

Bioethanol from Cellulosic Materials: A Renewable Motor Fuel from Biomass

AYHAN DEMİRBAŞ

Department of Chemical Engineering
Selcuk University, Konya, Turkey

Ethanol is the most widely used liquid biofuel. It is an alcohol and is fermented from sugars, starches or from cellulosic biomass. Cellulosic materials can be used to produce bioethanol. Bioethanol represents an important, renewable liquid fuel for motor vehicles. Production of bioethanol from biomass is one way to reduce both the consumption of crude oil and environmental pollution. Conversion technologies for producing ethanol from cellulosic biomass resources such as forest materials, agricultural residues and urban wastes are under development and have not yet been demonstrated commercially. In order to produce bioethanol from cellulosic biomass, a pretreatment process is used to reduce the sample size, break down the hemicelluloses to sugars, and open up the structure of the cellulose component. The cellulose portion is hydrolyzed by acids or enzymes into glucose sugar that is fermented to bioethanol. The sugars from the hemicelluloses are also fermented to bioethanol. The use of bioethanol as a motor fuel has as long a history as the car itself. It began with the use of ethanol in the internal combustion engine.

Keywords bioethanol, biomass, ethyl alcohol, fermentation, hydrolysis, sugar

In view of continuously rising petroleum costs and dependence upon fossil fuel resources, considerable attention has been focused on alternative energy resources. Production of ethanol or ethyl alcohol ($\text{CH}_3\text{CH}_2\text{OH}$) from biomass is one way to reduce both the consumption of crude oil and environmental pollution (Lang et al., 2001a). Primary consideration involves the production of ethyl alcohol from renewable resources and determination of the economic and technical feasibility of using alcohol as an automotive fuel blended with gasoline (Goldstein, 1981). Ethanol represents an important, renewable liquid fuel for motor vehicles (Lewis, 1996). The use of gasohol (ethanol and gasoline mixture) as an alternative motor fuel has been steadily increasing around the world for a number of reasons. Domestic production and use of ethanol for fuel can decrease dependence on foreign oil, reduce trade deficits, create jobs in rural areas, reduce air pollution, and reduce global climate change carbon dioxide buildup. Ethanol, unlike gasoline, is an oxygenated fuel that contains 35% oxygen, which reduces particulate and NO_x emissions from combustion. When burned, ethanol derived from fermentation produces no net increase in carbon dioxide in the atmosphere. It is an octane enhancing additive and removes free water which can plug fuel lines in cold climates (Lang et al., 2001b).

Received 29 May 2003; accepted 29 June 2003.

Address correspondence to Professor Ayhan Demirbaş, Selcuk University, Muh. Mim. Faculty, Department of Chemical Engineering, 42031 Konya, Turkey. E-mail: ayhandemirbas@hotmail.com

Table 1
Bioethanol production in different continents (billion liters/year)

Continents	America	Asia	Europe	Africa	Oceania
Production	22.3	5.7	4.6	0.5	0.2

Source: Berg, 1998.

Ethanol is the most widely used liquid biofuel. It is an alcohol and is fermented from sugars, starches or from cellulosic biomass. Most commercial production of ethanol is from sugar cane or sugar beet, as starches and cellulosic biomass usually require expensive pretreatment. It is used as a renewable energy fuel source as well as for manufacture of cosmetics, pharmaceuticals and also for the production of alcoholic beverages.

Ethyl alcohol is not only the oldest synthetic organic chemical used by man, but it is also one of the most important. In an earlier study (Taherzadeh, 1999), physiological effects of inhibitors on ethanol from lignocellulosic materials and fermentation strategies was comprehensively investigated.

Yeast based fermentation, for example, has yielded ethanol from sugar or crops. The production of ethanol by fermentation of sugar has already been commercially established but innovative studies could bring improvements to reactors and separation systems. To produce ethanol from lignocellulosic materials, it is essential to hydrolyse it before fermentation at the demonstration and industrial level. Enzymatic hydrolysis is still at an early stage, requiring substantial fundamental research (e.g., for increased yields) (Küçük and Demirbaş, 1997).

