Alcohol production from wood

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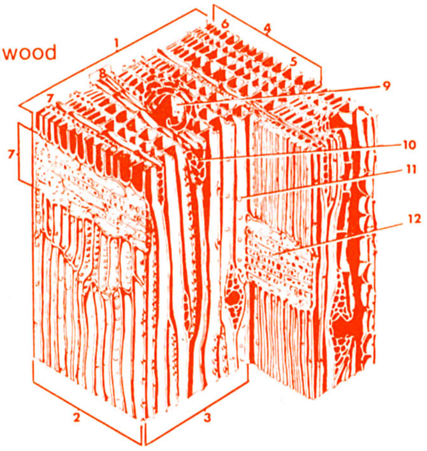


Wood structure of a softwood

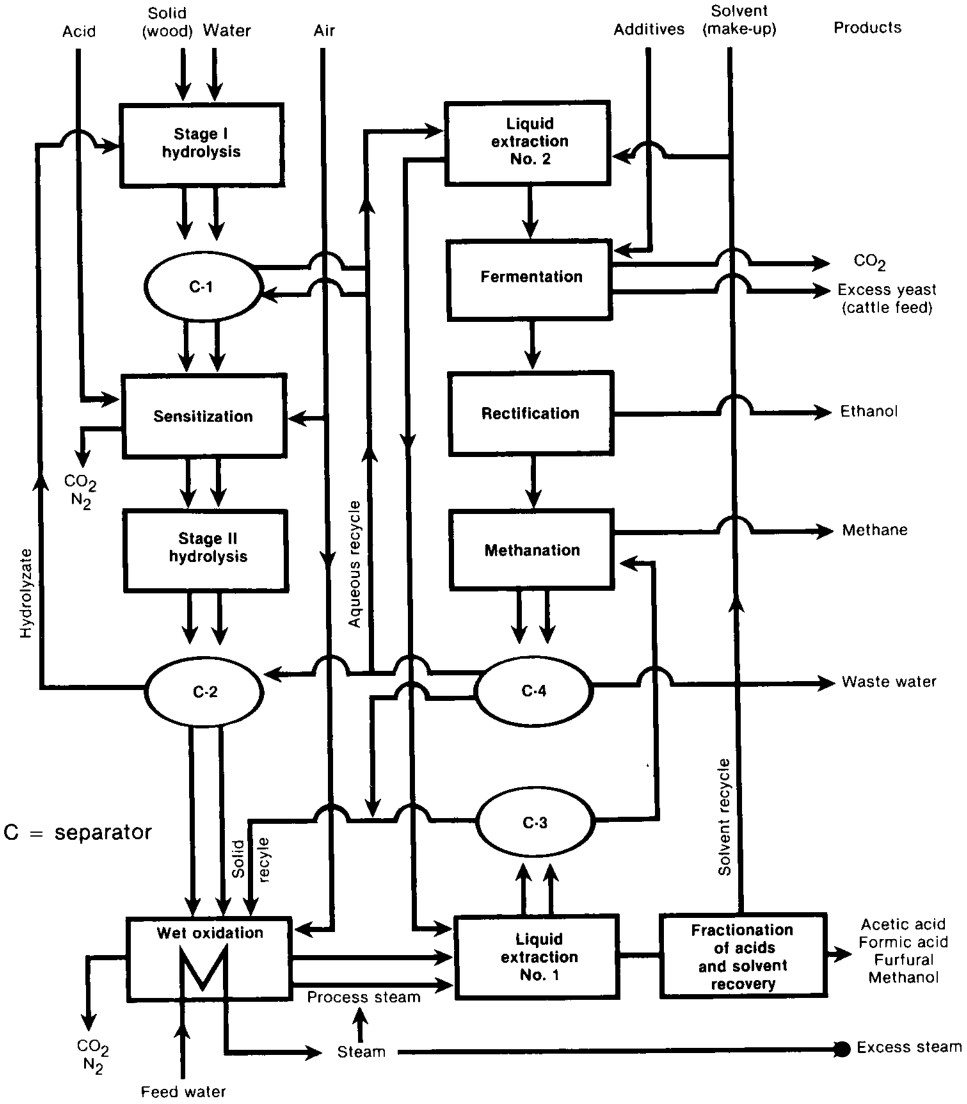
1. Cross-sectional face
2. Radial face
3. Tangential face
4. Annual ring
5. Earlywood
6. Latewood
7. Wood ray
8. Fusiform ray
9. Vertical resin duct
10. Horizontal resin duct
11. Bordered pit
12. Simple pit

Lignocellulose—the material forming the woody cell walls of plants—represents the single largest supply of polysaccharides (carbohydrates) produced in the plant kingdom that can be hydrolyzed to sugars and converted into fuel alcohol. Biomass materials that are preponderantly lignocellulosic include all wood residues generated in logging and sawmilling operations; prunings of orchard, vineyard, and ornamental plants; stalks of cotton plants; and stems of grasses including wheat, rice, barley, corn (stover), sugarcane (bagasse after extraction of sucrose), and bamboo.

