# <u>Sciences and Technology of Bioenergy</u>

Biomass offers the world tremendous opportunities for use as domestic and sustainable resources to provide our fuel and power. The term "biomass" means any organic matter available on a renewable basis. The energy derived from biomass is known as bioenergy (US Department of Energy).

Biomass is material derived from recently living organisms, for example, dedicated energy crops and trees, agricultural crop wastes and residues, wood wastes and residues, and aquatic plants as well as animal, municipal, and other wastes. Biomass is a renewable resource since it stores energy from sunlight through a process known as photosynthesis.

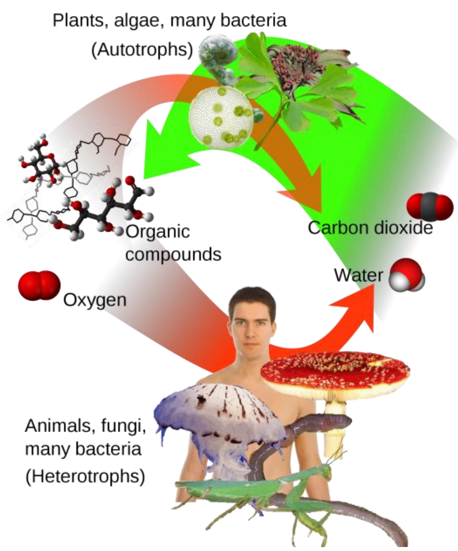
## Bioenergy and Biology

Photosynthesis occurs in plants, algae and many species of bacteria. It converts carbon dioxide into organic compound, especially sugar, using the energy from sunlight, releasing oxygen as a by-product. The overall chemical reaction for the type of photosynthesis is as follows:

$$6CO_2 + 6H_2O = C_6H_{12}O_6 + 6O_2$$

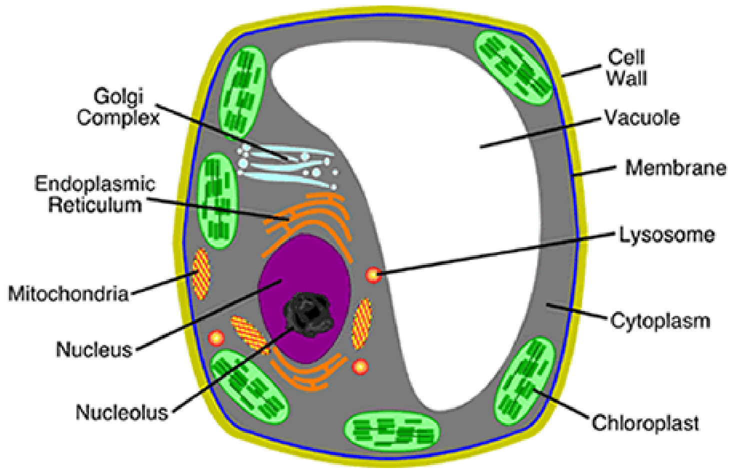
where $C_6H_{12}O_6$ is molecular formula of sugar.

Photosynthesis is the basis of life on earth, as shown in the following figure.




Renewable energy is what we can harvest from the natural process of vegetation or animal life.

The majority of available bioenergy sources are from plant matters. Thus, we will use plant cell to illustrate where and how energy is stored in living organism.




Besides small amount of oil and protein, the most relevant nutrient from a plant matter is sugar and starch stored in plant cells. Plants consume some of the nutrients for growing and sustaining their biological activities including reproduction. The other major part of energy is stored in cell walls as a structural component for plants to stand tall. For example, the major compounds that make up wood include cellulose, hemicellulose, and lignin. The stored nutrients may be converted to various forms of useful energy, such as ethanol as a liquid fuel.

**Bioenergy and Chemistry**

Sugar (also known as glucose in chemistry) is a simple organic made of carbon, hydrogen and oxygen. A typical chemical formula for sugar is $C_6H_{12}O_6$. That is, sugar molecule is composed of six carbon atoms, 12 hydrogen atoms and six oxygen atoms.

A polymer is a compound that is composed of repeating units in its molecule. The repeating unit is generally referred to monomer. For example, starch is a polymer made of hundreds of glucose as repeating units in one molecule. It is produced in all plants as a major energy store in plants. The biopolymer composed of sugar is also known as polysaccharide in biochemistry. Starch is considered as a major storage polysaccharide.

Cellulose is an organic compound with the formula $(C_6H_{10}O_5)_n$, consisting of a linear chain of several hundred to over ten thousand linked simple sugar. It is the most common organic compound on Earth. About 33% of all plant matter is cellulose (the cellulose content of cotton is 90% and that of wood is 40–50%).

It is noted that a polymer has different properties than its monomers. For example, humans can digest sugar (glucose) but not cellulose directly. Certain animals can digest cellulose, because bacteria possessing the enzyme are present in their gut. The classic example is the termite.

Unlike cellulose, hemicellulose consists of shorter chains - 500-3,000 sugar units as opposed to 7,000 - 15,000 glucose molecules per polymer seen in cellulose. In addition, hemicellulose is a branched polymer, while cellulose is unbranched (atoms are arranged one by one in a linear fashion). Typically, a branched polymer is more difficult to be broken down by other agents than linear polymer.