Conversion technologies for producing bioethanol from cellulosic biomass resources such as forest materials, agricultural residues and urban wastes are under development and have not yet been demonstrated commercially. Uncertainties regarding commercial scale performance and profitability combined with unclear market outlook in the longer term constrain private investment in such facilities.

The estimated world ethanol production in 1998 was 33.3 billion liters (Berg, 1998). Approximately 9% of the ethanol is produced synthetically, and consequently, fermentation is responsible for 91% of global ethanol production (Wheeler et al., 1991). Brazil is the dominant producer of alcohol with a production of 16.1 billion liters in 1998. The production of bioethanol in different continents is shown in Table 1.

The purposes of this study are to identify the types of biomass that can be used to produce bioethanol and evaluate biomass-to-ethanol opportunities and to investigate the sugars from both the cellulose and hemicelluloses to bioethanol via fermentation.

Cellulosic Biomass Resources

Cellulosic resources such as paper, cardboard, wood, agricultural residues and other fibrous plant material are in general very widespread and abundant. For example, forests comprise about 80% of the world's biomass.

Ethanol can be produced from different kinds of raw materials. The raw materials are classified into three categories of agricultural raw materials: simple sugars, starch and cellulose. Cellulosic biomass materials can be supplied from a variety of resources at a low price. They can be classified in four groups based on type of resource: wood, municipal solid waste, waste-paper and crop residue resources. The structural composition of various types of cellulosic biomass materials is given in Table 2.

Table 2
Composition of various types of cellulosic biomass materials (% dry weight)

Material	Cellulose	Hemicelluloses	Lignin	Ash	Extractives
Algae (green)	20–40	20–50	—	—	—
Cotton, flax, etc.	80–95	5–20	—	—	—
Grasses	25–40	25–50	10–30	—	—
Hardwoods	45±2	30±5	20±4	0.6±0.2	5±3
Hardwood barks	22–40	20–38	30–55	0.8±0.2	6±2
Softwoods	42±2	27±2	28±3	0.5±0.1	3±2
Softwood barks	18–38	15–33	30–60	0.8±0.2	4±2
Cornstalks	39–47	26–31	3–5	12–16	1–3
Wheat straw	37–41	27–32	13–15	11–14	7±2
Newspapers	40–55	25–40	18–30	—	—
Chemical pulps	60–80	20–30	2–10	—	—

Sources: Goldstein, 1981; Demirbaş, 1991; Demirbaş, 1998.

Being abundant and outside the human food chain makes cellulosic materials relatively inexpensive inputs for ethanol production. Cellulosic materials are comprised of lignin, hemicelluloses, and cellulose and are thus sometimes called lignocellulosic materials. Cellulose molecules consist of long chains of glucose molecules (6-carbon sugars) as do starch molecules, but have a different structural configuration. These structural characteristics plus the encapsulation by lignin makes cellulosic materials more difficult to hydrolyze than starchy materials. Hemicelluloses are also comprised of long chains of sugar molecules, but contain pentoses in addition to glucose. The relative abundance of individual sugars in carbohydrate fraction of wood is shown in Table 3.

Based on average 42% cellulose and 21% hemicelluloses in wood, the maximum theoretical yield of ethanol can be calculated to be 0.32 grams of ethanol per gram of wood. This calculation is based on a full conversion of cellulose and hemicelluloses to sugars, and conversion of sugars to ethanol at the theoretical yield of 0.51 g/g (Taherzadeh, 1999).

Since pentose molecules (5-carbon sugars) comprise a high percentage of the available sugars, the ability to recover and ferment them into ethanol is important for the efficiency and economics of the process. Recently, special microorganisms have been

Table 3
Relative abundance of individual sugars in carbohydrate fraction of wood (% by weight)

Sugar	In softwoods	In softwood bark	In hardwoods	In hardwood bark
Glucose	61–65	57–63	55–73	53–65
Xylose	9–13	11–15	20–39	18–36
Mannose	7–16	6–16	0.4–4	0.3–3
Galactose	6–17	1–5	1–4	1–6
Arabinose	<3.5	4–11	<1	2–8
Rhamnose	<1	<1	<1	<1
Uronic acids	4–7	—	4–7	—

Source: Goldstein, 1981.

genetically engineered which can ferment 5-carbon sugars into ethanol with relatively high efficiency. Bacteria have drawn special attention from researchers because of their speed of fermentation.

