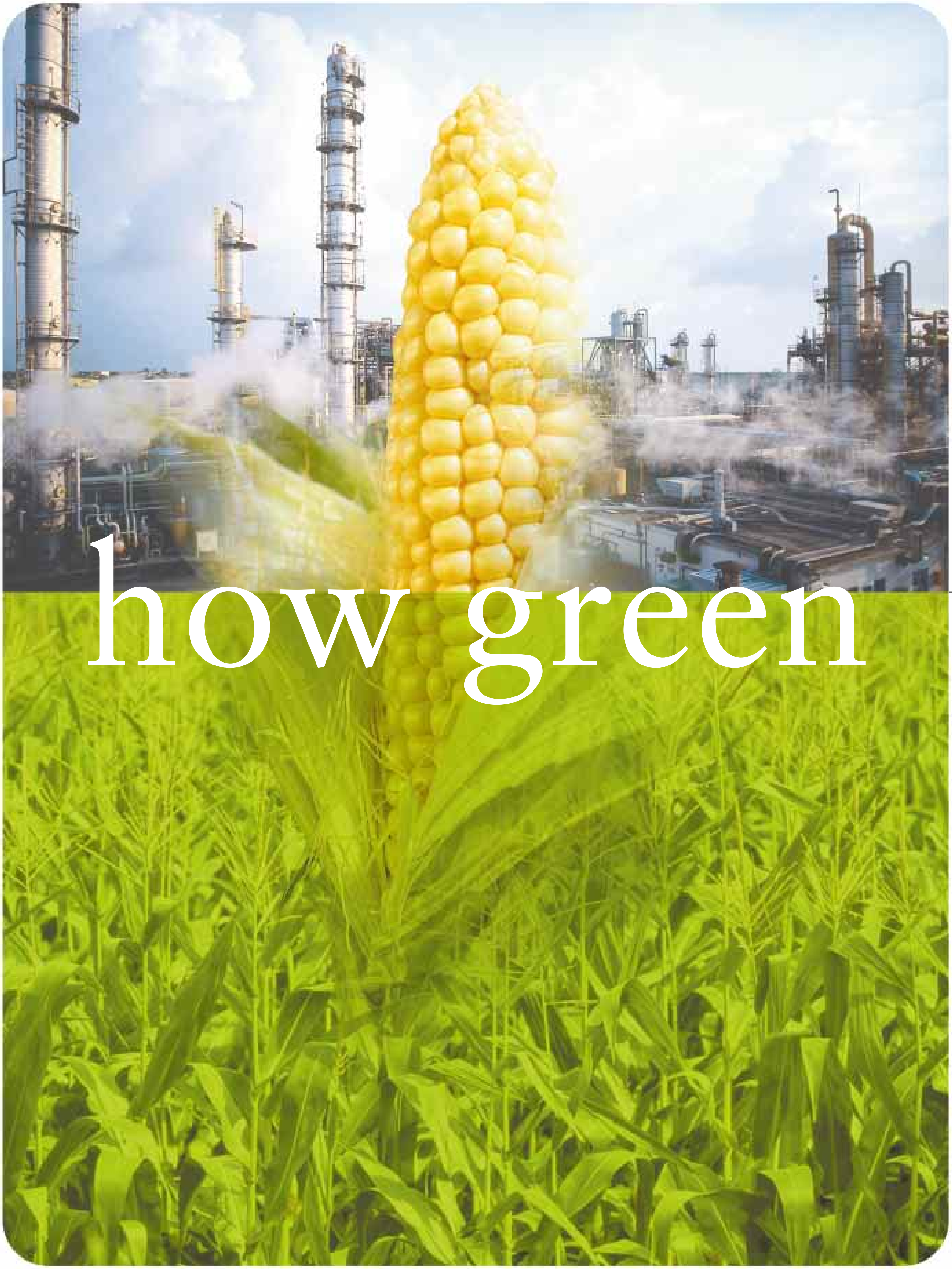

how green

*It is now technologically possible to make plastics using green plants rather than nonrenewable fossil fuels. But are these new plastics the environmental saviors researchers have hoped for?*

by Tillman U. Gerngross and Steven C. Slater

# are green plastics?

GROWING PLASTICS in plants once seemed to be an innovative way to lessen the global demand for fossil fuels.

