control the size of this granule pool. Illies *et al.* do show that $IP_7$ has little effect on the second phase of insulin release, though this should be firmly established.

The precise steps in insulin release that $IP_7$ controls, and the mechanisms, remain speculative. Nevertheless, the addition of this factor to our understanding of insulin secretion provides a foundation for further studies. Moreover, because $IP_7$ is widely present in other cell types, it is likely to have physiological function in other secretory cell types.

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CHEMISTRY

# Chemicals from Biomass

Many chemicals used by the chemical industry can be derived from biomass, potentially reducing the industry's reliance on petroleum.

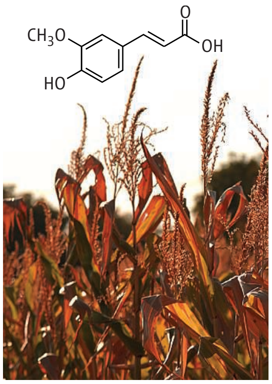
**David R. Dodds and Richard A. Gross**

Recently, there has been a strong political and technical focus on using biomass to produce transportation fuels (*1*, *2*). Much less attention has been given to biomass as a feedstock for organic chemicals. Replacement of petroleum-derived chemicals with those from biomass will play a key role in sustaining the growth of the chemical industry.

Currently, ~13% of the crude oil consumed by the United States is used for nonfuel chemical production (*3*). Biomass-based processes that could replace crude oil harness enzymatic methods, microbiology, and metabolic engineering to direct the transformation of sugars, lipids, and other biomass-derived molecules to the desired small molecules and polymers.

The biological production of commodity chemicals has considerable history. Between 1945 and 1950, 66% of the *n*-butanol and 10% of acetone in the United States were produced by fermentation of molasses and starch. Other commodity products produced by fermentation in the first half of the 20th century include acetic acid, citric acid, lactic acid, and itaconic acid (*4*). Increased prices of sugar feedstock and decreased prices of petrochemical feedstock ended the fermentative production of these commodities.

Now, the situation has reversed. A 2004 report by the U.S. Department of Energy (DOE) identified high-volume commodity chemicals that could be produced from biomass and can serve as starting materials for many chemical products via biological processes (*5*). A joint report by the DOE and the U.S. Department of Agriculture (*6*) concluded that U.S. agricultural and forest sources can renewably supply a billion tons per year of lignocellulosic biomass. This amount of biomass would not satisfy U.S. fuel demands, but could theoretically replace petrochemical feedstocks for chemical production.



**New feedstocks for the chemical industry.** Ferulic acid, a precursor for numerous aromatic chemicals used in the chemical industry, can be extracted from corn fiber. Many other important precursors can also be obtained from biomass.

Several commodity chemicals are already produced by fermentation, including glutamic acid (~1.7 billion kg/year worldwide), citric acid (~1.6 billion kg/year), and lysine (~850 million kg/year).

In addition to these commodity chemicals, commodity polymers may also be produced using biologically produced monomers combined with classical chemical methods, as well as through biological polymerization methods, either with isolated enzymes or in actively growing cells.

For example, lactic acid produced by fermentation (*7*) can be converted chemically to methyl lactate, lactide, and polylactic acid (PLA). The latter polymer—commercially available under different trade names—is a fully biodegradable replacement for polyethylene terephthalates (PETs) (*8*). Efforts are also under way to develop efficient processes for converting biologically produced lactic and hydroxypropionic acids to methacrylic and acrylic acids, respectively, both major commodity monomers consumed at ~1.6 billion kg/year worldwide.

Another well-known example is work by scientists at Genencor and DuPont, who have developed a cost-effective fermentative route to 1,3-propanediol (1,3PDO), the key building block in poly(propyleneterephthalate) (PPT, Sorona 3GT), which is not readily available from petrochemical feedstocks (*9*).

Immobilized enzyme catalysts have also been used to polymerize bio-derived monomers. For example, by using a commercially available lipase catalyst, direct polycondensations can be performed between sorbitol and/or glycerol with chemically or biologically produced diacids (*10*). This method dramatically reduces reaction temperatures and energy consumption relative to chemical polymerization processes, while also controlling branching during polymerization.

