Biofuels and Biotechnology

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The biofuels renaissance is here. Even though Henry Ford originally designed the Model T to run on ethanol 100 years ago, ethanol and other biofuels have not been used much, at least, not in the U.S. During the first energy crisis in the 1970s and early 1980s, the first modern generation of biofuels was born: corn-to-ethanol production. The resulting ethanol was mixed with gasoline — up to 10 percent — and was called "gasohol." Ever since then, ethanol has been mixed with gasoline, especially in the Midwestern U.S., where corn is an important commodity and most ethanol plants are sited. It was (and is) subsidized by the government, but production remained low; in 2002, approximately 2 billion gallons of ethanol were produced, which represents approximately double that of 1990 levels. This amount is but the proverbial drop in the bucket compared with the approximately 150 billion gallons of gasoline consumed in the U.S. in 2007.

Since 2005, the price of petroleum-based products has risen sharply and many governments are investing heavily in the next generation of biofuels as a means to offset dependency on petroleum for liquid transportation fuels. Not only are governments investing in research, but also large multinational corporations are beginning to view biofuels as the next big energy wave. Indeed, in the U.S. there has been a sharp increase in the production of ethanol to between 6 and 7 billion gallons in 2007 and a fraction of a billion gallons of biodiesel. Thus, along with the renewed research effort in providing biofuel solutions, we are certain to see technological innovations, including biotechnology, to make biofuels more economical and sustainable.

Question: What are biofuels?

Answer. Current technology starts with sugar or starch to get ethanol, or from vegetable oil if the objective is to get biodiesel. Thus, the first-generation biofuels are primarily corn-grain- or sugarcane-to-ethanol, and biodiesel from waste grease or oilseed plants such as soybean or canola. These first-generation biofuel crops are plants grown more commonly for food and feed. That is, the agronomic, harvesting, and processing technologies to handle the plant parts or seeds are already mature in their development.

However, sugar, starch, and vegetable oil are in short supply, while other plant parts — such as lignin and cellulose — are plentiful, but cannot be used efficiently with current technology, as described later. Accordingly, the second generation of biofuels will probably yield the same fuel products — alcohols or diesel — but will be made more efficiently and sustainably. A successful transition will necessitate new crops — feedstocks — that are likely not going to be annual plants currently used for food/feed, and will necessitate new conversion processes and technologies to convert biomass to usable bio-based products, including fuels.

Biomass conversion can be performed using thermochemical or biological processes, or a combination of the two. Thermochemical processes, as the name suggests, use heat and catalysts. These processes are more advanced with regards to science and engineering but are costly with regards to energy inputs and the requirement for chemical or biological catalysts. Biological conversion relies on microbes and their enzymes, which has the potential advantage of increased efficiency, but requires much research and development for commercialization.

There are two concepts that are commonly used to describe these developments. The first is lignocellulosics and the second is the biorefinery.

Question: What are lignocellulosic feedstocks and why aren't we using them currently?

Answer: Lignocellulosic feedstocks are comprised of a mixture of agricultural- and forestry-biomass waste and dedicated bioenergy crops. The "lingo" refers to lignin and related molecules that are important crosslinking-structural components of plant cell walls. "Cellulosic" refers to cellulose and hemicellulose, the most abundant polymers on earth and that are part of the cell wall. The building blocks of these polymers are simple sugars that can be converted into ethanol. In contrast to only using a small part of the plant to convert to energy, such as the corn kernel, lignocellulosics use the bulk of the above-ground plant.

Growing dedicated biomass crops such as switchgrass and hybrid poplars would be a way to gain large amounts of lignocellulosic material for processing — yielding over 10 dry tons per acre per year. The main reason why lignocellulosic feedstock is not used is several-fold (aspects will be discussed later). In essence, cell walls are very hard to efficiently digest into sugars that can subsequently be used to make alcohols and other products. Plant biologists and chemists are working on this problem. But in many ways, exactly what the biorefinery does is a crucial component to making second-generation biofuels.

Question: What is a biorefinery?

Answer: Several biorefineries are being built, but as of this writing, none is completed and running. In concept, the biorefinery is patterned after the petroleum refinery. In the latter, crude oil is the feedstock, which is processed to yield gasoline, diesel fuel, airplane fuel, plastics, and other products. The biorefinery would take lignocellulosic feedstock and produce ethanol, chemicals, plastics, and other products. Since the concept has not been demonstrated on a large scale, we don't exactly know what is possible or feasible. A new industry is being born.

