CHEMISTRY ON A HIGH-CARB DIET

The chemical industry thrives on a petroleum-based menu. Economic and environmental factors are now driving a trend toward greater use of bio-based feedstocks. Chemists are developing the technology needed to make the bio-based revolution a reality.

BY RANDY WEDIN

Thanks to his famous low-carb diet, the late Dr. Robert Atkins has helped many individual Americans reduce their daily intake of carbohydrates. By changing the type of food they put in their bodies, these Americans hope to achieve slimmer waistlines and healthier lives.

But not everyone is planning to cut down on the carbs.

Thanks to the emerging technology of bio-based processing, chemists and chemical engineers are helping industries increase their daily intake of carbohydrates. By changing the feedstock they use in their manufacturing facilities—from petroleum to dextrose, for example—these companies hope to achieve a healthier environment and a fatter bottom line.

The term "bio-based products" designates commercial or industrial products, other than food or feed, derived from biomass feedstocks. "Biomass" refers to any organic matter that is available on a renewable or recurring basis, including agricultural crops and trees. These materials include carbohydrates (such as sugars, starches, and cellulose) as well as vegetable oils and proteins.

Bio-based technology, according to the vision of leaders in this field, could convert an acre of corn into a rack of designer clothes. Or transform a boxcar of soybeans into a small mountain of polyurethane foam. Or turn a field of switchgrass into a tank car of ethanol.

Producing chemical products from renewable resources is not a new idea. In fact, until the early part of the twentieth century, most chemical products and materials came from renewable resources. Following the dramatic growth and success of the petrochemical industry in the twentieth century, however, only about 5% of all of today's chemical products are bio-based.

Recent scientific and technical developments in biotechnology—from novel enzymes and biocatalysis to genomics and metabolic engineering—are beginning to shift the balance back in the direction of renewable feedstocks. Economic and environmental considerations may speed that shift. But can we really expect to replace

petroleum and natural gas as the feedstocks for an entire industry?

Many leaders are convinced that the answer is yes. A "roadmap" developed by a high-level federal advisory committee suggests that production of chemicals and materials from bio-based feedstocks will increase rapidly from today's 5% level to 12% in 2010, 18% in 2020, and 25% in 2030.

And Pat Gruber (ACS '03), vice president and chief technology officer at Cargill Dow LLC, believes these linear projections don't fully reflect the more rapid evolution of technology that is occurring. Says Gruber, "I think we'll see, in reality, something more logarithmic. Once companies see that it really is possible to make money from products from a bio-based infrastructure, we'll see an acceleration."

James Stoppert, senior director for industrial bioproducts at Cargill, believes that two-thirds of the $1.5 trillion global chemical industry can eventually be based on renewable bioresources. "It's not a question of 'if' it will happen," Stoppert said. "It's just a question of 'how fast' it will happen."

Cargill is a private company with a strong record of success in the agriculture, food, and commodity world. (With annual revenues of $60 billion and nearly 100,000 employees, Cargill would rank #12 in the Fortune 500 if it were a public company.) It's just one of many leading companies making big investments in this area. Other major players around the world with ambitious plans in bio-based processing include BASF, Bayer, Degussa, DSM, Dow, Dupont, and Shell.

CARGILL

JAMES STOPPERT

Vision Versus Reality: Do Diets Really Work?

Diets—whether the Atkins Diet, the South Beach Diet, or the next new diet that will sweep the nation—make big promises. And sometimes they deliver on those promises. However, true dieting success requires a long-term change in personal lifestyle and behavior—from buying preferences and cooking techniques to smaller meal portions and a whole new wardrobe.

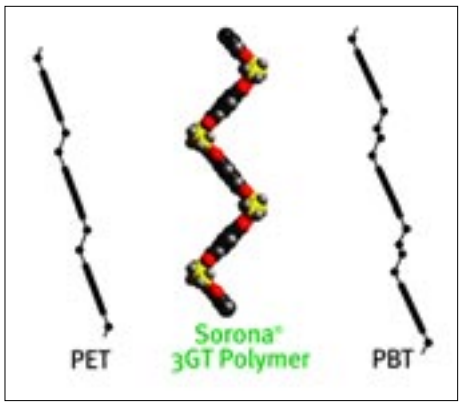
As the chemical industry considers the merits of a high-carb, bio-based diet, is the chemical community ready to embark on a long-term change in lifestyle? Can the chemical industry wean itself from feedstocks that rely on petroleum and natural gas? What benefits does this transformation promise? And what barriers stand in the way?