Because of cell wall and molecular structures, the polysaccharides, and especially the cellulose, of lignocellulosic materials are relatively inaccessible to enzymatic hydrolysis, when compared with other materials such as starch, and they require severe conditions in acid hydrolysis. However, either dilute acid or concentrated acid hydrolysis of these materials is technically feasible on a commercial scale.

Designs of processes using either type of acid hydrolysis have disadvantages, and both involve complicated technology. In any hydrolytic process using lignocellulosic materials to produce ethanol, it will be essential to completely utilize the raw material, including the 25 to 40 percent insoluble ligneous residue produced in hydrolysis; to be energy efficient; and to be environmentally benign.

The process also should be able to accommodate a wide spectrum of biomass, including materials with a low polysaccharide content, such as bark of trees and shrubs, or little or no lignin, such as herbaceous plants, leaves, fruit pulp and other residues from food-processing plants, and spoiled or surplus fruits, vegetables, and grains. Biomass materials received at a plant site will have moisture contents varying from virtually overdried to over 90 percent (green basis). No processing step should be needed to adjust moisture content except, perhaps, blending different raw materials to provide a more uniform feedstock. Drying should be avoided except under the unusual circumstance that moisture content is so high that it would be economically advantageous.



Lignocellulosic plant materials can be converted to alcohol by the oxidative hydrolysis-wet oxidation-fermentation process shown in this schematic.

The new process

A process designed at the University of California Forest Products Laboratory meets the criteria set forth above and is being studied to develop specifications for equipment and to perfect it for full-scale operation. Basically, the system consists of hydrolysis in steps to produce the solutions of monosaccharides (simple sugars); fermentation of the sugar solutions to produce ethanol or other products; methanation to convert to methane the soluble organic products that are not isolated from the water solutions; and wet oxidation to convert solids produced in the process to soluble organic products that can be methanated or isolated, carbon dioxide, and thermal energy. This process is illustrated by the schematic diagram. The process flow shown does not present the simplest design, but it illustrates the potentially available products using a relatively basic design. This design can be expanded to produce a greater variety of products.

The raw material is prepared by hammermilling, using a minimum of energy to provide the optimum particle size. After removal of tramp metal, sand, and the like, the hammermilled material is introduced into the stage I pressure vessel at the as-received moisture content.

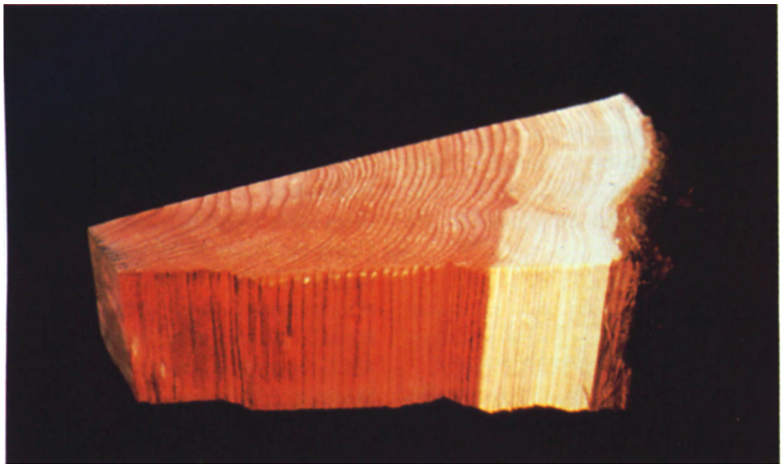
Stage I hydrolysis removes accessible polysaccharides, largely hemicellulose, from the feedstock. The result is a particle that can be readily crushed or refined to provide finely divided particles in a slurry. Substantially less energy is used than would be required to reduce the feedstock to the same size by only mechanical means.

Sensitization and stage II hydrolysis hydrolyze the more resistant (crystalline) or inaccessible cellulose and polysaccharides. Sensitization with oxygen increases the rate of cellulose hydrolysis. An acid added in this system provides a pH that will give an acceptable rate of hydrolysis at the elevated temperature used. Thus, this process is of the dilute acid type. The state II product—the hydrolyzate—may be introduced to stage I to carry out the hydrolysis of the accessible polysaccharides. Or separate hydrolyzates may be removed from either stage. If the latter design is used, acid and a stream of water from methanation must also be introduced to stage I.