Another potential ethanol raw material is starch. Starch molecules are made up of long chains of glucose molecules. Thus, starchy materials can also be fermented after breaking starch molecules into simple glucose molecules. Examples of starchy materials commonly used around the world for bioethanol production include cereal grains, potato, sweet potato, and cassava. Starchy materials require a reaction of starch with water (hydrolysis) to break down the starch into fermentable sugars (saccharification).

Use of Bioethanol as a Transporting Fuel

The use of ethanol as a motor fuel has as long a history as the car itself. It began with the use of ethanol in the internal combustion engine invented by Nikolas Otto in 1897 (Rothman et al., 1983). Alcohols have been used as fuels since the inception of the automobile. The term alcohol often has been used to denote either ethanol or methanol as a fuel. With the oil crises of the 1970s, ethanol became established as an alternative fuel. Many countries started programs to study and develop fuels in an economic way from available raw materials (Paul, 1979). The interest then waned as the price of oil dropped, until 1979 when we had another oil crisis. Since the 1980s, ethanol has been considered as one possible alternative fuel in many countries. Countries including Brazil and the USA have long promoted domestic bioethanol production. In addition to the energy rationale, ethanol/gasoline blends in the USA were promoted as an environmentally driven practice, initially as an octane enhancer to replace lead. Ethanol also has value as oxygenate in clean-burning gasoline to reduce vehicle exhaust emissions.

Ethanol performs well as a fuel in cars, either in a neat form or in a mixture with gasoline. In addition to ethanol/gasoline blend markets, ethanol has other motor fuel applications including: (1) use as E85, 85% ethanol and 15% gasoline, (2) use as E100, 100% ethanol with or without a fuel additive, and (3) use in oxy-diesel, typically a blend of 80% diesel fuel, 10% ethanol and 10% additives and blending agents. Table 4 shows the potential and available motor fuels.

According to the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC), agreed to in December 1997, marks an important turning

Table 4
Potential and available motor fuels

Fuel type	Available motor fuel
<i>Traditional fuels</i>	Diesel and gasoline
<i>Oxygenated fuels</i>	Ethanol 10% (E10), methanol, methyl tertiary butyl ether (MTBE), ethyl tertiary butyl ether (ETBE), tertiary butyl alcohol (TBA), and tertiary amyl methyl ether (TAME)
<i>Alternative fuels</i>	Liquefied petroleum gases (LPG), ethanol, 85% (E85), ethanol, 95% (E95), methanol, 85% (M85), methanol, neat (M100), compressed natural gas (CNG), liquefied natural gas (LNG), bio-diesel (BD), hydrogen, and electricity

Source: AFDC, 1997.

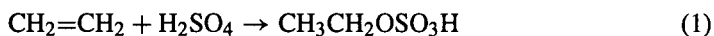
point in efforts to promote the use of renewable energy worldwide and that the developed countries should decrease the net emission of CO₂ (Demirbaş, 2003). An important reason for interest in renewable energy sources is the concern for the greenhouse effect. Development of ethanol as a motor fuel can work to fulfill this commitment. Greenhouse gas emission reductions should be estimated on an annual basis. Where the levels from year to year vary significantly, these should be specified on an annual basis. If bioethanol from biomass is used to drive a light-duty vehicle, the net CO₂ emission is less than 7% of that from the same car using reformulated gasoline (Bergeron, 1996).

Ethanol Production Methods

There are three principal methods to get the simple alcohols that are the backbone of aliphatic organic synthesis (Morrison and Boyd, 1983). These are: (a) by hydration of alkanes obtained from the cracking of petroleum; (b) by the hydrolysis of cellulosic materials; and (c) by fermentation of carbohydrates.

