Fall Semester, 2011
Energy Engineering
에너지공학

Biomass

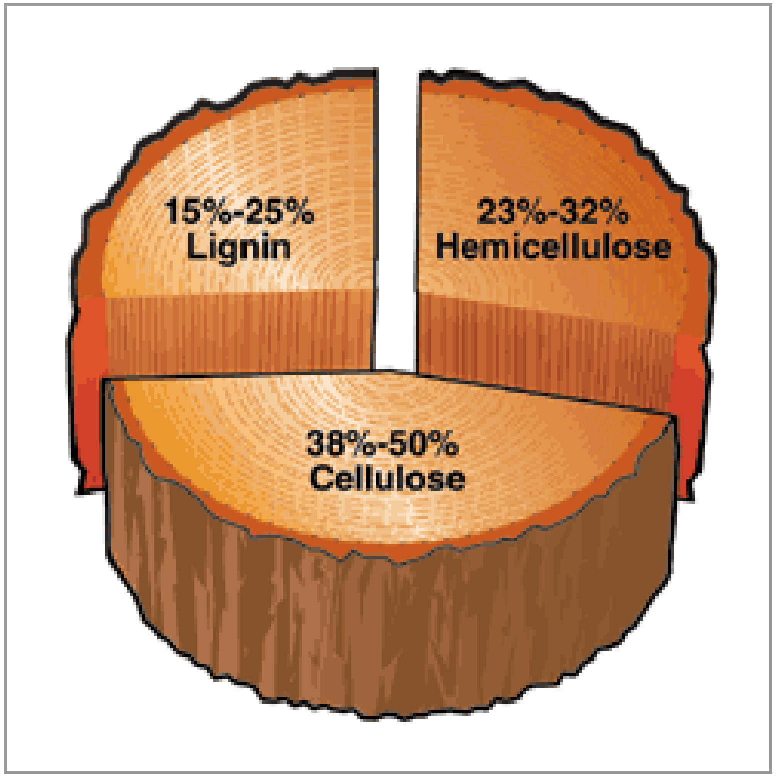
Biomass

Biomass is any organic material made from plants or animals. Domestic biomass resources include agricultural and forestry residues, municipal solid wastes, industrial wastes, and terrestrial and aquatic crops grown solely for energy purposes.

Biomass includes all plant and plant-derived material — essentially all energy originally captured by photosynthesis. This means that biomass is a fully renewable resource and that its use for biomass-derived fuels, power, chemicals, materials, or other products essentially generates no net greenhouse gas.

Sources of Biomass

Biomass energy or "bioenergy"—the energy from plants and plant-derived materials—since people began burning wood to cook food and keep warm. Wood is still the largest biomass energy resource today, but other sources of biomass can also be used. These include food crops, grassy and woody plants, residues from agriculture or forestry, and the organic component of municipal and industrial wastes. Even the fumes from landfills (which are methane, a natural gas) can be used as a biomass energy source.



Cellulose and hemicellulose, two of the three main components of the great bulk of biomass resources, are polymers of sugars and can be broken down to those component sugars for fermentation or other processing to ethanol and other valuable fuels and chemicals.

Biomass Basics

Biomass is already making key contributions today. It has surpassed hydro-electric power as the largest domestic source of renewable energy. Biomass currently supplies over 3% of the U.S. total energy consumption — mostly through industrial heat and steam production by the pulp and paper industry and electrical generation with forest industry residues and municipal solid waste. Of growing importance are biomass-derived ethanol and biodiesel which provide the only renewable alternative liquid fuel for transportation, a sector that strongly relies on imported oil.

In addition to today's uses of biomass, and historic ones for food, shelter, and clothing, there is significant potential for new biomass feedstocks to dramatically expand the use of biomass in order to continue to reduce our reliance on fossil fuels. The first feedstocks for this "new" biomass might come from opportunities with particular industrial residues, but beyond that, large-scale expansion of biomass is expected to come from forestry and agricultural residues. The latter includes cellulosic stalks, leaves, husks, and straw in addition to the starchy grains and oily seeds currently used. In the longer term, the biomass industry could support dedicated energy crops specifically grown for energy use.