One thing is certain — breaking down cell walls into building blocks for fuel and co-products in the biorefinery is much more difficult than breaking down starch to glucose from corn kernels and more difficult than refining petroleum. Starch to glucose uses a single enzyme (amylase), whereas lignocellulosic feedstocks are much more complex and more recalcitrant to digestion. Thus, the biorefinery might use process biotechnologies with improved enzymes or altered microbes in the cell-wall-to-product conversion process. These would likely not be controversial in their implementation since they would be used in a contained factory, a practice common in bioprocessing.

Question: Does it really take more energy to make a gallon of ethanol than the ethanol contains?

Answer: Most scientists and economists clearly answer "no." This is the case even with the first-generation feedstocks such as corn grain. While the input costs, such as planting the seeds, and chemical costs for weed, insect, and disease control are energy-intensive, better crop genetics and farming practices have resulted in a quadrupling of average corn yield since 1940 and a better than 50 percent increase in the past 20 years. Most researchers believe that the net energy gain for corn is about 1.3-1.5. That is, 1.3 units of energy are gained for every 1 unit put into the system. Why scientists and companies are excited about lignocellulosic crops, such as perennial grasses like switchgrass, is that the net energy gain is thought to be somewhere between 5 and 20 for these feedstocks.

Question: Why is the net energy gain so much higher for switchgrass than for corn grain?

Answer: There are at least three reasons. First, for switchgrass, much of the above-ground part of the plant is harvested and used in the biorefinery — up to 20 times more biomass than for corn grain. Second, unlike corn that has to be planted every year, switchgrass is planted once every dozen years or so and it resprouts each spring and summer from underground parts of the plant, much like turfgrass in lawns. Third, switchgrass can be cultivated on marginal land and does not require many farm-inputs such as fertilizer, and it has few pest problems. The lower fertilizer use and runoff — compared with corn — is a very important environmental consideration. We cannot sustainably grow more and more corn for fuel without environmental consequences.

Finally, there is another important reason to start using biomass crops that are not food or feed plants. Even though the U.S. farmers grew more acres of corn in 2007 than in any year since World War II, the commodity price continues to greatly increase because of the large demand for corn grain for ethanol (doubling between 2004 and 2007) and from countries under development. Clearly there is a food versus fuel dilemma that must be addressed. It is an agricultural, economic, and ethical question that can be answered, in large part, by growing lignocellulosic feedstocks on land not currently used for food crops. Thus, lignocellulosic crops should enhance, and not disrupt, the agricultural economic sector.

Question: So, if switchgrass and other biomass crops are so great, why is genetic improvement by breeding and biotechnology needed?

Answer: Recall that one of the reasons for the improvements in considerable net energy gain for the corn-grain-to-ethanol path is greater corn yield in recent years. Another reason is improved processing technology. Unlike corn, switchgrass (Figure 1) and other biomass crops are largely wild plants that have not been domesticated. Domestication traits in grasses such as predictable branching, erect leaves, dwarfing via shortened internodes, and efficient nutrient use are the reason behind the large yield gains of grain crops during the "Green Revolution" in the 1960s and 1970s.

The large amount of genomics information from DNA sequencing projects has led to the identification of many genes responsible for domestication traits, often in species other than bioenergy plants. Thus, genetic improvement using breeding or biotechnology will certainly increase the amount of biomass that can be grown per acre. It is also certain that genomics information will be useful in understanding how cell walls are made and how they might be better degraded in the biorefinery. Some of the key cell wall components to be modified are lignin (need less and perhaps different kinds) and cellulose (need more). In fact, some researchers believe that the plant itself could signal for cell walls to begin degradation in the field.

Biotechnology could enable or hasten the development of more easily processed feedstock. It is possible that digestive enzymes and enzymes coding for co-products could be overproduced in plants. Finally, genetic improvement must be done responsibly for sustainable deployment. Switchgrass, for example, is native to the U.S. where switchgrass as a biomass crop would be grown.

Biotechnology is almost certainly going to be part of the bioenergy equation, and honest discussions need to continue about how it will best be used. It will likely have benefits as a tool to discover how cell walls are made and broken down, and then implemented in improving the feedstock itself, as well as processing. The key will be to produce plants that have a low environmental impact, and that provide maximum gallons per acre so as to decrease the price per gallon of fuel and require less land to feed a biorefinery.

There are many things we don't know in this very young industry. We don't know the optimal feedstock plant(s) and which processes will be most useful in a biorefinery. Finally, while most of this article is about lignocellulosic feedstocks to ethanol, the pathway most developed for the second-generation biofuel, it might be that other fuels could be produced such as methanol, butanol, and/or biogas. And even though the biodiesel market is smaller than the ethanol market, there are also efforts to examine new perennial plants that could be used sustainably for oils to be converted to biodiesel.

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QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Figure 1. Switchgrass in growth chamber. (Photo courtesy of N. Stewart / University of Tennessee.)