TOM DRAPER DESIGN

Driving down a dusty gravel road in central Iowa, a farmer gazes toward the horizon at rows of tall, leafy corn plants shuddering in the breeze as far as the eye can see. The farmer smiles to himself, because he knows something about his crop that few people realize. Not only are kernels of corn growing in the ears, but granules of plastic are sprouting in the stalks and leaves.

This idyllic notion of growing plastic, achievable in the foreseeable future, seems vastly more appealing than manufacturing plastic in petrochemical factories, which consume about 270 million tons of oil and gas every year worldwide. Fossil fuels provide both the power and the raw materials that transform crude oil into common plastics such as polystyrene, polyethylene and polypropylene. From milk jugs and soda bottles to clothing and car parts, it is difficult to imagine everyday life without plastics, but the sustainability of their production has increasingly been called into question. Known global reserves of oil are expected to run dry in approximately 80 years, natural gas in 70 years and coal in 700 years, but the economic impact of their depletion could hit much sooner. As the resources diminish, prices will go up—a reality that has not escaped the attention of policymakers. President Bill Clinton issued an executive order in August 1999 insisting that researchers work toward replacing fossil resources with plant material both as fuel and as raw material.

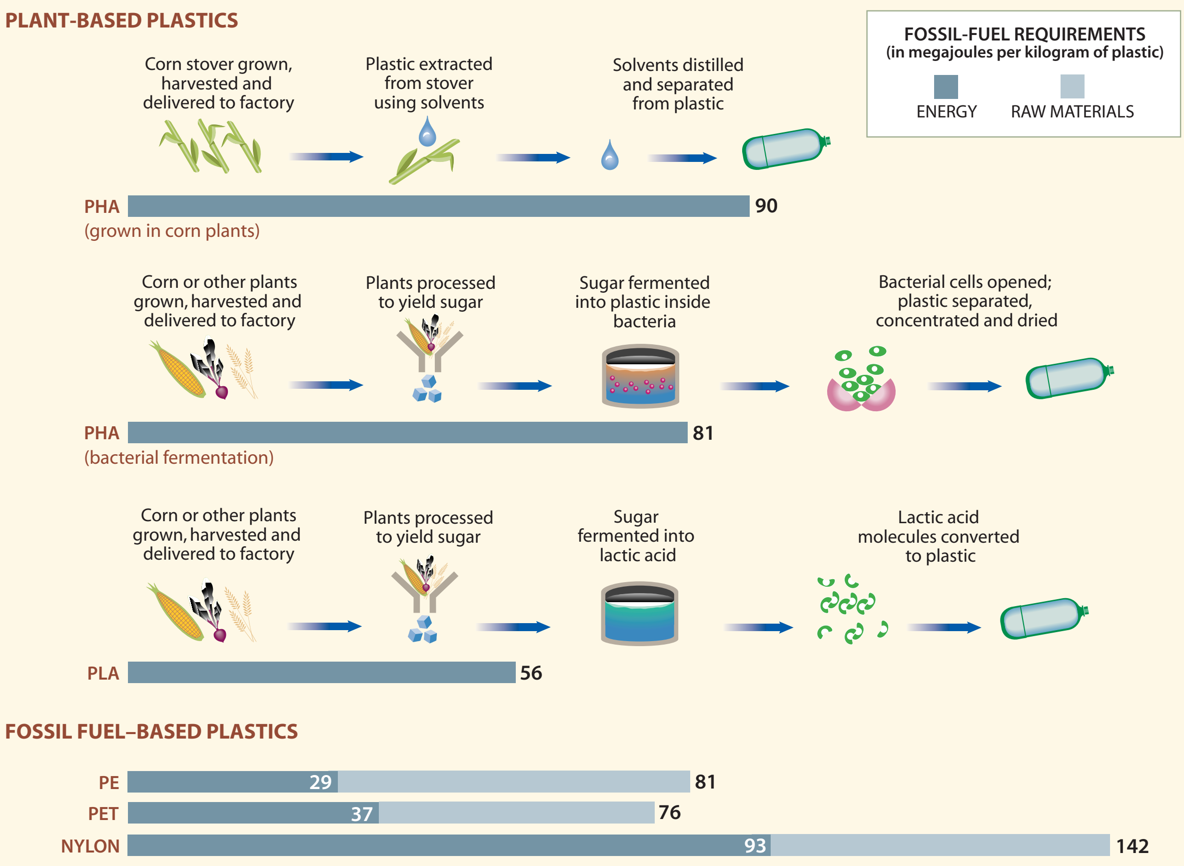
With those concerns in mind, biochemical engineers, including the two of us, were delighted by the discovery of how to grow plastic in plants. On the surface, this technological breakthrough seemed to be the final answer to the sustainability question, because this plant-based plastic would be "green" in two ways: it would be made from a renewable resource, and it would eventually break down, or biodegrade, upon disposal. Other types of plastics, also made from plants, hold similar appeal. Recent research, however, has raised doubts about the utility of these approaches. For one, biodegradability has a hidden cost: the biological breakdown of plastics releases carbon dioxide and methane, heat-trapping greenhouse gases that international efforts currently aim to reduce. What is more, fossil fuels would still be needed to power the process that extracts the plastic from the plants, an energy requirement that we discovered is much greater than anyone had thought. Successfully making green plastics depends on whether researchers can overcome these energy-consumption obstacles economically—and without creating additional environmental burdens.