Bio-Based Benefits

The first and foremost benefit is that renewable feedstocks will reduce the chemical industry's dependence on fossil fuels. U.S. national and economic security will be strengthened as domestic industries free themselves from reliance on foreign oil. The United States has rich land and agricultural resources that will enable it to meet a growing demand for biological raw materials.

Feedstocks based on fossil fuels have two major economic drawbacks—the volatile nature of prices and the inevitable upward trend in prices. In sharp contrast, the costs for renewable resources have been stable for years and have even decreased in some cases. As these trends continue over the next few decades, renewable materials will become increasingly attractive as feedstocks.

Advances in research and development promise to further improve the economic



DUPONT

The properties of Sorona 3GT polymer derive from its unique molecular structure; strain deformation occurs first in the crystalline regions, allowing complete recovery.

attractiveness of bio-based products. For petroleum-based industrial products, the total product cost includes relatively high material costs and relatively low processing costs. Because of the already low processing costs, improvements in processing technology won't yield dramatic decreases in the total product cost. For bio-based products, however, the processing costs are relatively high, and material costs are relatively low. Therefore, as scientists and engineers develop more efficient processing technologies, the overall costs of bio-based products will drop significantly.

In addition to the economic benefits, bio-based products also help the environment. Bio-based processes, such as those involving fermentation in aqueous solution, often result in less pollution and fewer negative impacts to the environment than do petroleum-based technologies. Unlike those that are petroleum-based, renewable feedstocks do not contribute carbon dioxide to the atmosphere—an increasingly important concern with respect to climate change and global warming.

A number of new bio-based technologies, such as those developed by Cargill and by Dupont, have earned Presidential Green Chemistry Challenge Awards, which were granted in recognition of the environmentally friendly features of bio-based processing. The environmental advantages of bio-based products are also being embraced enthusiastically in Europe, where industrial biotechnology is known as

CARGILL DOW LLC

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BIO-BASED CONSUMER POLYMERS
Cargill Dow LLC is the first company to reach the consumer market with bio-based polymers. Products, such as fibers used in blankets and plastics used for packaging, are derived from corn grain in a process that includes processing (corn starch to dextrose), fermentation (dextrose to lactic acid), condensation (from lactic acid to the lactide monomer), and polymerization (from lactide to PLA, polylactic acid).

"white biotechnology." ("Green biotechnology" relates to agriculture and foods, "red biotechnology" relates to health care, and "black biotechnology" relates to bioterrorism and bioweapons.)

The possibility of new products exhibiting increased functionality and added value offers a third potential benefit. For example, Dupont recently unveiled Sorona, a family of polymers made from 1,3-propanediol. The first commercially available polymer from the Sorona polymer platform, Sorona 3GT polymer, promises to combine "the best properties of polyester and nylon while minimizing some of the manufacturing and production challenges associated with each." Although Dupont has been aware of the attractive properties of 3GT polymers for more than 50 years, this polymer family has only become commercially viable now that a bio-based process has been developed for the production of 1,3-propanediol.

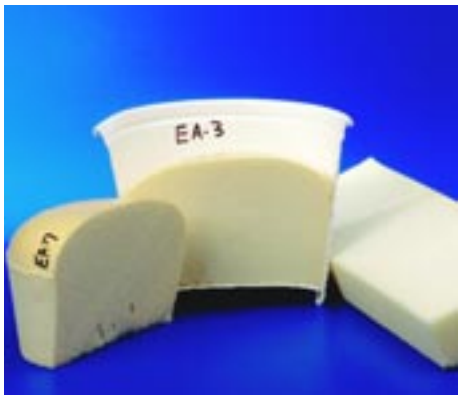
Given this triad of benefits—economic, environmental, and functional—it seems obvious that bio-based products have a bright future. However, a number of economic barriers and technical challenges still stand in the way of market success.

Bio-Based Barriers: Economic

The first barrier is cost. Most bio-based products are still more expensive than the same products produced from fossil fuels. The chemical industry has already invested billions of dollars of capital in the technology that uses petroleum-based feedstocks. Faced by the recent excess of capacity in the world chemical markets, companies haven't been eager to invest in new facilities and technologies.

"When there's hardware already in the ground, we'll never beat incremental economics," Cargill's Stoppert noted. "We're focused on the next time someone has to make a decision to build a plant. What technology are they going to build?"