Of the many possible conversion technologies for expanded biomass use, two of the most promising are the sugar platform and the thermochemical platform. These are referred to as "platforms" because the basic technology would generate base or platform chemicals from which industry could make a wide range of fuels, chemicals, materials, and power. These platform chemicals and wide range of products are analogous to the current petrochemicals industry. The promotion of “biorefineries" as a major new domestic biomass industry is, along with reducing dependence on imported oil.

Sugar platform technology uses thermochemical hydrolysis pretreatment of hemicellulose and enzymatic hydrolysis of cellulose to break those two polymeric carbohydrates down to their component sugars for subsequent fermentation or other processing to valuable fuels, chemicals, and materials. Separated lignin — the third component comprising the bulk of biomass material — can also be processed into valuable products or can be burned to provide heat, steam, and electricity for the process operation.

<u>Thermochemical platform technology</u> heats biomass with limited oxygen to gasify it to synthesis gas (a mixture of carbon monoxide and hydrogen) or liquefy it to pyrolysis oil. Because combustion and catalytic conversion processes are a function of the interaction of the individual molecules of feedstock material with oxygen or a catalyst, respectively, work better with liquids and gases than with solids. Therefore, biomass converted to synthesis gas, pyrolysis oil, or hydrothermal liquid (from another thermochemical platform process) burns more efficiently than if it were in its original solid state. Or, instead of burning them, these biomass-derived gases or liquids can be catalytically converted to other valuable fuels, chemicals, or materials.

Benefits of Using Biomass

Biomass can be used for fuels, power production, and products that would otherwise be made from fossil fuels. In such scenarios, biomass can provide an array of benefits. For example:

- The use of biomass energy has the potential to greatly reduce greenhouse gas emissions. Burning biomass releases about the same amount of carbon dioxide as burning fossil fuels. However, fossil fuels release carbon dioxide captured by photosynthesis millions of years ago—an essentially "new" greenhouse gas. Biomass, on the other hand, releases carbon dioxide that is largely balanced by the carbon dioxide captured in its own growth (depending how much energy was used to grow, harvest, and process the fuel).

-The use of biomass can reduce dependence on foreign oil because biofuels are the only renewable liquid transportation fuels available.

-The main biomass feedstocks for power are paper mill residue, lumber mill scrap, and municipal waste. For biomass fuels, the feedstocks are corn (for ethanol) and soybeans (for biodiesel), both surplus crops. In the near future agricultural residues such as corn stover (the stalks, leaves, and husks of the plant) and wheat straw will also be used. Long-term plans include growing and using dedicated energy crops, such as fast-growing trees and grasses, that can grow sustainably on land that will not support intensive food crops.

Biofuels

Unlike other renewable energy sources, biomass can be converted directly into liquid fuels, called "biofuels," to help meet transportation fuel needs. The two most common types of biofuels are ethanol and biodiesel.

Ethanol is an alcohol, the same as in beer and wine (although ethanol used as a fuel is modified to make it undrinkable). It is made by fermenting any biomass high in carbohydrates through a process similar to beer brewing. Today, ethanol is made from starches and sugars, but scientists are developing technology to allow it to be made from cellulose and hemicellulose, the fibrous material that makes up the bulk of most plant matter. Ethanol is mostly used as blending agent with gasoline to increase octane and cut down carbon monoxide and other smog-causing emissions.

Biodiesel is made by combining alcohol (usually methanol) with vegetable oil, animal fat, or recycled cooking grease. It can be used as an additive (typically 20%) to reduce vehicle emissions or in its pure form as a renewable alternative fuel for diesel engines.

Biopower

Biopower, or biomass power, is the use of biomass to generate electricity. Biopower system technologies include direct-firing, cofiring, gasification, pyrolysis, and anaerobic digestion.

Most biopower plants use direct-fired systems. They burn bioenergy feedstocks directly to produce steam. This steam drives a turbine, which turns a generator that converts the power into electricity. In some biomass industries, the spent steam from the power plant is also used for manufacturing processes or to heat buildings. Such combined heat and power systems greatly increase overall energy efficiency. Paper mills, the largest current producers of biomass power, generate electricity or process heat as part of the process for recovering pulping chemicals.

