Advances in Technology at the National Renewable Energy Laboratory

Technology Brief

Cellulose Conversion Key to Fuel of the Future

NREL Improving Key Step in Producing Ethanol from Biomass

Do you have waste disposal problems? Do you have land sitting idle because it is not quite good enough for food crops? Would you like to be in on a major new industry—and help solve air pollution and global warming problems? The U.S. Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL) may have just the ticket—technology to convert cellulosic biomass such as agricultural residues and wastes to ethanol, a clean-burning alternative transportation fuel. Fundamental to the technology are the cellulose conversion processes under development at NREL.

David Parsons, NREL

Researcher monitors a continuous SSF system. This is a small-scale version of how a commercial system will likely operate.

Industries of all kinds—food processing, forest products, and pulp and paper, to name a few—face major problems with disposal of wastes derived from plant material. Large acreages of agricultural land, suitable for "energy crops" such as fast-growing grasses grown specifically for fuel production, are sitting idle, often suffering erosion damage. Americans want to recycle, but used newspaper markets are saturated. Many landfills are closing to avoid tougher regulations. Others are filling with paper and paperboard (38%), yard trimmings (18%), food waste (7%), and wood (6%)—all cellulosic materials that can be converted to fuels.

The technology developed at NREL solves such problems and others. For example, ethanol and its derivative, ethyl tertiary butyl ether (ETBE), are among the best additives available that meet the fuel oxygenate requirements of the Clean Air Act Amendments of 1990. Ethanol is also one of the best choices for complying with the alternative fuel vehicle requirements of the Energy Policy Act of 1992, as well as the new emissions regulations in California and other states. Domestic production of fuel ethanol also can help reduce U.S. dependence on foreign oil, improve our trade balance, and create jobs.

From Corn to Cellulose

Ethanol already contributes substantially to the world's transportation fuel supply. Ethanol made from sugarcane provides about half of the fuel for passenger cars and light-duty vehicles in Brazil. In the United States, ethanol made primarily from the starch in corn is used extensively as an oxygenated fuel extender. But DOE sees such great potential for fuel ethanol that it is eager to improve the efficiency of corn ethanol production and develop additional biomass resources for ethanol production. With DOE funding and industry cooperation, NREL scientists are expanding the range of potential feedstocks to include troublesome waste materials and non-food-source "energy crops."

Cellulose comprises nearly half of the dry weight of most plant material. Its breakdown to component sugars and subsequent fermentation is central to the U.S. Department of Energy's and NREL's efforts to develop biomass-to-ethanol technology.

NREL biomass-to-ethanol technology is moving toward commercial operation, integrating new technologies with those that are already commercially established. One of the largest U.S. ethanol producers, New Energy Company of Indiana, is working with NREL to ferment the cellulosic fiber in corn kernels, as well as the starch, with expectations of increasing ethanol yields by as much as 13%. Preliminary results were so encouraging that this pilot-plant project is being expanded to include corn cobs, husks, and stalks. As another example, one of the largest U.S. oil companies, Amoco Corporation, is working cooperatively with NREL to develop technology to produce ethanol from various cellulosic waste materials that often end up in landfills. Other major corporations such as Cargill and Weyerhauser that work with cellulosic resources have also expressed interest in the technology.

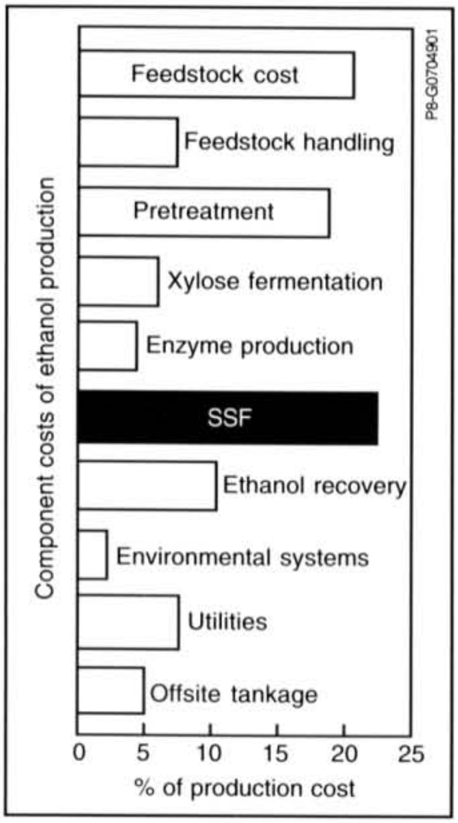
From Two Steps to One

Because cellulose comprises nearly half the dry weight of most plant material, the efficient and cost-effective breakdown (hydrolysis) of cellulose to its component sugars and their subsequent fermentation to ethanol is central to biomass-to-ethanol technology. NREL's conversion technology combines these two processes into a single step called simultaneous saccharification and fermentation (SSF). After a brief chemical pretreatment to render the lignocellulosic structure of the biomass more accessible to enzymatic attack, hydrolysis (saccharification) uses enzymes to transform the material into sugars that common yeasts can then ferment to ethanol. By fermenting the sugars as soon as they form, SSF eliminates problems with high sugar levels that would otherwise accumulate and inhibit enzyme activity. The single-step SSF process also saves on capital equipment costs because it requires about half as many vessels.