The federal government is doing its part to increase the competitiveness of bio-based products by increasing market demand. The Federal Bio-Based Procurement Program, authorized by the 2002 farm bill, will require federal agencies to greatly increase their use of bio-based industrial products.



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POLYURETHANE FOAM FROM SOY-BASED POLYOLS
Which of these polyurethane foam samples were made from soybean oil? All three, thanks to a research partnership between Cargill and the Kansas Polymer Research Center at Pittsburg State University. From left to right: Sample EA-7 is Flexible Polyurethane Foam containing 30% soybean oil by weight. Sample EA-3 is Rigid Polyurethane Foam containing 40% soybean oil by weight. Unlabeled sample is Automotive Seating Grade Foam containing 15% soybean oil by weight.

CARGILL

BIO-BASED REFINERY
Biorefineries like Cargill's pioneering facility in Blair, NE, will yield many of the same products currently produced by petroleum refineries (liquid fuels, organic chemicals, and materials). The Cargill corn wet mill is designed to use all parts of renewable feedstock, getting the greatest value out of each part, from starch and cellulose to vegetable oil and protein.

"This program will improve environmental health by using renewable resources from our farms and forests to produce products that have been previously derived from fossil energy sources," U. S. Department of Agriculture (USDA) Secretary Ann M. Veneman said in announcing guidelines in December 2003. "This program will enhance the development of high-performing and environmentally friendly products."

When fully implemented, the federal program will require agencies to purchase bio-based industrial products whenever the cost is not substantially higher than for fossil-energy-based alternatives. This applies when bio-based industrial products are available and they meet the performance requirements of the federal user.

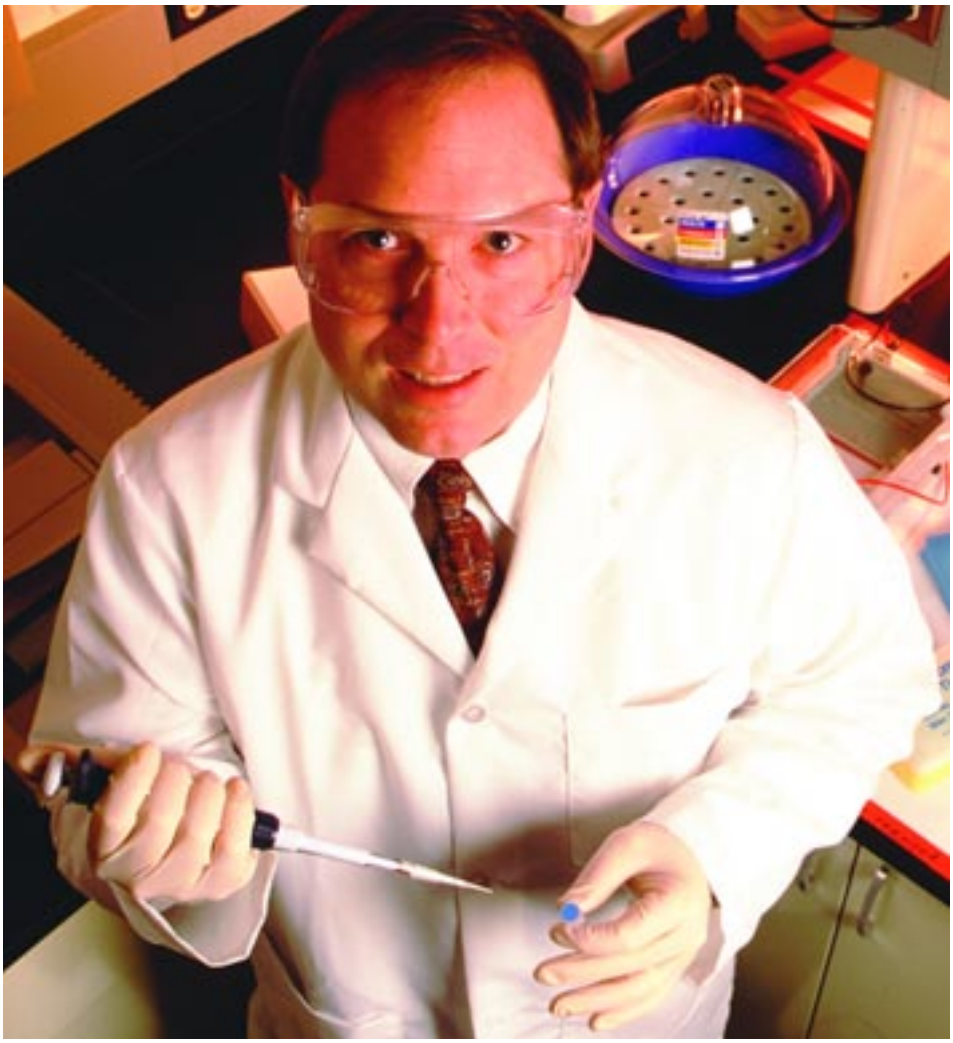
Chemical companies are expected to be among the first to take advantage of these new procurement policies. Cargill's Industrial Oils and Lubricants business announced its readiness to serve this market with products such as soybean-based transformer fluid, biodegradable grease, and hydraulic and transmission fluid containing 50% plant-based esters.