Synthetic Ethanol Production Processes

The hydration of ethylene is the oldest process among the two major ethanol production methods from ethylene (CH₂=CH₂), and was started more than one hundred years ago. The ethanol is prepared from ethylene in a three-step process using sulfuric acid (H₂SO₄) (John, 1969). In the first step, the hydrocarbon feedstock containing 35–95% ethylene is exposed to 95–98% sulfuric acid in a column reactor to form mono-sulfate:

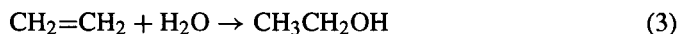


It is subsequently hydrolyzed with enough water to give 50–60% aqueous sulfuric acid solution:



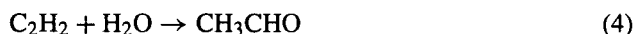
The ethanol is then separated from the dilute sulfuric acid in a stripper column. The last step of this process is to concentrate the sulfuric acid and recycle to the process.

In the direct hydration process, an ethylene-rich gas is combined with water and passes through a fixed-bed catalyst reactor, in which ethanol is formed according to the following reaction (Nelson and Courter, 1954):



The ethanol is then recovered in a distillation system.

Ethanol can be obtained from acetylene process in the presence of the proper catalyst such as H₂SO₄ and HgSO₄, ethylene react with water to yield acetaldehyde:



Acetaldehyde can be readily reduced by catalytic hydrogenation to ethyl alcohol:



The classical catalyst is octacarbonyldicobalt, Co₂(CO)₈, formed by reaction of metallic cobalt with carbon monoxide.

Bioethanol Production by Fermentation of Carbohydrates

Fermentation using genetically engineered yeast or bacteria will utilize all five of the major biomass sugars: glucose, xylose, mannose, galactose and arabinose. Bioethanol may be produced by direct fermentation of sugars, or from other carbohydrates that can be converted to sugar, such as starch and cellulose. Fermentation of sugars by yeast, the oldest synthetic chemical process used by man, is still of enormous importance for the preparation of ethyl alcohol. The sugars come from a variety of sources, mostly molasses from sugar cane, or starch obtained from various grains; the name "grain alcohols" has been given to ethyl alcohol for this reason. The raw materials are classified into three categories of agricultural raw materials: (1) simple sugars from sugar cane, sugar beet, molasses, and fruit; (2) starch from grains, potatoes, and root crops; and (3) cellulose from wood, agricultural residue, municipal solid wastes, waste papers, and crop residues.

Some sugars can be converted directly to bioethanol, whereas starch and cellulose must first be hydrolyzed to sugar before conversion to bioethanol. Most of the polymeric raw materials are available at prices lower than refined sugars. However, transportation costs of the raw materials make it necessary to use locally available raw material (Taherzadeh, 1999).

The fermentation method generally uses three steps: (a) the formation of a solution of fermentable sugars, (b) the fermentation of these sugars to bioethanol, and (c) the separation and purification of the ethanol, usually by distillation.

Fermentation involves microorganisms that use the fermentable sugars for food and in the process produces ethyl alcohol and other byproducts. These microorganisms can typically use the 6-carbon sugars, one of the most common being glucose. Therefore, cellulosic biomass materials containing high levels of glucose or precursors to glucose are the easiest to convert to ethanol. Microorganisms, termed ethanologens, presently convert an inadequate portion of the sugars from biomass to ethanol. Although fungi, bacteria, and yeast microorganisms can be used for fermentation, specific yeast (*Saccharomyces cerevisiae* also known as Bakers' yeast) is frequently used to ferment glucose to bioethanol.

Theoretically, 100 grams of glucose will produce 51.4 g of bioethanol and 48.8 g of carbon dioxide. However, in practice, the microorganisms use some of the glucose for growth and the actual yield is less than 100%.