Co-firing refers to mixing biomass with fossil fuels in conventional power plants. Coal-fired power plants can use co-firing systems to significantly reduce emissions, especially sulfur dioxide emissions. Gasification systems use high temperatures and an oxygen-starved environment to convert biomass into synthesis gas, a mixture of hydrogen and carbon monoxide. The synthesis gas, or "syngas," can then be chemically converted into other fuels or products, burned in a conventional boiler, or used instead of natural gas in a gas turbine. Gas turbines are very much like jet engines, only they turn electric generators instead of propelling a jet. High-efficiency to begin with, they can be made to operate in a "combined cycle," in which their exhaust gases are used to boil water for steam, a second round of power generation, and even higher efficiency.

Using a similar thermochemical process but different conditions (totally excluding rather than limiting oxygen, in a simplified sense) will pyrolyze biomass to a liquid rather than gasify it. As with syngas, pyrolysis oil can be burned to generate electricity or used as a chemical source for making plastics, adhesives, or other bioproducts.

The natural decay of biomass produces methane, which can be captured and used for power production. In landfills, wells can be drilled to release the methane from decaying organic matter. Then pipes from each well carry the methane to a central point, where it is filtered and cleaned before burning. This produces electricity and reduces the release of methane (a very potent greenhouse gas) into the atmosphere.

Methane can also be produced from biomass through a process called anaerobic digestion. Natural consortia of bacteria are used to decompose organic matter in the absence of oxygen in closed reactors. Gas suitable for power production is produced, and possibly troublesome wastes (such as those at sewage treatment plants or feedlots) are turned to usable compost.

Gasification, anaerobic digestion, and other biomass power technologies can be used in small, modular systems with internal combustion or other generators. These could be helpful for providing electrical power to villages remote from the electrical grid—particularly if they can use the waste heat for crop drying or other local industries. Small, modular systems can also fit well with distributed energy generation systems.