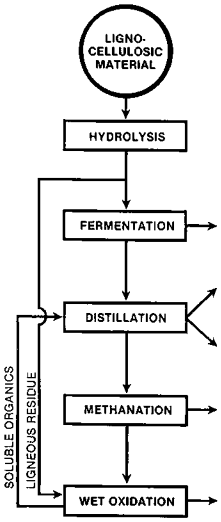
Liquid extraction number 2 may be required to remove any organic product from the hydrolyzate that may decrease the rates or the yields obtained in the fermentation reaction. Also, it is an optional step that can be taken to isolate extractable organic products, if such products are produced in sufficient amounts to make the additional processing economically attractive.

Fermentation is carried out using conventional equipment and techniques. This will include the modification that will be necessary to ferment pentoses (5-carbon sugars) when this technology is developed. Pentoses comprise about 20 to 30 percent, and hexoses (6-carbon sugars like glucose) about 45 to 60 percent of the weight of lignocellulosic materials.

Rectification of the beer from fermentation to produce ethanol at the desired purity



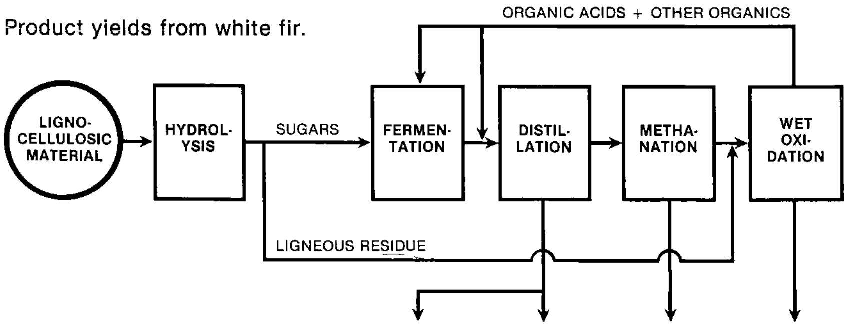
Wood and other lignocellulosic materials are abundant sources of carbohydrates for conversion to alcohol, but their cell walls and molecular structures make them difficult to break down.



Product yields per oven-dried ton of lignocellulosic material

	White fir	Maple	Cotton stalks	Sugarcane bagasse	Cereal grain	Rice
	pounds (gallons in parentheses)					
YEAST	—	—	—	—	—	—
ETHYL ALCOHOL	376 (57)	427 (65)	385 (59)	405 (62)	370 (56)	338 (51)
METHYL ALCOHOL	56 (9)	44 (7)	49 (7)	37 (6)	31 (5)	23 (3)
METHANE	243	211	221	238	193	160
THERMAL ENERGY	(To process)					

Product yields from white fir.



	WHITE FIR	SUGARS	LIGNEOUS RESIDUE	ETHYL ALCOHOL	METHYL ALCOHOL	METHANE	THERMAL	TOTAL
Pounds	2,000	1,422	522	376	56	243	—	675
Btu x 10^{-6}	16.96	9.57	6.49	4.82	0.54	5.78	3.19	14.33
Percent (Wt)	100	71.1	26.1	18.8	2.8	12.1	—	33.7
Percent (Btu)	100	56.4	38.3	28.4	3.2	34.1	18.8	84.5

and other volatile products (fusel oil) is performed using conventional equipment and processing.

Methanation produces methane from products in the aqueous still bottoms discharged from rectification and in the aqueous system discharged from wet oxidation. Again, conventional procedures and equipment are used.

Most of the water discharge from methanation is recycled to wash the solids in C-2 and C-1, and some is discharged as waste water from the process. The ratio of wash water to waste water determines the buildup of soluble inorganic materials in the process water. Make-up water (not shown in the schematic) is added to C-1 to improve washing of soluble hydrolysis products from the ligneous residue.

The amount of make-up water added is controlled to maintain the water balance in the system. Thus, make-up water is the difference between water output and water input (excluding make-up water). The output comprises water in the waste water discharge and water vapor in the off-gases of wet oxidation and fermentation and in the produce gas from methanation. The input, excluding make-up water, is water charged to the system in the raw material, in the acid reagent, and in the solution of additives used in fermentation.

The soluble solids content of the waste-water discharge is essentially inorganic, because soluble organics are consumed in the methanation step. This inorganic material originates from the soluble inorganic compounds present in the feedstock and from small amounts of chemicals and nutrients added during processing. These materials in the waste water should function as soil amendments when that water is used for irrigation.

Wet oxidation of the washed ligneous residue and organic solids from fermentation and methanation produces a large amount of heat used to produce steam. Either oxygen in air or gaseous oxygen is used as the oxidant in this step. Depending on conditions used, biomass is oxidized to variable amounts of products including water, carbon dioxide, a small amount of carbon monoxide, a mixture of organic acids, neutrals, and finely divided, partially oxidized, ligneous particles. Ultimate products of wet oxidation are carbon dioxide and water.