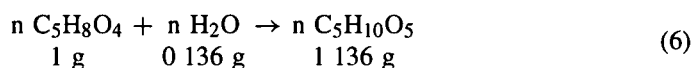
Operating temperatures are less than desired and the organism performance can be inhibited by components inherent in the process. Three recombinant fermentation strains were considered to be candidates for short term improvement by the participants: *Saccharomyces*, *E. coli* and *Zymomonas*. There is a clear preference for yeast by the existing grain ethanol producers, particularly *Saccharomyces*. This yeast is widely used, known and fits existing equipment. Others mentioned included *Klebsiella*, *Pichia stipitis*, *B. Stearothermophilus* and *Kluveromyces*. A number of other naturally occurring organisms that convert pentoses to ethanol were named. These included *P. stipitis*, *Pachysolen tanophilus* and *Candida shehatae*.

Cellulose hydrolysis produces glucose, which is readily fermented with existing organisms in much the same way as has been done for centuries. Hemicelluloses hydrolysis produces both hexose and pentose sugars: mannose, galactose, xylose and arabinose that are not all fermented with existing strains.

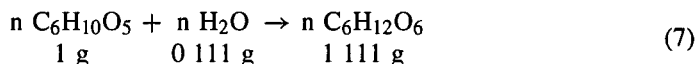
The hemicelluloses fraction typically produces a mixture of sugars including xylose, arabinose, galactose and mannose. These are both pentosans: xylose and arabinose, and hexosans: galactose and mannose. The quantities are dependent on the material and also the growing environment and storage history of the material.

The amount of product formed per unit of substrate consumed by the organism is a useful way to refer to yields. The yields of fermentation are expressed on either molar or weight basis. In this case the primary stoichiometric equations for the bioethanol production are as follows.

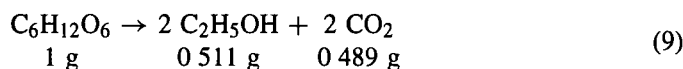
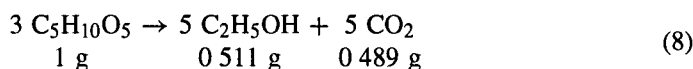
Pentosan to pentose:



Hexosan to hexose:



Pentose and hexose to bioethanol, 0.511 grams per gram hexose or pentose:



A reduction in yield below theoretical always occurs since the microorganism requires a portion of the substrate for cell growth and maintenance. For *E. coli* and *S. cerevisiae* these values are approximately 0.054 and 0.018 grams of glucose/g dry cell weight-hour, respectively (Roels and Kossen, 1978).

Microorganisms for ethanol fermentation can best be described in terms of their performance parameters and other requirements such as compatibility with existing products, processes and equipment. The performance parameters of fermentation are: temperature range, pH range, alcohol tolerance, growth rate, productivity, osmotic tolerance, specificity, yield, genetic stability, and inhibitor tolerance.

Bioethanol Production by Hydrolysis of Cellulosic Biomass Materials

Pretreatment methods refer to the solubilization and separation of one or more of the four major components of biomass (hemicellulose, cellulose, lignin, and extractives) to make the remaining solid biomass more accessible to further chemical or biological treatment. Hydrolysis (saccharification) breaks down the hydrogen bonds in the hemicellulose and cellulose fractions into their sugar components: pentoses and hexoses. These sugars can then be fermented into bioethanol.

After the pretreatment process, there are two types of processes to hydrolyze the cellulosic biomass for fermentation into bioethanol. The most commonly applied methods can be classified in two groups: chemical hydrolysis (dilute and concentrated acid hydrolysis) and enzymatic hydrolysis. In addition, there are some other hydrolysis methods in which no chemicals or enzymes are applied. For instance, lignocellulose may be hydrolyzed by gamma-ray or electron-beam irradiation, or microwave irradiation. However, those processes are commercially unimportant.

Both enzymatic and chemical hydrolyses require a pretreatment to increase the susceptibility of cellulosic materials. In the chemical hydrolysis, the pretreatment and the hydrolysis may be carried out in a single step. There are two basic types of acid hydrolysis processes commonly used: dilute acid and concentrated acid, each with variations.