Bioproduct

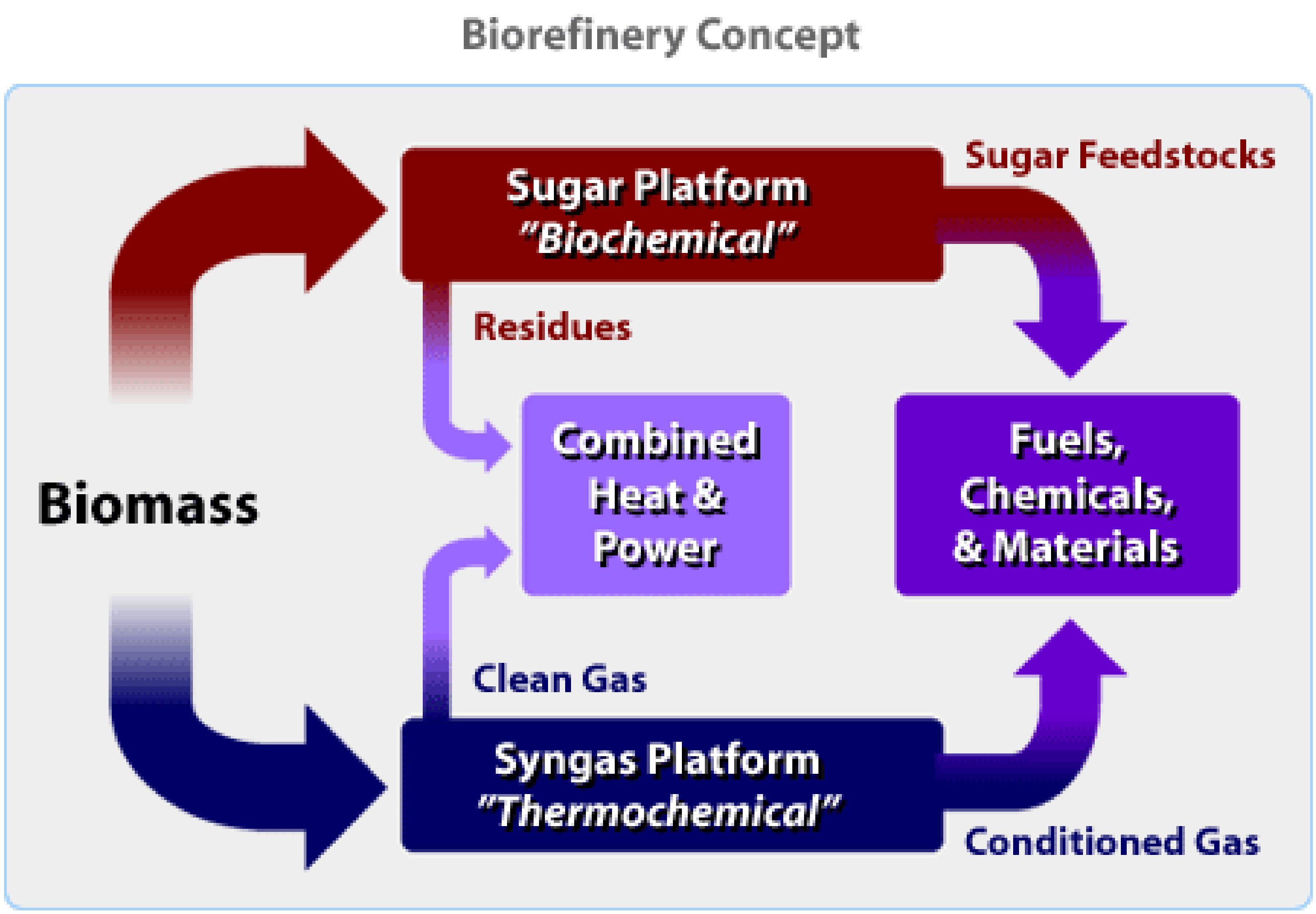
The petrochemical industry makes a myriad of products from fossil fuels. These plastics, chemicals, and other products are integral to modern life. The same or similar products can, for the most part, be made from biomass.

Fossil fuels are hydrocarbons, which are various combinations of carbon and hydrogen. Biomass components are carbohydrates, which are various combinations of carbon, hydrogen, and oxygen. The presence of oxygen makes it more challenging to create some products and easier to create others. In addition, the wide range of types of biomass should make it possible to make new and valuable products not made from petrochemicals.

The processes are similar. The petrochemical industry breaks oil and natural gas down to base chemicals and then builds desired products from them. Biofuel technology breaks biomass down to component sugars, and biopower technology breaks biomass down to carbon monoxide and hydrogen. Fermentation, chemical catalysis, and other processes can then be used to create new products.

The biorefinery concept posits that some of these products, while possibly small in volume, could be high in value. A particular biorefinery would make a mix of low-volume/high-value products and high-volume/low-value fuels needed to meet energy needs.

Bioproducts that can be made from sugars include antifreeze, plastics, glues, artificial sweeteners, and gel for toothpaste. Bioproducts that can be made from carbon monoxide and hydrogen of syngas include plastics and acids, which can be used to make photographic films, textiles, and synthetic fabrics. Bioproducts that can be made from phenol, one possible extraction from pyrolysis oil, include wood adhesives, molded plastic, and foam insulation.


Biorefinery Concept
Sugar Platform
"Biochemical"
Sugar Feedstocks
Residues
Biomass
Combined Heat & Power
Fuels, Chemicals, & Materials
Clean Gas
Syngas Platform
"Thermochemical"
Conditioned Gas

Biomass Technology

<u>Ethanol</u>

Ethanol, also known as ethyl alcohol or grain alcohol, can be used either as an alternative fuel or as an octane-boosting, pollution-reducing additive to gasoline. The U.S. ethanol industry produced more than 3.4 billion gallons in 2004, up from 2.8 billion gallons in 2003 and 2.1 billion gallons in 2002. Although this number is small when compared with fossil fuel consumption for transportation, as individual states continue to ban the use of MTBE (Methyl Tertiary Butyl Ether) and with the possibility of a Federal ban, ethanol consumption is due for a significant boost. Because of the increased demand on ethanol as a gasoline additive, efforts to increase supplies are necessary in order to meet the increase in demand. As of the start of 2005, 81 ethanol plants in 20 states have the capacity to produce nearly 4.4 billion gallons annually and an additional 16 plants are under construction to add another 750 million gallons of capacity.