Clearly, cost presents a major barrier for the growth of bio-based products. But is price really that big a barrier? Even if bio-based products cost a bit more, won't most customers pay a premium for "going green," for buying a product if it's better for the environment?

The value of "going green" may vary from country to country. A recent survey of European consumers conducted for Cargill found that approximately 40% would pay 20 Euro cents extra per item for "fresh foods wrapped in nature-based packaging." Cargill manufactures NatureWork PLA, a plastic that "offers the convenience of traditional plastic packaging while helping reduce environmental impact." Cargill's Stoppert said consumers want to feel good about the products they use, and industry wants to feel good about the products they produce.

"If consumers can buy a product that's more environmentally friendly than the alternative and not have to pay a premium, that's an easy decision," Stoppert continued. "The same thing applies to companies. They'll take the renewable-based raw material every time—if they don't have to pay a premium for it. If they have to pay a premium, only a very small segment of the population will do that. We can't count on being subsidized. We can't count on consumers paying a premium."

Cargill therefore follows a twofold focus and strategy. First, it seeks to deliver products that bring a performance advantage and open up new markets. Second, it offers to existing markets products that bring customers' costs down through improved product performance, lower product costs, or both.



CARGILL

DOUGLAS CAMERON (ACS '81)

Bio-Based Barriers: Technical

In addition to the formidable economic barriers, the bio-based industrial sector faces a broad range of scientific and technical challenges. The federal government is playing a leadership role in this area as well, using grants to stimulate research and development. Through the "Biomass Research and Development Initiative" (http://www.bioproducts-bioenergy.gov/default.asp), USDA and the U.S. Department of Energy awarded $23 million to 19 industrial and academic projects late in 2003, and more research grants will be made in 2004.

Chemists and chemical engineers are key members of the teams involved in these projects. Douglas Cameron (ACS '81), biotechnology director of Cargill's biotechnology development center (and a former University of Wisconsin–Madison professor of chemical and biological engineering), identified some of the chemistry-related research opportunities that have captured the attention of the research community:

Chemistry's Bio-Based Future: Tips for Your Own High-Carb Diet

Some pointers for individuals who want to participate in the coming transformation of the chemical industry:

• Take some bio courses and some business courses. If you're a chemistry or a chemical engineering student, be sure to supplement your training with classes in biochemistry, molecular biology, microbiology, and bioprocessing. Cargill's Pat Gruber believes that everyone should also take some business classes "to learn about P&Ls, balance sheets, strategy decision, and organizational behavior."

• Read the patent literature. Students, as well as practicing scientists and engineers, need to become familiar with intellectual property issues and with searching the patent literature. Cargill's Doug Cameron points out that as many as 70% of the developments in the area of bio-based technology are reported in the patent literature, not the scientific literature.

• Network with colleagues through trade associations and/or scientific societies. Among the leading organizations:

ACS, American Chemical Society (www.chemistry.org), see especially the Biochemical Technology Division and the Green Chemistry Institute.

AIChE, American Institute of Chemical Engineers (www.aiche.org), see especially the newly created Society for Biological Engineering (bio.aiche.org).

BIO, Biotechnology Industry Organization (www.bio.org), see the Industrial and Environmental Section.

EuropaBio, the European Association for Bioindustries (www.europabio.org), see the section on "white biotechnology."

NABC, National Agriculture Biotechnology Council (www.cals.cornell.edu/extension/nabc).

SIM, Society for Industrial Microbiology (www.simhq.org).

