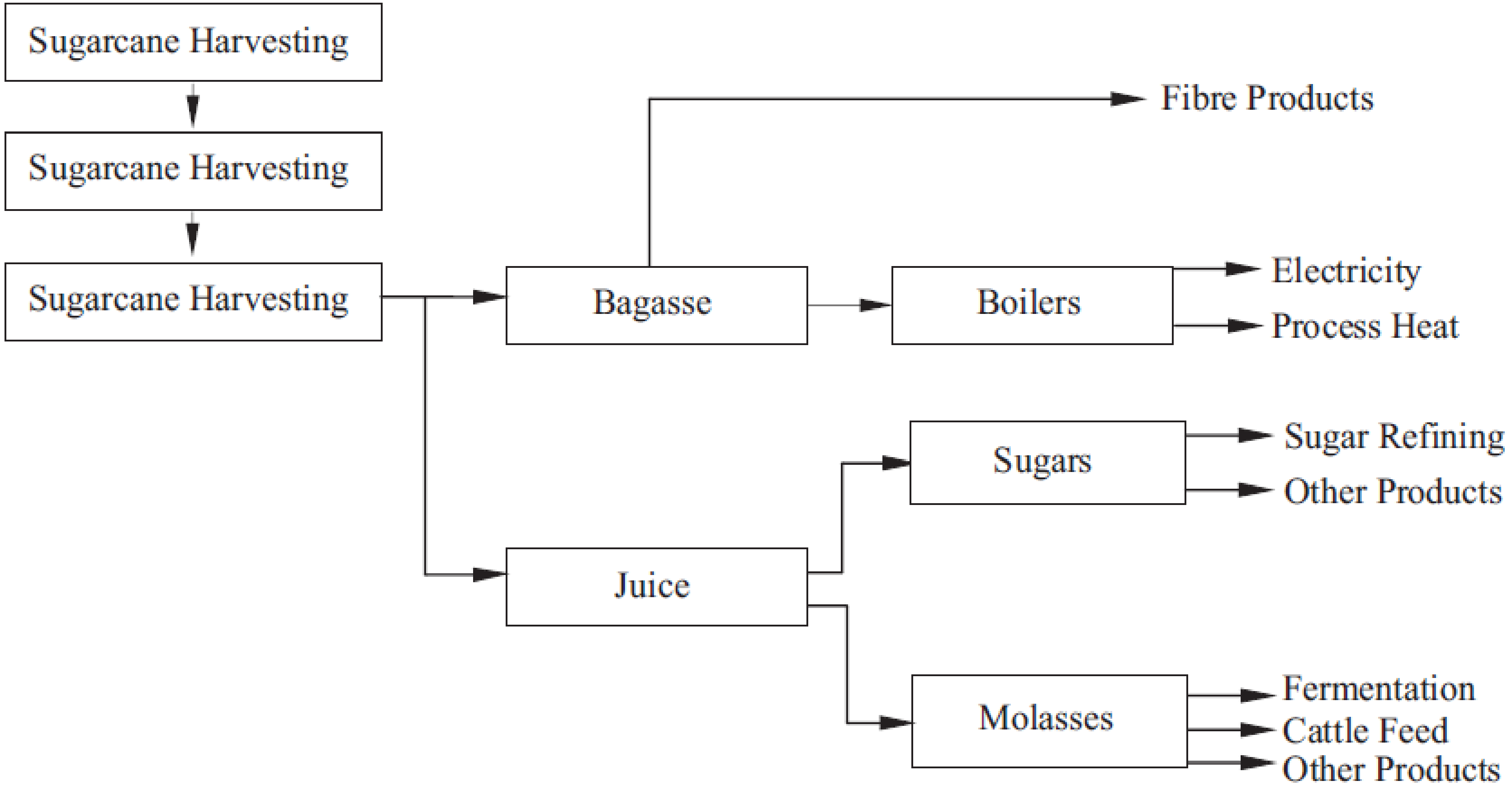
Table 4.5 Density and volumetric energy content of various solid and liquid fuels.[5]

Fuel	*Density (kg/m^3)*	*Volumetric energy content (GJ/m^3)*
Ethanol	790	23.5
Methanol	790	17.6
Biodiesel	900	35.6
Pyrolysis oil	1280	10.6
Petrol	740	35.7
Diesel fuel	850	39.1
Agricultural residues	50–200	0.8–3.6
Wood	160–400	3–9
Coal	600–900	11–33

ENERGY FARMING

- Energy farming is defined as the production of crops to be used as fuels or energy as a main or subsidiary product of (i) agriculture (fields), (ii) silviculture (forests) and (iii) aquaculture (fresh and sea water).
- The crops grown are called energy crops in the energy-farming system. It is to be noted that wood obtained from an old-growth forest does not constitute an energy crop.
- An energy crop is planted and harvested periodically. Harvesting may occur on an annual basis. The cycle of planting and harvesting over a relatively short time assures that the resource is used in a sustainable fashion.
- Energy crops can fulfil one or more market values. The grown plant may also be used as feedstock for production of electricity or liquid fuels, or both. Such is the case when trees are grown and harvested specifically as boiler fuel for steam power plants
- For example, alfalfa is being evaluated for its potential to yield both energy and feed from a single crop. The high protein leaves are removed after harvesting and it is processed into animal feed, while the fibrous stems are used as fuel for gasification of power plants.

- Milling sugarcane extracts sugar for fermentation to ethanol and discards the rest of the plant material (known as bagasse). It is an example of a conversion process that is wasteful of biomass resource. A better strategy for utilising this resource is to extract the sugar as food and to utilise bagasse for electricity generation



Factors Affecting Yields from Energy Farming

- The yield of a plant is directly related to the soil composition, inputs (fertiliser) and irrigation (water transmission efficiency).
- Other parameters that affect the yield are (i) tree species (ii) range of soil (iii) spacing and tree density (iv) management practices (v) weeding and fertiliser timings.
- Another important factor is the utilisation of the land sources.
- Water supply, nutrient supply and temperature control are the other fundamental aspects to be given importance. Fast growing and high yielding varieties should also be introduced.
- Thus, for large-scale renewable energy farming, technological and managerial skills are needed to maximise energy capture.

Advantages of Energy Farming

- (i) storage of solar energy in chemical energy form;
- (ii) large potential supply (for transport fuel and electricity generation);
- (iii) linked with established agriculture and forestry;
- (iv) encourages integrated farming practice to farmers;
- (v) efficient uses of byproducts, residues and wastes for power generation through gasification
- required;
- (vi) environmental improvement by reducing the level of carbon dioxide;
- (vii) establishes agroindustry that may include full range of technical tasks and processes, for skilled and trained personnel.

Disadvantages

- (i) may lead to soil infertility and erosion;
- (ii) may compete with food production;
- (iii) due to low energy density, large land requirements, transport and storage problems become uneconomical;
- (iv) large-scale agroindustry may be too complex for efficient operation;
- (v) poorly designed and incompletely integrated systems may produce pollution of water and air.

BIOFUEL PRODUCTION PROCESSES