There are four basic steps in converting biomass to bioethanol:

a) Producing biomass results in the fixing of atmospheric carbon dioxide into organic carbon.

b) Converting this biomass to a useable fermentation feedstock (typically some form of sugar) can be achieved using a variety of different process technologies. These processes for fermentation feedstock production constitute the critical differences among all of the bioethanol technology options.

c) Fermenting the biomass intermediates using biocatalysts (microorganisms including yeast and bacteria) to produce ethanol in a relatively dilute aqueous solution is probably the oldest form of biotechnology developed by humankind.

d) Processing the fermentation product yields fuel-grade ethanol and byproducts that can be used to produce other fuels, chemicals, heat and/or electricity.

Corn and other starches and sugars are only a small fraction of biomass that can be used to make ethanol. Advanced Bioethanol Technology allows fuel ethanol to be made from cellulosic (plant fiber) biomass, such as agricultural forestry residues, industrial waste, material in municipal solid waste, trees, and grasses. Cellulose and hemicellulose, the two main components of plants-and the ones that give plants their structure-are also made of sugars, but those sugars are tied together in long chains. Advanced bioethanol technology can break those chains down into their component sugars and then ferment them to make ethanol. This technology turns ordinary low-value plant materials such as corn stalks, sawdust, or waste paper into fuel ethanol.

Renewable Diesel Fuel

Biodiesel

Biodiesel is made by transforming animal fat or vegetable oil with alcohol and can be directly substituted for diesel either as neat fuel (B100) or as an oxygenate additive (typically 20%-B20). B20 earns credits for alternative fuel use under the Energy Policy Act of 1992, and it's the only fuel that does not require the purchase of a new vehicle. In Europe, the largest producer and user of biodiesel, the fuel is usually made from rapeseed (canola) oil. In the United States, the second largest producer and user of biodiesel, the fuel is usually made from soybean oil or recycled restaurant grease. In 2002, 15 million gallons of biodiesel was consumed in the United States, a trade association for biodiesel producers, is a good source of additional information.

E-diesel

E-Diesel is a fuel that uses additives in order to allow blending of ethanol with diesel. It includes ethanol blends of 7.7% to 15% and up to 5% special additives that prevent the ethanol and diesel from separating at very low temperatures or if water contamination occurs. Use of E-diesel would also increase demand for ethanol, as diesel vehicles in the U.S. consume approximately 36 billion gallons of diesel a year.

E-Diesel is currently an experimental fuel and is being developed by many companies, who can receive federal ethanol tax credit when blending ethanol with diesel. Demonstrations are currently being conducted on the use of E-diesel in heavy-duty trucks, buses, and farm machinery. There is a light increase in operating costs due to a slight (7-10%) mileage decreases with E-diesel use. However, there are many environmental benefits to using e-diesel, such as reduced emissions of Particulate Matter from 27% to 41%, Carbon Monoxide from 20% to 27%, Nitrogen oxides 4% to 5%.

Supporters of E-diesel see it as a major new market for ethanol and an effective way to help engine manufacturers meet tough new emission standards from the U.S. Environmental Protection Agency. For instance, it can take up to 10 years for manufacturers to phase in new engine designs that reduce emissions and meet tough new EPA standards. However, switching to E-diesel gets immediate the environmental benefits.