Traditional manufacturing of plastics uses a surprisingly large amount of fossil fuel. Automobiles, trucks, jets and power plants account for more than 90 percent of the output from crude-oil refineries, but plastics consume the bulk of the remainder, around 80 million tons a year in the U.S. alone. To date, the efforts of the biotechnology and agricultural industries to replace conventional plastics with plant-derived alternatives have embraced three main approaches: converting plant sugars into plastic, producing plastic inside microorganisms, and growing plastic in corn and other crops.

Cargill, an agricultural business giant, and Dow Chemical, a top chemical firm, joined forces three years ago to develop the

## PRODUCTION AND ENERGY DEMANDS

**Plant-derived plastics require more energy to produce—and thus result in higher emissions of greenhouse gases associated with burning fossil fuels—than do many of their petrochemical counterparts.**

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first approach, which turns sugar from corn and other plants into a plastic called polylactide (PLA). Microorganisms transform the sugar into lactic acid, and another step chemically links the molecules of lactic acid into chains of plastic with attributes similar to polyethylene terephthalate (PET), a petrochemical plastic used in soda bottles and clothing fibers.

Looking for new products based on corn sugar was a natural extension of Cargill's activities within the existing corn-wet-milling industry, which converts corn grain to products such as high-fructose corn syrup, citric acid, vegetable oil, bioethanol and animal feed. In 1999 this industry processed almost 39 million tons of corn—roughly 15 percent of the entire U.S. harvest for that year. Indeed, Cargill Dow earlier this year launched a $300-million effort to begin mass-producing its new plastic, NatureWorks™ PLA, by the end of 2001 [*see box on page 40*].

Other companies, including Imperial Chemical Industries, developed ways to produce a second plastic, called polyhydroxyalkanoate (PHA). Like PLA, PHA is made from plant sugar and is biodegradable. In the case of PHA, however, the bacterium *Ralstonia eutropha* converts sugar directly into plastic. PLA requires a chemical step outside the organism to synthesize the plastic, but PHA naturally accumulates within the microbes as granules that can constitute up to 90 percent of a single cell's mass.

In response to the oil crises of the 1970s, Imperial Chemical Industries established an industrial-scale fermentation process in which microorganisms busily converted plant sugar into several tons of PHA a year. Other companies molded the plastic into commercial items such as biodegradable razors and shampoo bottles and sold them in niche markets, but this plastic turned out to cost substantially more than its fossil fuel–based counterparts and offered no performance advantages other than biodegradability. Monsanto bought the process and associated patents in 1995, but profitability remained elusive.

Many corporate and academic groups, including Monsanto, have since channeled their efforts to produce PHA into the third approach: growing the plastic in plants. Modifying the genetic makeup of an agricultural crop so that it could synthesize plastic as it grew would eliminate the fermentation process altogether. Instead of growing the crop, harvesting it, processing the plants to yield sugar and fermenting the sugar to convert it to plastic, one could produce the plastic directly in the plant. Many researchers viewed this approach as the most efficient—and most elegant—solution for making plastic from a renewable resource. Numerous groups were (and still are) in hot pursuit of this goal.

In the mid-1980s one of us (Slater) was part of a group that isolated the genes that enable the bacteria to make plastic. Investigators predicted that inserting these enzymes into a plant would drive the conversion of acetyl coenzyme A—a compound that forms naturally as the plant converts sunlight into energy—into a type of plastic. In 1992 a collaboration of scientists at Michigan State University and James Madison University first accomplished this task. The researchers genetically engineered the plant *Arabidopsis thaliana* to produce a brittle type of PHA. Two years later Monsanto began working to produce a more flexible PHA within a common agricultural plant: corn.