Effective Cellulose-to-Sugar Conversion Essential

Unlike starches and sugars, cellulose is a carbohydrate that humans and most animals cannot digest and yeasts cannot ferment. The common enzymes that convert starch to sugar are ineffective on the bonds that hold together the strands of sugar molecules in cellulose. Additional interactions between cellulose strands form a crystalline structure that gives wood its strength. This structure is not soluble in water, making enzymatic attack difficult.

Researchers have identified a number of microscopic fungi and bacteria that produce enzymes called cellulases that are capable of breaking down the cellulose structure into fermentable sugars. While some NREL scientists are working to select, improve, and produce the best enzymes and microorganisms, a primary challenge for NREL biochemical engineers is to develop processes to use the enzymes efficiently. Cellulose is the largest component of biomass—usually about half by weight—and its conversion to sugar accounts for about a quarter of the total projected cost of producing ethanol from biomass (see figure at the left). Cost-effective cellulose conversion processes are essential to the commercialization of biomass-to-ethanol technology.

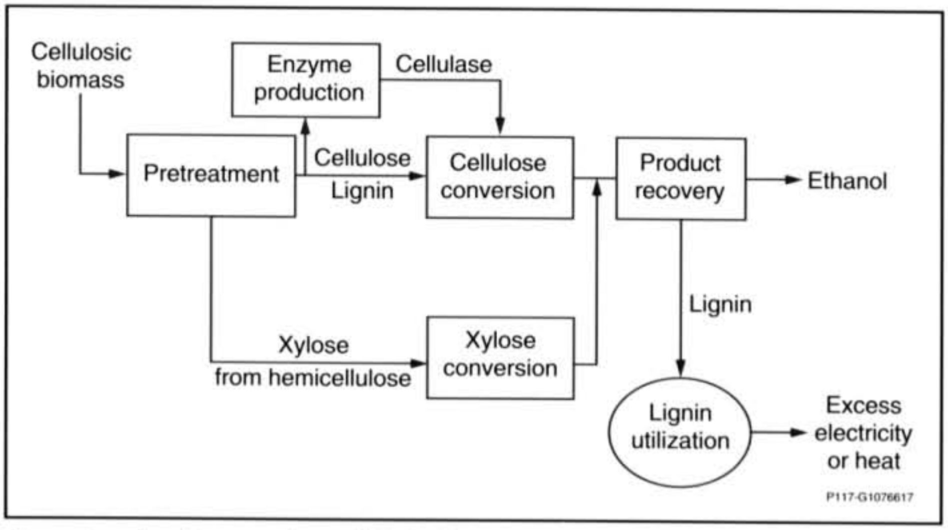


Cost breakdown for the NREL biomass-to-ethanol technology. Simultaneous saccharification and fermentation (SSF) of cellulose is central to making ethanol from biomass. It is also the single most expensive component. So improvements and cost savings in this area will greatly aid the economics of the technology.

From Good Yield to Better

One of the main challenges posed by SSF is selecting the best yeasts. In addition to having good fermentation yield and productivity, the yeasts must have demonstrated characteristics compatible with the enzymes. High-temperature tolerance is particularly important because hydrolysis proceeds at a faster pace at high temperatures. NREL has obtained the best results using the yeast *Saccharomyces cerevisiae* at a temperature of 38°C (100°F).

By using the best enzymes, yeasts, and operating conditions validated by mathematical modeling (see sidebar on page 3) and trials with various types of biomass, NREL is now able to convert more than 80% of cellulosic biomass to ethanol. The DOE and NREL goal is to achieve 95% yield while improving the final ethanol concentrations and productivity rates. Higher productivity and higher final concentration reduce operating and equipment costs, and higher concentration reduces ethanol recovery costs. Reducing the amount of enzyme required for hydrolysis will also significantly improve process economics.



The major steps in converting cellulosic biomass to ethanol

A primary NREL objective is to make the ethanol process flexible enough to accommodate a variety of different feedstocks and industry needs.

From Batch to Continuous Processing

NREL researchers are working to adapt the SSF technology from batch processing to continuous operation. In batch processing, one or more fermentors are used to process one particular batch of biomass. The fermentor is then cleaned out, and the process is started again with a new batch of biomass. In continuous processing, biomass material is continuously fed into and moved through a processing system so that, at any given time, each stage of the process is operating. For SSF, NREL's initial scale-up to continuous processing will likely use a series or cascade of separate fermentors.