The chemical structure of lignin has not been clearly defined yet. It is believed that it is a polymer consisting of $C_{10}H_{12}O_3$ as the main monomer. In plant cells, lignin crosslinks with other polymers, which is more difficult to break down by other agents such as bacteria than linear or branched polymers.

## Conversion Technology of Biomass to Energy

There are two major categories of processes to convert biomass to energy. One is biological and the other is thermal chemical process (White & Plaskett, 1981). Biological conversion include anaerobic digestion and ethanol fermentation. Thermal chemical conversion include pyrolysis and gasification.

## Anaerobic Digestion

During anaerobic digestion (also known as methane fermentation), organic matter is broken down to carbon dioxide ($CO_2$) and methane gas ($CH_4$) as a part of metabolic process for microbial organisms. The term "anaerobic" refers a process where oxygen is not present. Anaerobic digestion occurs in many ecosystems such as in sewage and organic waste digestors, landfills, aquatic sediments of lakes, marine systems, flooded soils, tundra, peat bogs, and marshes.

The anaerobic process involves many different kinds of interacting microbial species with bacteria as the main biological agents. (Sofer & Zaborsky, 1981) Under appropriate condition including temperature, those biological agents can degrade polysaccharides such as cellulose, hemicellulose, and starch. This breaking down is usually called hydrolysis in chemistry. It is believed that some anaerobic microorganisms generate hydrogen and acetate before other bacteria convert them into carbon dioxide and methane gas.

Lignin is not digestible in the anaerobic digestion. As a matter of fact, the amount of lignin in the cell wall affects the digestibility of cellulose and hemicellulose.

Methane is a very clean energy. But, its release to atmosphere acts 21 times stronger than carbon dioxide as a permanent green house gas (Gupta & Demirbas, 2010). Thus, it is important to capture methane gas released from landfills and utilize the energy. Anaerobic digestion has been used successfully to process sewage and animal waste including cattle manure.

## Ethanol Fermentation

The conversion of agricultural substrates into alcoholic drink is an ancient practice that certainly predates the science of microbiology, the chemistry of distillation, and the engineering of an ethanol fermentation plant. Nevertheless, the large scale production of ethanol ($C_2H_5OH$) from agricultural commodities for blending into the fuel infrastructure is a recent event.

The basic biochemistry of ethanol fermentation consists of a series of reactions that lead to the overall conversion (White & Plaskett, 1981):

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

The above fermentation process is dependent upon the conditions provided to microorganisms. When microorganisms grow on sugar in the presence of oxygen, they consume some nutrients and produce carbon dioxide and water as their metabolic waste products. Certain microorganisms such as yeasts are also able to grow without oxygen. During the anaerobic growth, the microorganisms produce ethanol as a part of their metabolic process. Thus, it is noted that control of the process condition is essential for the production of ethanol from organic matters.

A wide range of plant matters can be anaerobically metabolized by microorganisms to produce ethanol. These substrates may be derived from agricultural commodities such as corn, potato, sugar cane, sugar beet, grains, or other crops high in starch or sugar content. Fermentable substrates can also come from cellulosic materials such as wood, straw, or newspaper. Cellulosic materials are the largest carbohydrate reserve on earth. Those materials can serve as substrates for ethanol fermentation if properly pre-treated (Sofer & Zaborsky, 1981). Termites and rumens have the natural ability to digest cellulose.

**Pyrolysis and Gasification**

Pyrolysis and gasification are directly related to combustion, a process that humans have mastered at least 400,000 years ago (Bhanoo, 2011). Fire was considered the first major technology that enabled humans to evolve to what we are now, including our cooking and diet.

When sufficient oxygen is available, carbon in the plant will react with oxygen and produce carbon dioxide and heat (Pinto, Andre, & Gulyurtlu, 2009).

$$C + O_2 = CO_2 + \text{Heat}$$

The hydrogen in biomass will react with oxygen to produce steam and heat.

$$2H_2 + O_2 = 2H_2O + \text{Heat}$$

When the biomass is simply heated without any oxygen, pyrolysis occurs. During pyrolysis, the most obvious reaction is the loss of water from the molecular structure of the biomass, which results in biochar (mainly carbon).

$$C_{6n}(H_2O)_{5n} \rightarrow 6n\,C + 5n\,H_2O$$

Please note this loss of water happens at a higher temperature, which is different from drying biomass from the surface water.

At a high temperature, the carbon will react with water, as follows:

$$C + H_2O = CO + H_2$$

Other chemical reaction may also happen among CO, $H_2$ and $H_2O$, for example,

$$2CO + 2\,H_2 \leftrightarrow CH_4 + CO_2$$

$$C + 2\,H_2 \leftrightarrow C\,H_4$$

$$C + 2\,H_2O \leftrightarrow CO_2 + 2\,H_2$$

Please note the "↔ " above indicates that the chemical reaction may go either way depending upon the temperature and concentration of the gas components. Thus, the end results of pyrolysis will include biochar and various amounts of gases including CO, $CO_2$, $H_2$ and $CH_4$.