Electrical Power generation

Power from biomass is a proven commercial electricity generation option in the United States. With about 9,733 megawatts (MW) in 2002 of installed capacity, biomass is the single largest source of non-hydro renewable electricity. This 9,733 MW of capacity includes about 5,886 MW of forest product and agricultural residues, 3,308 MW of generating capacity from municipal solid waste, and 539 MW of other capacity such as landfill gas. The majority of electricity production from biomass is used as base load power in the existing electrical distribution system. Biopower also includes industrial process heat and steam. More than 200 companies outside the wood products and food industries generate biomass power in the United States. Where power producers have access to very low cost biomass supplies, the choice to use biomass in the fuel mix enhances their competitiveness in the market place. This is particularly true in the near term for power companies choosing to co-fire biomass with coal to save fuel costs and earn emissions credits. An increasing number of power marketers are starting to offer environmentally friendly electricity, including biomass power, in response to consumer demand and regulatory requirements.

There are four primary classes of biomass power systems: <u>direct-fired, co-fired, gasification, and modular systems</u>. Most of today's biomass power plants are <u>direct-fired systems</u> that are similar to most fossil-fuel fired power plants. The biomass fuel is burned in a boiler to produce high-pressure steam. This steam is introduced into a steam turbine, where it flows over a series of aerodynamic turbine blades, causing the turbine to rotate. The turbine is connected to an electric generator, so as the steam flow causes the turbine to rotate, the electric generator turns and electricity is produced.

While steam generation technology is very dependable and proven, its efficiency is limited. Biomass power boilers are typically in the 20-50 MW range, compared to coal-fired plants in the 100-1500 MW range. The small capacity plants tend to be lower in efficiency because of economic trade-offs; efficiency-enhancing equipment cannot pay for itself in small plants. Although techniques exist to push biomass steam generation efficiency over 40%, actual plant efficiencies are in the low 20% range.

<u>Co-firing</u> involves substituting biomass for a portion of coal in an existing power plant furnace. It is the most economic near-term option for introducing new biomass power generation. Because much of the existing power plant equipment can be used without major modifications, co-firing is far less expensive than building a new biomass power plant. Compared to the coal it replaces, biomass reduces sulfur dioxide (SO2), nitrogen oxides (NOx), and other air emissions. After "tuning" the boiler for peak performance, there is little or no loss in efficiency from adding biomass. This allows the energy in biomass to be converted to electricity with the high efficiency (in the 33-37% range) of a modern coal-fired power plant.

Biomass gasifiers operate by heating biomass in an environment where the solid biomass breaks down to form a flammable gas. This offers advantages over directly burning the biomass. The biogas can be cleaned and filtered to remove problem chemical compounds. The gas can be used in more efficient power generation systems called combined-cycles, which combine gas turbines and steam turbines to produce electricity. The efficiency of these systems can reach 60%.

Gasification systems will be coupled with fuel cell systems for future applications. Fuel cells convert hydrogen gas to electricity (and heat) using an electro-chemical process. There are very little air emissions and the primary exhaust is water vapor. As the costs of fuel cells and biomass gasifiers come down, these systems will proliferate.

Modular systems employ some of the same technologies mentioned above, but on a smaller scale that is more applicable to villages, farms, and small industry. These systems are now under development and could be most useful in remote areas where biomass is abundant and electricity is scarce. There are many opportunities for these systems in developing countries.

Biomass Feedstocks

The degree of complexity and feasibility of biomass conversion technology depends on the nature of the feedstock from which we start.

Monomeric Sugars

The least complicated approach to fuel ethanol production is to use biomass that contains monomeric sugars, which can be fermented directly to ethanol. Sugarcane and sugar beets are examples of biomass that contain substantial amounts of monomeric sugars. Up until the 1930s, industrial grade ethanol was produced in USA via fermentation of molasses derived from such sugar crops. The high cost of sugar from these crops has made these sources prohibitively expensive in USA.

Starch

Sugars are more commonly found in the form of biopolymers that must be chemically processed to yield simple sugars. In USA, today's fuel ethanol is derived almost entirely from the starch (a biopolymer of glucose) contained in corn. Starch consists of glucose molecules strung together by a-glycosidic linkages. These linkages occur in chains of a-1,4 linkages with branches formed as a result of a-1,6 linkages (see Figure).