Wet oxidation can be carried out to maximize production of methane or to maximize production of thermal energy. It is highly pertinent that this thermal energy supplies all of the requirements of the process. Thus, the process is energy self-sufficient. The off-gases from wet oxidation are expanded through turbines to produce energy and are then processed to remove the small amount of carbon monoxide and trace amounts of any volatile organics that may be present. The volume of the gas to be processed will be greatly reduced if gaseous oxygen rather than air is used in wet oxidation. This would simplify any steps required for removing trace amounts of organic compounds that would be present in the off-gas from the process.

Liquid extraction number 1 is an optional step that can be included to isolate organic acids and some neutral products. Some of the compounds that can be produced are given in the schematic.

Potential of Alcohol and Energy from Lignocellulose as an Alternative to Motor Fuel in the United States

Fuel	Production equivalent/acre/year*		
	gal	*ft*^{3}	*Btu*
Ethanol	580	—	4.894 x 10^7
Methanol	70	—	0.444 x 10^7
Methane	—	50,000	5.342 x 10^7

Item	Import equivalent	Total
Motor fuel consumed, 1977		
Gallons x 10^{-9}	54.5	115
Btu x 10^{-15}	6.76	14.26
Acreage to replace motor fuel with ethanol & methanol (x 10^6)	126.6	267.1
% of forest and cropland†	10.7	22.6
Methane produced, Btu x 10^{-15}	6.76	14.27
Total energy produced, Btu x 10^{-15}	13.52	28.53
% of total energy consumption, 1977	17.6	37.1

*Produced by hydrolysis-wet oxidation-fermentation, assuming 10 tons oven-dried lignocellulosic material per acre per year.

†Forest land and cropland = 1,181 x 10^6 acres, Forest Statistics for the United States, Forest Services, U.S. Department of Agriculture, 1972, p. 2.

Conclusion

The new process, designed to fully utilize the raw material, to be energy-efficient, and to be environmentally benign, also accommodates a wide variety of biomass materials and an extreme range of moisture contents. It produces only three products—ethanol, methane, and thermal energy—but has the flexibility to produce additional materials—yeast that may be used in food or feed, organic acids, and several neutral compounds.

The system can produce one hydrolyzate containing all monosaccharides or, when processing biomass from angiosperms, separate hydrolyzates, one with a high percentage of glucose and the other with a high percentage of xylose (a pentose). The biological agents used in fermentation can be varied to provide a variety of metabolic products.

The thermal energy that can be developed by wet oxidation can be used to supply heat to other steps of the process so that it is energy-independent. The process has a low water requirement because of its high ratio of recycled water to discharged water. The waste-water discharge contains the inorganic matter of the biomass raw materials with small increments of inorganic agents added to control hydrolysis and fermentation steps. Organic matter is essentially absent.

Alcohol production from lignocellulose can provide a substantial percentage of the energy used in the United States, and this could be accomplished as rapidly as any program involving utilization of fossil or nuclear fuels. By processing of the type described, the amount of alcohols and methane produced from a ton of representative feedstocks is given in the table of process steps and products. The yields obtained from white fir as well as energy contents of these fuels are given in the table for white fir. Using the latter as typical of lignocellulose, in general, the potential of alcohol production by processing of this kind is given in the table showing the import equivalent and total motor fuel consumed in the United States in 1977.

For illustrative purposes, the basic assumption is made that 10 tons of lignocellulosic residue is produced annually per acre. Then the amount of alcohols produced on 126.6 million acres of land would be equivalent to the motor fuel produced from crude oil imported in 1977. This amounts to 6.76 x 10^{15} (10^{15} = quadrillion) Btu or 6.76 quads of energy. The total energy used in the United States during 1977 amounted to about 77 quads. An amount of energy almost equivalent to that in the alcohols is produced as methane. Thus, the total production of energy from the alcohols plus methane would have amounted to about 17.6 percent of the national energy consumption of that year. To replace the total motor fuel consumed that year, 267.1 million acres would be required. These land areas of 126.6 and 267.1 million acres amount to approximately 10.7 and 22.6 percent of the total U.S. forest and croplands. It is to be emphasized that residues, not the primary product, would be utilized.

In addition to weaning the United States from petroleum-based fuel, a national program to utilize lignocellulose in production of this kind would avoid the potential hazards of nuclear energy and the environmental impacts of coal utilization. Indeed, substantial benefits would accrue due to increased productivity from our crop and forest lands, increased employment opportunities, a new and stable all-year industry, and improvement in, rather than degradation of, our environment.

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