If we supply limited amount of oxygen in the process, the predominate products will be gases at a high temperature (for example, 800 - 1000 $^oC$ or 1472 - 1832 $^oF$). This process is known as gasification. Typical chemical reactions during gasification may include (Rajvanshi, 1986):

$$C + C\,O_2 = 2CO$$

This reaction is known as Boudouard reaction (Pinto, Andre, & Gulyurtlu, 2009).

$$C + H_2O = CO + H_2$$

This is known as primary water-gas reaction. Secondary water-gas reaction also takes place a follows (Pinto, Andre, & Gulyurtlu, 2009):

$$C + 2\,H_2O \leftrightarrow CO_2 + 2\,H_2$$

Another reaction, known as water-gas shift reaction takes place, as follows:

$$CO + H_2O = CO_2 + H_2$$

Methane gas may also be produced during gasification, as follows:

$$C + 2H_2 = CH_4$$

As a result of the biomass gasification, carbon monoxide (CO), hydrogen ($H_2$), and carbon dioxide ($CO_2$) are produced with a small amount of methane ($CH_4$). The CO, $H_2$ and $CH_4$ are combustible gases, which can be used to heat a boiler to generate steam or electricity. The gas generated from the gasification process is called syngas or producers gas. Using air as an oxygen supply, a typical syngas consists of 21% CO, 9.7%$CO_2$, 14.5%$H_2$, 4.8%$H_2O$, 1.6%$CH_4$ and 48.4%$N_2$ (Reed & Das, 1988).

In theory, the heat for pyrolysis or gasification may come from outside sources. In practice, many operations will involve partially combustng the biomass to generate the heat needed for gasification. As a matter of fact, combustion, pyrolysis and gasification may happen concurrently in a typical biomass gasifier. A process may be optimized for its intended purpose, either producing biochar or syngas.

**What else we can do besides burning CO and $H_2$ from gasification?**

Besides combustion to generate heat, syngas can be used as feedstock for many chemical processes. For example, methanol can be synthesized from CO and $H_2$, as follows (Basu, 2010):

$$CO + 2\ H_2(catalysts) = \ CH_3OH$$

Methanol ($CH_3OH$) is a basic building block of many products, including gasoline.

Hydrogen gas can also be combined with nitrogen from air to form ammonia ($CH_3$), as follows:

$$3\ H_2 + \ N_2\ (catalysts) = \ 2\ NH_3$$

This above process is usually known as ammonia synthesis. Ammonia ($NH_3$) is an important feedstock for fertilizer production.

A mixture of CO and $H_2$ can also synthesized into a range of hydrocarbons, including diesel oil. The general reaction is as follows:

$$(2n + 1)H_2 + \ nCO\ (catalysts) \rightarrow \ C_nH_{(2n+2)} + \ n\ H_2O$$

where $C_nH_{(2n+2)}$ represents a mixture of hydrocarbons ranging from methane gas, gasoline and wax. Their relative proportion depends on the catalysts used and other conditions such as temperature and pressure. The above process is known as Fischer-Tropsch reaction. The fuel produced using the process is also called Fischer-Tropsh fuel.

Postscript: This article was intended to provide students or researchers an overview of sciences related to bioenergy, written by a non-scientist. Some of the descriptions may not be exactly complete as expected from rigorous scientific journal. Reader discretion is advised.

## Works Cited

Basu, P. (2010). *Biomass Gasification and Pyrolysis: Practical Design and Theory.* Burlington, MA: Academic Press.

Bhanoo, S. N. (2011, March 14). *Humans' First Use of Fire May Not Be So Long Ago.* Retrieved March 16, 2011, from New York Times: http://www.nytimes.com/2011/03/15/science/15obfire.html?_r=1&pagewanted=print

Gupta, R. B., & Demirbas, A. (2010). *Gasoline, Diesel, and Ethnol Biofuels from Grasses and Plants.* New York, NY: Cambridge University Press.

Pinto, F., Andre, R. N., & Gulyurtlu, I. (2009). Innovation on biomass waste utilization through gasification and co-gasificaiton, stage of development and needs for futher r & d. In J.-P. Badeau, & A. Levi, *Biomass Gasification: Chemistry, Processes and Applications* (pp. 7-69). New York: Nova Science Publishers, Inc.

Rajvanshi, A. K. (1986). Biomass Gasification. In D. Y. Goswami, *Alternative Energy in Agriculture, vol. II* (pp. 83-102). Boca Raton, FL: CRC Press.

Reed, T. B., & Das, A. (1988). *Handbook of Biomass Downdraft Gasifier Engine Systems.* Golden, CO: Solar Energy Research Institute.

Sofer, S. S., & Zaborsky, O. R. (1981). *Biomass Conversion Processes for Energy and Fuels.* New York: Plenum Press.

US Department of Energy. (n.d.). *Bioenergy*. Retrieved March 4, 2011, from Department of Energy: http://www.energy.gov/energysources/bioenergy.htm

White, L. P., & Plaskett, L. G. (1981). *Biomass as Fuel.* London: Academic Press.