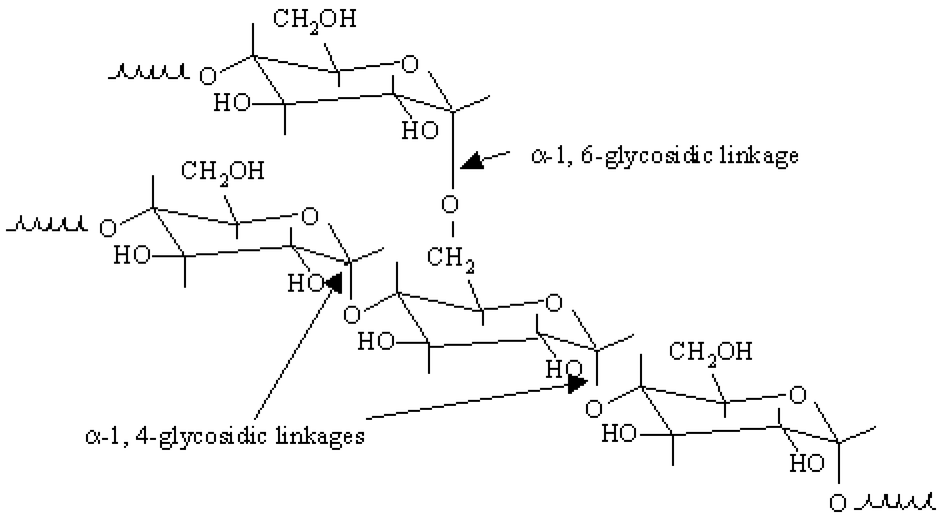


Figure : The polymeric structure of glucose in starch tends to be amorphous

The terms a and ß are used to describe different stereoisomers of glucose. A not-so-obvious consequence of the a linkages in starch is that this polymer is highly amorphous, making it more readily attacked by human and animal enzyme systems. The ability to commercially produce sugars from starch is the result of one of the earliest examples of modern industrial enzyme technology—the production and use of a-amylases, glucoamylases and glucose isomerase in starch processing. Researchers have long hoped to emulate the success of this industry in the conversion of cellulosic biomass to sugar.

Cellulose

Cellulose, the most common form of carbon in biomass, is also a biopolymer of glucose. In this case, the glucose moieties are strung together by ß-glycosidic linkages. The ß-linkages in cellulose form linear chains that are highly stable and much more resistant to chemical attack because of the high degree of hydrogen bonding that can occur between chains of cellulose (see Figure). Hydrogen bonding between cellulose chains makes the polymers more rigid, inhibiting the flexing of the molecules that must occur in the hydrolytic breaking of the glycosidic linkages.