Dilute Acid Hydrolysis

The dilute acid process is conducted under high temperature and pressure, and has a reaction time in the range of seconds or minutes, which facilitates continuous processing. As an example, using a dilute acid process with 1% sulfuric acid in a continuous flow reactor at a residence time of 0.22 minutes and a temperature of 510 K with pure cellulose provided a yield over 50% sugars. In this case, 1000 kg of dry wood would yield about 164 kg of pure ethanol. The combination of acid and high temperature and pressure dictate special reactor materials, which can make the reactor expensive. The first reaction converts the cellulosic materials to sugar and the second reaction converts the sugars to other chemicals. Unfortunately, the conditions that cause the first reaction to occur also are the right conditions for the second to occur.

The biggest advantage of dilute acid processes is their fast rate of reaction, which facilitates continuous processing. Since 5-carbon sugars degrade more rapidly than 6-carbon sugars, one way to decrease sugar degradation is to have a two-stage process. The first stage is conducted under mild process conditions to recover the 5-carbon sugars while the second stage is conducted under harsher conditions to recover the 6-carbon sugars.

Concentrated Acid Hydrolysis

Hydrolysis of cellulosic materials by concentrated sulfuric or hydrochloric acids is a relatively old process. The concentrated acid process uses relatively mild temperatures, and the only pressures involved are those created by pumping materials from vessel to vessel. Reaction times are typically much longer than for dilute acid. This method generally uses concentrated sulfuric acid followed by a dilution with water to dissolve and hydrolyze or convert the substrate into sugar. This process provides a complete and rapid conversion of cellulose to glucose and hemicelluloses to 5-carbon sugars with little degradation. The critical factors needed to make this process economically viable are to optimize sugar recovery and cost effectively recovers the acid for recycling. The solid residue from the first stage is dewatered and soaked in a 30 to 40% concentration of sulfuric acid for 1 to 4 hours as a pre-cellulose hydrolysis step. The solution is again dewatered and dried, increasing the acid concentration to about 70%. After reacting in another vessel for 1 to 4 hours at low temperatures, the contents are separated to recover the sugar and acid. The sugar/acid solution from the second stage is recycled to the first stage to provide the acid for the first stage hydrolysis.

The primary advantage of the concentrated acid process is the potential for high sugar recovery efficiency. Table 5 shows the yields of bioethanol by concentrated sulfuric acid hydrolysis from cornstalks. The acid and sugar are separated via ion exchange and then acid is re-concentrated via multiple effect evaporators. The low temperatures and pressures employed allow the use of relatively low cost materials such as fiberglass tanks and piping. The low temperatures and pressures also minimize the degradation of sugars. Unfortunately, it is a relatively slow process and cost effective acid recovery systems have been difficult to develop. Without acid recovery, large quantities of lime must be used to neutralize the acid in the sugar solution. This neutralization forms large quantities of calcium sulfate, which requires disposal and creates additional expense.

Enzymatic Hydrolysis

Another basic method of hydrolysis is enzymatic hydrolysis. Enzymes are naturally occurring plant proteins that cause certain chemical reactions to occur. There are two technological developments: enzymatic and direct microbial conversion methods.

Table 5
Yields of bioethanol by concentrated sulfuric acid hydrolysis from cornstalks
(% dry weight)

<i>Amount of cornstalk (kg)</i>	1000
Cellulose content (kg)	430
Cellulose conversion and recovery efficiency	0.76
Ethanol stoichiometric yield	0.51
Glucose fermentation efficiency	0.75
Ethanol yield from glucose (kg)	130
<i>Amount of cornstalk (kg)</i>	1000
Hemicelluloses content (kg)	290
Hemicelluloses conversion and recovery efficiency	0.90
Ethanol stoichiometric yield	0.51
Xylose fermentation efficiency	0.50
Ethanol yield from xylose (kg)	66
<i>Total ethanol yield from 1000 kg of cornstalks</i>	196 kg (225.7 L = 59 gallons)