So that plastic production would not compete with food production, the researchers targeted part of the corn plant that is not typically harvested—the leaves and stem, together called the stover. Growing plastic in stover would still allow farmers to harvest the corn grain with a traditional combine; they could comb the fields a second time to remove the plastic-containing stalks and leaves. Unlike production of PLA and PHA made by fermentation, which theoretically compete for land used to grow crops for other purposes, growing PHA in corn stover would enable both grain and plastic to be reaped from the same field. (Using plants that can grow in marginal environments, such as switchgrass, would also avoid competition between plastic production and other needs for land.)

### The Problem: Energy and Emissions

Researchers have made significant technological progress toward increasing the amount of plastic in the plant and altering the composition of the plastic to give it useful properties. Although these results are encouraging when viewed individually, achieving both a useful composition *and* high plastic content in the plant turns out to be difficult. The chloroplasts of the leaves have so far shown themselves to be the best location for producing plastic. But the chloroplast is the green organelle that captures light, and high concentrations of plastic could thus inhibit photosynthesis and reduce grain yields.

The challenges of separating the plastic from the plant, too, are formidable. Researchers at Monsanto originally viewed the extraction facility as an adjunct to an existing corn-processing plant. But when they designed a theoretical facility, they determined that extracting and collecting the plastic would require large amounts of solvent, which would have to be recovered after use. This processing infrastructure rivaled existing petrochemical plastic factories in magnitude and exceeded the size of the original corn mill.

Given sufficient time and funding, researchers could overcome these technical obstacles. Both of us, in fact, had planned for the development of biodegradable plastics to fill the next several years of our research agendas. But a greater concern has made us question whether those solutions are worth pursuing. When we calculated all the energy and raw materials required for each step of growing PHA in plants—harvesting and drying the corn stover, extracting PHA from the stover, purifying the plastic, separating and recycling the solvent, and blending the plastic to produce a resin—we discovered that this approach would consume even more fossil resources than most petrochemical manufacturing routes.

In our most recent study, completed this past spring, we and our colleagues found that making one kilogram of PHA from genetically modified corn plants would require about 300 percent more energy than the 29 megajoules needed to manufacture an equal amount of fossil fuel–based polyethylene (PE). To our disappointment, the benefit of using corn instead of oil as a raw material could not offset this substantially higher energy demand.

Based on current patterns of energy use in the corn-processing industry, it would take 2.65 kilograms of fossil fuel to power the production of a single kilogram of PHA. Using data collected by the Association of European Plastics Manufacturers for 36 European plastic factories, we estimated that one kilogram of polyethylene, in contrast, requires about 2.2 kilograms of oil and natural gas, nearly half of which ends up in the final product. That means only 60 percent of the total—or 1.3 kilograms—is burned to generate energy.

Given this comparison, it is impossible to argue that plastic grown in corn and extracted with energy from fossil fuels would conserve fossil resources. What is gained by substituting the renewable resource for the finite one is lost in the additional requirement for energy. In an earlier study, one of us (Gerngross) discovered that producing a kilogram of PHA by microbial fermentation requires a similar quantity—2.39 kilograms—of fossil fuel. These disheartening realizations are part of the reason that Monsanto, the technological leader in the area of plant-derived PHA, announced late last year that it would terminate development of these plastic-production systems.

> ***Growing PHA in corn stover would enable both grain and plastic to be reaped from the same field.***

The only plant-based plastic that is currently being commercialized is Cargill Dow's PLA. Fueling this process requires 20 to 50 percent fewer fossil resources than does making plastics from oil, but it is still significantly more energy intensive than most petrochemical processes are. Company officials anticipate eventually reducing the energy requirement. The process has yet to profit from the decades of work that have benefited the petrochemical industry. Developing alternative plant-sugar sources that require less energy to process, such as wheat and beets, is one way to attenuate the use of fossil fuels. In the meantime, scientists at Cargill Dow estimate that the first PLA manufacturing facility, now being built in Blair, Neb., will expend at most 56 megajoules of energy for every kilogram of plastic—50 percent more than is needed for PET but 40 percent less than for nylon, another of PLA's petrochemical competitors.