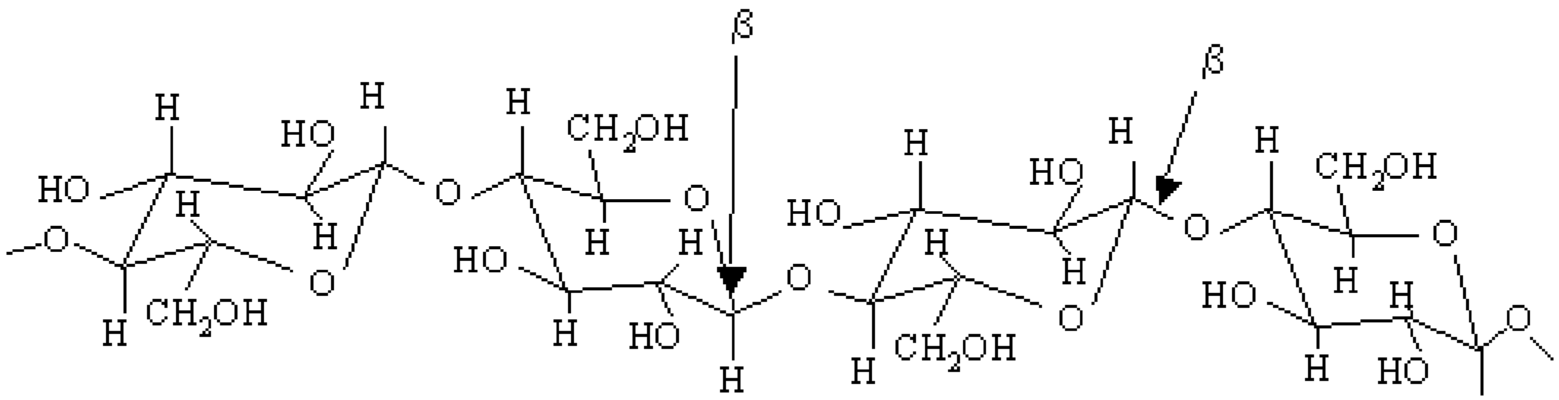


Figure: Linear chains of glucose linked by b-Glycosidic bonds comprise cellulose

Hemicellulose

Yet a fourth form of sugar polymers found in biomass is hemicellulose. Hemicellulose consists of short, highly branched, chains of sugars. It contains five-carbon sugars (usually D-xylose and L-arabinose) and six-carbon sugars (D-galactose, D-glucose and D-mannose) and uronic acid. The sugars are highly substituted with acetic acid. Its branched nature renders hemicellulose amorphous and relatively easy to hydrolyze to its constituent sugars. When hydrolyzed, the hemicellulose from hardwoods releases products high in xylose (a five-carbon sugar). The hemicellulose contained in softwoods, by contrast, yields more six-carbon sugars.

The four forms of sugar in biomass represent a range of accessibility that is reflected in the history of ethanol production. Simple sugars are the oldest and easiest-to-use feedstock for fermentation to ethanol. Next comes starch, now the preferred choice of feedstock for fuel ethanol. Starch-containing grain crops, like sugar crops, have higher value for food and feed applications. Because many animals (including humans) can digest starch, but not cellulose, starch will likely continue to serve a unique and important role in agriculture. The remaining two forms—cellulose and hemicellulose—are the most prevalent forms of carbon in nature, and yet they are also the most difficult to utilize. Cellulose's crystalline structure renders it highly insoluble and resistant to attack, while hemicellulose contains some sugars that have not, until recently, been readily fermentable to alcohol.

Biomass for Energy

In order to expand the available resource base for sugars and to identify lower cost sources, we have focused on the use of non-starch, non-food-related biomass such as trees, grasses, and waste materials. The three largest components of these biomass sources are cellulose, hemicellulose, and lignin. Lignin is a biopolymer rich in phenolic components, which provides structural integrity to plants. Ranges of cellulose, hemicellulose, and lignin contents in biomass are presented in Table 1. Ranges for five-and six-carbon sugar content in hardwoods, softwoods, and agricultural residues are provided in Table 2. The combination of hemicellulose and lignin provide a protective sheath around the cellulose, which must be modified or removed before efficient hydrolysis of cellulose can occur. Lignin is often referred to as "clean" (i.e., sulfur-free) coal because it is the lignin portion of plants that is the ancestor of coal (which is, after all, fossilized biomass). Lignin remains as residual material after the sugars in biomass have been fermented to ethanol. Economic use of this byproduct is critical to the financial feasibility of biomass-to-ethanol technology.

Table : Typical levels of cellulose, hemicellulose and lignin in biomass

Component	Percent Dry Weight
Cellulose	40-60%
Hemicellulose	20-40%
Lignin	10-25%

Table : Sugar and Ash Composition of Various Biomass Feedstocks (wt%)

Material	Six-Carbon Sugars	Five-Carbon Sugars	Lignin	Ash
Hardwoods	39-50%	18-28%	15-28%	0.3-1.0%
Softwoods	41-57%	8-12%	24-27%	0.1-0.4%
Ag Residues	30-42%	12-39%	11-29%	2-18%

Photosynthesis (efficiency ~0.5 %)

$CO_2 + H_2O + h\nu \rightarrow O_2 + [CH_2O]$, 16 MJ/kg (16 GJ/ton)

Annual solar energy ~1000 kWh/m^2 → 10 GWh/ha = 36 TJ/ha (1 ha = 10^4 m^2)
→ energy of biomass production ~180 GJ/ha

Biomass yield ~ 11 ton/ha/year ~ 5 kW/ha ~ 0.5 MW/km^2