The chemical pretreatment of the cellulosic biomass is necessary before enzymatic hydrolysis. The first application of enzymatic hydrolysis was used in separate hydrolysis and fermentation steps. Enzymatic hydrolysis is accomplished by cellulolytic enzymes. Different kinds of "cellulases" may be used to cleave the cellulose and hemicelluloses. A mixture of endoglucanases, exoglucanases, -glucosidases and cellobiohydrolases is commonly used (Ingram and Doran, 1995; Laymon et al., 1996). The endoglucanases randomly attack cellulose chains to produce polysaccharides of shorter length, whereas exoglucanases attach to the nonreducing ends of these shorter chains and remove cellobiose moieties. -glucosidases hydrolyze cellobiose and other oligosaccharides to glucose (Philippidis and Smith, 1995).

For enzymes to work efficiently, they must obtain access to the molecules to be hydrolyzed. This requires some kind of pretreatment process to remove hemicelluloses and break down the crystalline structure of the cellulose or removal of the lignin to expose hemicelluloses and cellulose molecules.

Thermochemical Bioethanol Production Processes

There are two ethanol production processes that currently employ thermochemical reactions in their processes. The first system is actually a hybrid thermochemical and biological system. Cellulosic biomass materials are first thermochemically gasified and the synthesis gas (a mixture of hydrogen and carbon monoxide) bubbled through specially designed fermenters. Biomass gasification reaction is:



A microorganism that is capable of converting the synthesis gas is introduced into the fermenters under specific process conditions to cause fermentation to bioethanol.

The second thermochemical ethanol production process does not use any microorganisms. In this process, biomass materials are first thermochemically gasified and

the synthesis gas passed through a reactor containing catalysts, which cause the gas to be converted into ethanol. Numerous efforts have been made since then to develop commercially viable thermochemical-to-ethanol processes. Ethanol yields up to 50% have been obtained using synthesis gas-to-ethanol processes. Some processes that first produce methanol and then use catalytic shifts to produce ethanol have obtained ethanol yields in the range of 80%. Unfortunately, like the other processes, finding a cost-effective all-thermochemical process has been difficult.

Conclusions

Biomass residues available from agricultural and forest processing constitute a potential source for production of chemicals such as ethanol, reducing sugars and furfural, using enzyme or acid-catalysed hydrolysis. Bioethanol can be produced from plentiful, domestic, cellulosic biomass resources such as herbaceous and woody plants, agricultural and forestry residues, and a large portion of municipal solid waste and industrial waste streams. To ensure that a low-cost energy feedstock is available, researchers are examining dedicated energy crops, wood and grass species that have been selected to produce high yields.

To produce bioethanol from cellulosic biomass, a pretreatment process is used to reduce the sample size, break down the hemicellulose to sugars, and open up the structure of the cellulose component. The cellulose portion is hydrolyzed by enzymes into glucose sugar that is fermented to bioethanol. The sugars from the hemicellulose are also fermented to bioethanol.

The worldwide desire to reduce greenhouse gas emission will lead to an increased interest in renewable resources for energy production. Cellulosic biomass materials are among the candidates to be used as a renewable resource. Ethanol has very good characteristics to be used as a fuel either in a neat form or in a mixture with gasoline. Bioethanol is a domestically produced liquid fuel from cellulosic biomass resources. It is a high-octane fuel that can contribute substantially to the automotive fuel supply. Ethanol is a potentially clean-burning fuel that reduces smog and emissions of carbon monoxide.

The use of gasohol (ethanol and gasoline mixture) as an alternative motor fuel has been steadily increasing around the world for a number of reasons. Domestic production and use of ethanol for fuel can decrease dependence on foreign oil, reduce trade deficits, create jobs in rural areas, reduce air pollution, and reduce global climate change carbon dioxide buildup. Ethanol, unlike gasoline, is an oxygenated fuel that contains 35% oxygen, which reduces particulate and NO_x emissions from combustion.