The energy necessary for producing plant-derived plastics gives rise to a second, perhaps even greater, environmental concern. Fossil oil is the primary resource for conventional plastic production, but making plastic from plants depends mainly on coal and natural gas, which are used to power the corn-farming and corn-processing industries. Any of the plant-based methods, therefore, involve switching from a less abundant fuel (oil) to a more abundant one (coal). Some experts argue that this switch is a step toward sustainability. Missing in this logic, however, is the fact that all

## GREEN PLASTIC GETS PRACTICAL

**Patrick Gruber, vice president of technology for Cargill Dow, answers questions about his company's new plant-derived plastic.**

**How will NatureWorks™ PLA compete with petrochemical plastics?**

NatureWorks™ PLA combines several attributes into a single family of plastics. Its glossiness and ability to retain twists and folds better than its petrochemical counterparts, for example, appeal to companies that are developing PLA for candy wrappers and other kinds of consumer packaging. PLA also offers fabric manufacturers a natural fiber that can compete with synthetics, such as nylon, in both performance and ease of processing. Overall, industry sources have identified several billion pounds of market potential for PLA in areas such as apparel, activewear, hygiene products, carpet fibers and packaging.

**What are the environmental advantages of PLA?**

Because we use plant sugar rather than fossil fuels as the raw material for PLA, its production consumes 20 to 50 percent fewer fossil resources than do conventional plastics. PLA can be broken down into its original chemical components for reuse, or it can be recycled. One of our customers already plans to use PLA in recyclable carpet tiles. PLA will also biodegrade, much in the way that paper does, in municipal composting facilities. For these reasons, PLA will reduce society's dependency on fossil fuels while providing products that fit current disposal methods. These clear environmental benefits of PLA are a bonus—we believe that people will buy this plastic primarily because it performs well and can compete with existing technologies.

**Do these benefits offset the fact that the energy required to produce PLA is greater than that needed to produce some petrochemical plastics?**

It is important to realize that our PLA-manufacturing technology is only 10 years old and has yet to profit from the nearly 100 years during which petrochemical-plastic manufacturing has been improving. Even our first manufacturing facility, now being built in Nebraska, will use only 40 percent of the fossil-fuel energy that is required to power the production of conventional nylon. As our scientists and engineers optimize the production of PLA, we expect to reduce the energy requirements of our second and third manufacturing facilities, targeted for construction as early as 2004, by as much as 50 percent.

**Do you plan to address what Gerngross and Slater call "the environmental shortcomings" of PLA?**

Yes. Not only are we developing production methods that require less energy, we are also investigating more efficient ways to generate energy, including co-generation and use of renewable fuels such as plant material, or biomass. We are also pursuing alternative raw materials for PLA. Using fermentable sugars from corn stover would allow a second crop to be harvested from the same land used to grow corn grain. PLA can also be derived from wheat, beets and other crops best suited to particular climates.

**CANDY WRAPPERS are just one of the products that companies plan to manufacture from Cargill Dow's new plant-based plastic when it hits the market in late 2001.**

CARGILL DOW

fossil fuels used to make plastics from renewable raw materials (corn) must be burned to generate energy, whereas the petrochemical processes incorporate a significant portion of the fossil resource into the final product.

Burning more fossil fuels exacerbates an established global climate problem by increasing emissions of greenhouse gases, such as carbon dioxide [see "Is Global Warming Harmful to Health?" by Paul R. Epstein, on page 50]. Naturally, other emissions associated with fossil energy, such as sulfur dioxide, are also likely to increase. This gas contributes to acid rain and should be viewed with concern. What is more, any manufacturing process that increases such emissions stands in direct opposition to the Kyoto Protocol, an international effort led by the United Nations to improve air quality and curtail global warming by reducing carbon dioxide and other gases in the atmosphere.

The conclusions from our analyses were inescapable. The environmental benefit of growing plastic in plants is overshadowed by unjustifiable increases in energy consumption and gas emissions. PLA seems to be the only plant-based plastic that has a chance of becoming competitive in this regard. Though perhaps not as elegant a solution as making PHA in plants, it takes advantage of major factors contributing to an efficient process: low energy requirements and high conversion yields (almost 80 percent of each kilogram of plant sugar used ends up in the final plastic product). But despite the advantages of PLA over other plant-based plastics, its production will inevitably emit more greenhouse gases than do many of its petrochemical counterparts.

### The Answer: Renewable Energy

As sobering as our initial analyses were, we did not immediately assume that these plant-based technologies were doomed forever. We imagined that burning plant material, or biomass, could offset the additional energy requirement. Emissions generated in this way can be viewed more favorably than the carbon dioxide released by burning fossil carbon, which has been trapped underground for millions of years. Burning the carbon contained in corn stalks and other plants would not increase net carbon dioxide in the atmosphere, because new plants growing the following spring would, in theory, absorb an equal amount of the gas. (For the same reason, plant-based plastics do not increase carbon dioxide levels when they are incinerated after use.)