Although the concept and advantage of SSF is to have both hydrolysis and fermentation occurring in the same vessel, the use of a series of separate vessels will allow researchers to optimize conditions at each stage of the process. For example, the first vessels in the series can be maintained at optimum conditions for hydrolysis (such as a higher temperature), while the last vessels can have optimum conditions for fermentation (such as a longer residence time). In moving to continuous processing, NREL's development team will also be seeking to improve vessel configuration to allow lower power mixing. This will help facilitate and preserve enzyme activity and maintain uniform temperatures while reducing costs.

From Laboratory to Pilot Plant

Refinement of the continuous process for SSF (and other conversion technology areas) is one of several major NREL efforts geared toward commercialization. Improving process integration—connecting all the different elements of ethanol production as they would be connected in an industrial facility—is another. The NREL process development unit (PDU) will allow practical application of such process research. The PDU scales up the process to a pilot-plant size of 900 kg (1 dry ton) per day feedstock capacity. The new NREL Alternative Fuels Users Facility (AFUF) will house both the process integration and PDU projects and be a unique facility available to outside researchers as well.

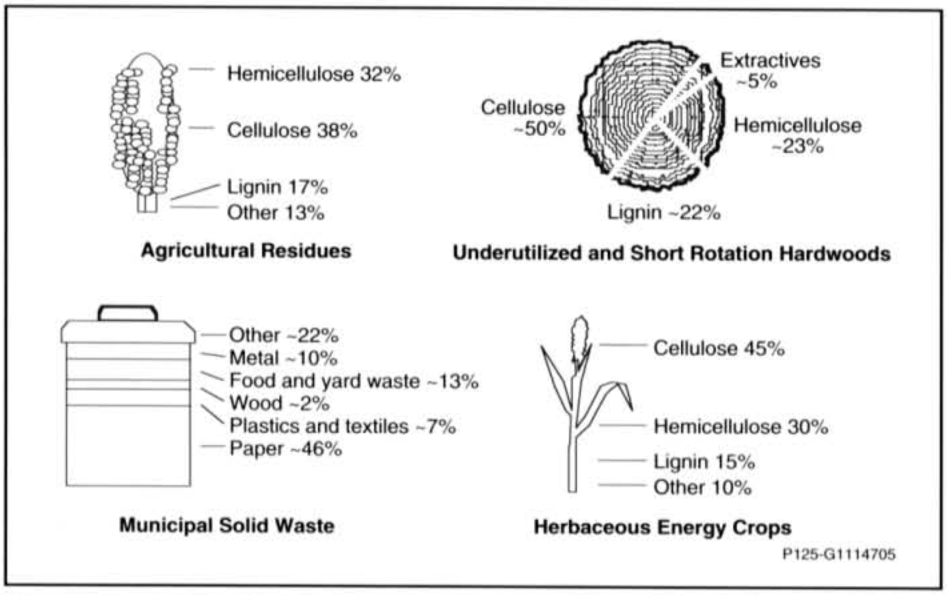
SSF is the heart of biomass-to-ethanol production. NREL's research in continuous process development is generating the data that will be used to design continuous SSF systems. The goal of all this work is to make SSF and the biomass-to-ethanol

SSF Model Guides Improvements Leading to Commercialization

By mathematically modeling the kinetics of SSF, NREL researchers have strengthened their understanding of the biomass-to-ethanol production process and increased their ability to improve it. Based on a nine-step description of the hydrolysis and fermentation process, the model takes into account characteristics of the biomass, enzymes, and microorganisms fed into the process and the interactions among them. Using this model, NREL researchers have been able to experimentally determine desired SSF characteristics within a 95% confidence level.

NREL researchers are also able to better determine the most effective ratio of enzymes to biomass and other optimal operating conditions by using the model. The model is invaluable for approximating answers to scale-up and commercialization questions. For example, researchers can use it to determine how changing the temperature or amount of enzyme would affect the final cost of the ethanol. The model is published and available to other researchers.

process both cost effective and flexible enough to accommodate a variety of biomass feedstocks and industry needs. With a well-demonstrated and cost-effective technology for cellulose conversion, ethanol from biomass will be poised to play a major role as an alternative transportation fuel. That role is one that can reduce U.S. dependence on foreign oil and balance of payments problems, improve air quality, reduce greenhouse gas emissions by as much as 90%, and create jobs in U.S. agriculture and industry.



The cellulose and hemicellulose components of a variety of different biomass feedstocks (including paper and yard waste) can be broken down to sugars and fermented into ethanol.

Other Possibilities

Although simultaneous saccharification and fermentation has proven to be the most effective process thus far, NREL is supporting research to explore several other potential cellulose conversion technologies. One possibility is the development of a single microbe that could effectively hydrolyze and ferment the cellulose directly. Researchers have identified bacteria and other organisms that both produce cellulase and ferment glucose. Because a process based on a direct-fermenting organism would involve fewer steps, it would save on capital equipment and operating costs. Other options that are being investigated to reduce process costs include combining cellulose conversion with other process steps such as ethanol removal or biocatalyst recycling. In addition, NREL researchers are employing both classical genetics and genetic engineering to develop more effective organisms, such as ethanol-tolerant fermenters.

Publications

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