• Attend ACS national and regional meetings and other conferences. If you had the time and money, you could attend a conference every week on this subject, but three meetings may top any list. One is the first annual **"World Congress on Industrial Biotechnology and Bioprocessing: Linking Biotechnology, Chemistry and Agriculture to Create New Value Chains"** (www.bio.org/worldcongress), sponsored by BIO, ACS, and the NABC, to be held April 21–23 in Orlando. The second is the **"26th Symposium on Biotechnology for Fuels and Chemicals."** (www.ct.ornl.gov/symposium), hosted by Oak Ridge National Laboratory, to be held May 9–12 in Chattanooga, TN. Finally, **"Metabolic Engineering V: Genome to Product"** (www.engconfintl.org/4ay.html), sponsored by Engineering Conferences International, will be held September 19–23 in Lake Tahoe, CA.

• Read reports from the experts. Four reports will quickly bring you up to speed on this field:

Biobased Industrial Products: Priorities for Research and Commercialization (books.nap.edu/html/biobased_products), produced by the National Research Council and published by the National Academy Press, 1999.

Industrial Bioproducts: Today and Tomorrow (www.bioproducts-bioenergy.gov/pdfs/BioProductsOpportunitiesReportFinal.pdf), a report prepared by Energetics, Inc., for the Department of Energy's Office of Biomass Programs, July 2003.

Roadmap for Biomass Technologies in the United States (www.bioproducts-bioenergy.gov/pdfs/FinalBiomassRoadmap.pdf), produced by a high-level advisory committee providing advice to federal agencies, including DOE, EPA, NSF, OSTP, and USDA, December 2002.

White Biotechnology: Gateway to a More Sustainable Future (http://www.europabio.org/upload/documents/wb_100403/Innenseiten_final_screen.pdf), a report from EuropaBio, April 2003

—RW

• Development of technologies to economically and efficiently break down cellulosic, hemicellulosic, or lignocelluolosic materials. Currently, industry must rely solely on starch from corn grain as the renewable feedstock. These new technologies would also allow, for example, the use of the stalks, husks, cobs, and leaves of the corn plant (known as "corn stover").

• Development of catalysts (including enzymatic, microbial, and traditional chemical catalysts) to transform carbohydrates or vegetable oils into useful chemical entities. New catalysts offer the possibility of stereospecific conversions, mild reaction conditions, and less-toxic byproducts.

• Use of metabolic engineering to build new metabolic pathways within whole-cell catalysts. Scientists are now able to select useful genes from a variety of sources, design new genes for novel reactions, and assemble these genes in a unique pathway. Drawing on some of the same modeling techniques used by chemical engineers, these metabolic engineers are essentially designing and building a factory-within-a-cell.

• Development of technologies for downstream processing, especially recovery of chemicals from dilute aqueous solutions. Most bio-based technologies, such as fermentation, involve aqueous solutions and will require different separation and purification technologies from those currently used in petrochemical processing. Promising research areas include membrane technology and liquid–liquid extraction.

• Development of "biorefineries," integrated processing plants that yield a variety of products. The goal of a biorefinery—such as the one based on Cargill's corn wet mill in Blair, NE—is to make use of all parts of the renewable feedstock. The challenge is to get the greatest value out of each part, from starch and cellulose to vegetable oil and protein. Over time, biorefineries will yield many products currently produced by petroleum refineries (liquid fuels, organic chemicals,

and materials). Biorefineries, however, will also be able to produce different products, including foods, feeds, and biochemicals.

Chemistry Tips the Balance

With any diet, the moment of truth comes when the individual steps on the balance scale and watches, at least metaphorically, as the balance arm hovers near the horizontal. Which way will the balance tip?

Malcolm Gladwell tackled the question in his popular book, *The Tipping Point: How Little Things Can Make a Big Difference*. He views major transformations in society as often resulting from a series of apparently small changes. If enough small changes in behavior or beliefs take place, a tipping point is reached, and a major transformation then becomes inevitable.

As the economic and environmental benefits of bio-based technology continue to grow, and as the economic and technical barriers continue to shrink, the chemical industry may be reaching a tipping point. Will our oil-based economy be transformed to a carbohydrate-based economy? And will chemists and chemical engineers tip the balance? ⬢

Randy Wedin (ACS '77) uses his chemistry Ph.D. in his career as a science writer and consultant. After working on ACS headquarters staff, he became president of Wedin Communications in Wayzata, MN. Randy is a frequent contributor to Chemistry.

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