We and other researchers reasoned that using renewable biomass as a primary energy source in the corn-processing industry would uncouple the production of plastics from fossil resources, but such a shift would require hurdling some lingering technological barriers and building an entirely new power-generation infrastructure. Our next question was, "Will that ever happen?" Indeed, energy-production patterns in corn-farming states show the exact opposite trend. Most of these states drew a disproportionate amount of their electrical energy from coal—86 percent in Iowa, for example, and 98 percent in Indiana—compared with a national average of around 56 percent in 1998. (Other states derive more of their energy from sources such as natural gas, oil and hydroelectric generators.)

Both Monsanto and Cargill Dow have been looking at strategies for deriving energy from biomass. In its theoretical analysis, Monsanto burned all the corn stover that remained after extraction of the plastic to generate electricity and steam. In this scenario, biomass-derived electricity was more than sufficient to power PHA extraction. The excess energy could be exported from the PHA-extraction facility to replace some of the fossil fuel burned at a nearby electric power facility, thus reducing overall greenhouse gas emissions while producing a valuable plastic.

Interestingly, it was switching to a plant-based energy source—not using plants as a raw material—that generated the primary environmental benefit. Once we considered the production of plastics and the production of energy separately, we saw that a rational scheme would dictate the use of renewable energy over fossil energy for many industrial processes, regardless of the approach to making plastics. In other words, why worry about supplying energy to a process that inherently requires more energy when we have the option of making conventional plastics with much less energy and therefore fewer greenhouse gas emissions? It appears that both emissions and the depletion of fossil resources would be abated by continuing to make plastics from oil while substituting renewable biomass as the fuel.

**We did not immediately assume that these plant-based technologies were doomed forever.**

Unfortunately, no single strategy can overcome all the environmental, technical and economic limitations of the various manufacturing approaches. Conventional plastics require fossil fuels as a raw material; PLA and PHA do not. Conventional plastics provide a broader range of material properties than PLA and PHA, but they are not biodegradable. Biodegradability helps to relieve the problem of solid-waste disposal, but degradation gives off greenhouse gases, thereby compromising air quality. Plant-based PLA and PHA by fermentation are technologically simpler to produce than PHA grown in corn, but they compete with other needs for agricultural land. And although PLA production uses fewer fossil resources than its petrochemical counterparts, it still requires more energy and thus emits more greenhouse gases during manufacture.

The choices that we as a society will make ultimately depend on how we prioritize the depletion of fossil resources, emissions of greenhouse gases, land use, solid-waste disposal and profitability—all of which are subject to their own interpretation, political constituencies and value systems. Regardless of the particular approach to making plastics, energy use and the resulting emissions constitute the most significant impact on the environment.

In light of this fact, we propose that any scheme to produce plastics should not only reduce greenhouse gas emissions but should also go a step beyond that, to reverse the flux of carbon into the atmosphere. To accomplish this goal will require finding ways to produce *non*degradable plastic from resources that absorb carbon dioxide from the atmosphere, such as plants. The plastic could then be buried after use, which would sequester the carbon in the ground instead of returning it to the atmosphere. Some biodegradable plastics may also end up sequestering carbon, because landfills, where many plastic products end up, typically do not have the proper conditions to initiate rapid degradation.

In the end, reducing atmospheric levels of carbon dioxide may be too much to ask of the plastics industry. But any manufacturing process, not just those for plastics, would benefit from the use of renewable raw materials *and* renewable energy. The significant changes that would be required of the world's electrical power infrastructure to make this shift might well be worth the effort. After all, renewable energy is the essential ingredient in any comprehensive scheme for building a sustainable economy, and as such, it remains the primary barrier to producing truly "green" plastics. SA

## *The Authors*

TILLMAN U. GERNGROSS and STEVEN C. SLATER have each worked for more than eight years in industry and academia to develop technologies for making biodegradable plastics. Both researchers have contributed to understanding the enzymology and genetics of plastic-producing bacteria. In the past two years, they have turned their interests toward the broader issue of how plastics manufacturing affects the environment. Gerngross is an assistant professor at Dartmouth College, and Slater is a senior researcher at Cereon Genomics, a subsidiary of Monsanto, in Cambridge, Mass.

## *Further Information*

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