References

- Alternative Fuel Data Center (AFDC). 1997. *Replacement fuel & alternative fuel vehicle technical & policy analysis, an overview and summary*. The United States Department of Energy.
- Berg, C. 1998. *Towards a world ethanol market?* F.O. Licht Commodity Analysis, Germany.
- Bergeron, P. 1996. Environmental impacts of bioethanol, In C. H. Wyman (ed.), *Handbook on bioethanol: Production and utilization*. Taylor & Francis, Washington DC, pp. 163–178.
- Demirbaş, A. 1991. Catalytic conversion of residual lignocellulosic materials to an acetone-soluble oil. *Fuel Sci. Technol. Int.* 9:425–435.
- Demirbaş, A. 1998. Determination of combustion heat of fuels by using non-calorimetric experimental data. *Energy Edu. Sci. Technol.* 1:7–12.
- Demirbaş, A. 2003. Energy and environmental issues relating to greenhouse gas emissions in Turkey. *Energy Convers. Mgmt.* 44:201–213.

- Goldstein, I. S. 1981. *Organics Chemicals from Biomass*. CRC Press, Inc., Boca Raton, Florida, USA.
- Ingram, L. O., and Doran, J. B. 1995. Conversion of cellulosic materials to ethanol. *FEMS Microbiol. Rev.* 16:235–241.
- John, J. A. 1969. Hydration, in Miller SA (ed.), *Ethylene and industrial derivatives*. Ernest Benn, London, 690–801.
- Küçük, M. M., and Demirbaş, A. 1997. Biomass conversion processes. *Energy Convers. Mgmt.* 38:151–165.
- Lang, X., Macdonald, D. G., and Hill, G. A. 2001a. Recycle bioreactor for bioethanol production from wheat starch II. Fermentation and economics. *Energy Sources* 23:427–436.
- Lang, X., Hill, G. A., and Macdonald, D. G. 2001b. Recycle bioreactor for bioethanol production from wheat starch I. Cold enzyme hydrolysis. *Energy Sources* 23:417–425.
- Laymon, R. A., Adney, W. S., Mohagheghi, A., Himmel, M. E., and Thomas, S. R. 1996. Cloning and expression of fulllength *Trichoderma reesei* cellobiohydrolase I cDNAs in *Escherichia coli*. *Appl. Biochem. Biotechnol.* 57/58:389–397.
- Lewis, S. M. 1996. Fermentation alcohol. In T. Godfrey and S. West (eds.), *Industrial Enzymology*, 2nd Ed., New York: Stockton Press, pp. 12–48.
- Morrison, R. T., and Boyd, R. N. 1983. *Organic Chemistry*. Fourth Edition, Allyn and Bacon, Inc., New York, USA.
- Nelson, C. R., and Courter, M. L. 1954. Ethanol by hydration of ethylene. *Chem. Eng. Prog.* 50: 526–532.
- Paul, J. K. 1979. *Ethyl alcohol production and use as a motor fuel*. Noyes Data Corporation, New Jersey.
- Philippidis, G. P., and Smith, T. K. 1995. Limiting factors in the simultaneous saccharification and fermentation process for conversion of cellulosic biomass to fuel ethanol. *Appl. Biochem. Biotechnol.* 51/52:117–124.
- Roels, J. A., and Kossen, N. W. F. 1978. On the modeling of microbial metabolism. *Progress in Industrial Microbiology* 14:95–108.
- Rothman, H., Greenshields, R., and Calle, F. R. 1983. *The alcohol economy: Fuel ethanol and the Brazilian experience*. Francis Printer, London.
- Taherzadeh, M. J. 1999. *Ethanol from Lignocellulose: Physiological Effects of Inhibitors and Fermentation Strategies*. Thesis for the Degree of Doctor of Philosophy, Department of Chemical Reaction Engineering, Chalmers University of Technology, Göteborg, Sweden.
- Wheeler, K., Janshekar, H., and Sakuma, Y. 1991. *Ethyl alcohol*, In Chemical Economics Handbook. SRI International, USA.

Copyright of Energy Sources is the property of Taylor & Francis Ltd and its content may not be copied or emailed to multiple sites or posted to a listserv without the copyright holder's express written permission. However, users may print, download, or email articles for individual use.