Fermentation by various microorganisms has been used to produce succinic acid (*11*, *12*), which may potentially replace maleic anhydride, now produced from butane at ~1.8 billion kg/year worldwide. (Maleic anhydride is the starting material for various polymers and industrial solvents.) In another example of microorganism-based production, the shikimic acid pathway in *Escherichia coli* has been reengineered to transform glucose to catechol and other aromatic alcohols (*13*); these indus-

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trial chemicals are currently produced from benzene. Further manipulation of this metabolic pathway leads to *cis,cis*-muconic acid, which can be converted chemically to adipic acid. The latter is one of two components required to produce Nylon 6,6 (*14*).

Polymers from biomass have also been produced completely within microbial cells. A notable example is the microbial synthesis of poly-3-hydroxyalkanoates (PHAs) (*15*).

Nor is fermentation a required action for the use of biomass-derived feedstock. Fischer-Tropsch chemistry has been run on pyrolysed biomass, and some commodity chemicals could be derived directly from biomass via conventional extraction methods. For example, corn fiber contains a high percentage of ferulic acid (see the figure), a flexible feedstock for various fine chemicals such as vanillin and guaicol. An estimated 1 billion kg/year of ferulic acid could be recovered from corn fiber separated in current corn-milling operations (*16*).

The rapid growth in the biodiesel industry, which uses chemical methods to synthesize its product, has decreased the market price of glycerol; many biodiesel production facilities now view crude glycerol as waste. Chemical companies can use this glycerol as a low-cost chemical building block. Dow Chemical Company, Huntsman Corporation, Cargill, and Archer Daniels Midland Corporation have begun, or announced plans, to chemically convert glycerol to propylene glycol (*17*). Dow Chemical Company and Solvay plan to build plants that use glycerol to produce epichlorohydrin (*18*).

Other innovative chemical methods convert fatty acids to polymer building blocks. For example, Cargill, working with the Kansas Polymer Research Center, has developed a bio-derived polyol (BiOH) by the chemical conversion of triglyceride carbon-carbon double bonds to alcohol and methoxy groups. Polyols are important precursors to numerous polyurethane materials (*19*).

Despite these achievements, the transition of industrial chemical production from petrochemical to biomass feedstock faces real hurdles. Biological processes do not require the high pressures and temperatures associated with most nonbiological chemical processes and thus have the potential to reduce costs. However, current processes for production of commodity chemicals have evolved through considerable investment to become highly efficient, often continuous, and well integrated. To be successful, new biological processes must rapidly approach similar levels of efficiency and productivity. Nevertheless, economic opportunities, available technologies, and environmental imperatives make the use of biomass and biological methods for industrial chemical production not only feasible but highly attractive from multiple perspectives.

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PHYSICS

# Better Computing with Photons

New findings in quantum optics reported at a recent conference are stimulating advances in quantum computing.

**Timothy C. Ralph and Robert W. Boyd**

For decades, researchers have been fascinated by the ways in which light acts as a quantum particle (photon). For almost as long, they have also pursued schemes in which photons can be used as information carriers and processors. As they have done every 6 years since the 1960s, the quantum optics community gathered to hear the latest results at the CQO (Coherence and Quantum Optics) and ICQI (International Conference on Quantum Information) conferences held 11 to 15 June 2007 at the University of Rochester in Rochester, New York, USA (*1*, *2*). This year's meeting did not disappoint, with a number of exciting developments combining quantum optics with quantum information.

Quantum optics (*3*–*5*) plays an important role in quantum information science (*6*–*9*) not only because light can manipulate matter with high precision, but also because the photon is so versatile as a quantum bit (qubit). The polarization of photons in a light beam acts as an ideal quantum mechanical two-level system that can be easily controlled and measured. For example, we can assign logical bit values of 0 and 1 to horizontal and vertical polarizations, respectively. Diagonal and elliptical polarizations, which are superpositions of the vertical and horizontal polarizations, then represent qubit states. Photons are also robust; when they travel through free space, their polarization is stable. Optics therefore represents an ideal way to transmit quantum information over large distances. For communication through an optical fiber, which tends not to preserve the polarization state, other variables such as timing or frequency can be used.

Although photons have their quantum information virtues, they also have their vices. First, they are very difficult to store. Thus, although great communicators, photons are not very good as quantum information memories. Second, it is difficult to make photons interact; in the absence of matter, photons take little notice of each other. Yet such interactions are required for processing quantum information, and without them it will be impossible to build large-scale quantum processors (also known as quantum computers). Third, and perhaps most important, high-quality single-photon states are difficult to produce on demand. The goal is to produce one and only one photon in successive identical pulses.

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