

Bioconversion and Biorefineries of the Future

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I. Introduction

Although the environmental, economic and social impacts are still being debated, it is clear that the atmospheric concentrations of greenhouse gases (GHG) are increasing. The atmosphere in 2000 held about 774 Pg (774 billion metric tonnes) of carbon (C) as carbon dioxide (CO₂), corresponding to an average concentration of 369 parts per million by volume (vppm) (Marland & Boden, 2001). At the present rate of emission, the projected total will double by the end of this century. To achieve the goal of stabilizing the total carbon in the atmosphere at about 550 vppm, it will be necessary to reduce GHG emissions. The USA alone is expected to release 1.8 Pg of carbon in 2010 and 2.1 Pg of carbon in 2020, about 25% of the world total (EIA 2000). To maintain the target carbon dioxide concentration through the end of this century, current anticipated emissions must be reduced by 1500 Pg C (Edmonds. this volume).

Most of current carbon emission to the atmosphere is a direct result of the use of fossil fuels. The enormity of the problem suggests that many different and coordinated actions must be taken. One approach to reduction of carbon emissions is to substitute renewable biological sources for fossil sources of combustion fuel and other products. The US

Government has enunciated the goal of displacing 10% of the petroleum used in the USA with biomass derived fuel and products by 2020 (DOE Vision for Bioenergy and Biobased Products in the United States, October 2002). The vision is the development of the technical, commercial and political infrastructure analogous to the current oil refinery concept. In the “biorefinery” renewable biomass is “cracked” to useful components using “bioconversion” technology. The resulting components are separated into useful streams for production of fuels, power and products. Here we explore the current biorefinery concept with respect to its potential contribution to reduction in greenhouse gas emissions.

Sources and nature of biomass

The biomass of the world is synthesized via the photosynthetic process that converts atmospheric carbon dioxide to sugar. Plants use the sugar to synthesize the complex materials that are biomass. Biorefineries require a large and constant supply of biomass. Biomass for use in the biorefinery could include grains such as corn, wheat and barley, oils, agricultural residues, waste wood and forest trimmings and dedicated energy crops such as switchgrass (*Panicum virgatum*) or hybrid poplar (*Populus*). Use of grains and oils for energy reduces their availability for use as food or feed. The part of the plant that remains following harvesting of the grains and oils-- the stover and straw == are also sources of biomass but their use does not reduce the supply of food. Corn stover is the leading candidate as a biomass source to support a lignocellulosic Biorefinery because of large quantities available. It has been estimated that in the USA there is a potential supply of between 60 to 100 million tons per year (Elander, 2002; Kadam & McMillan, 2003). Municipal solid waste and waste from wood processing and from forest thinning operations are additional sources of biomass for use in producing fuel, power and products in biorefineries.

All forms of biomass have the same major components--cellulose, hemicellulose, and lignin. Cellulose is the largest fraction (40 to 50%), hemicellulose is next (20 to 30%) and lignin is usually 15 to 20% of biomass. The structures of these substances are shown in Figures 1,2 and 3.

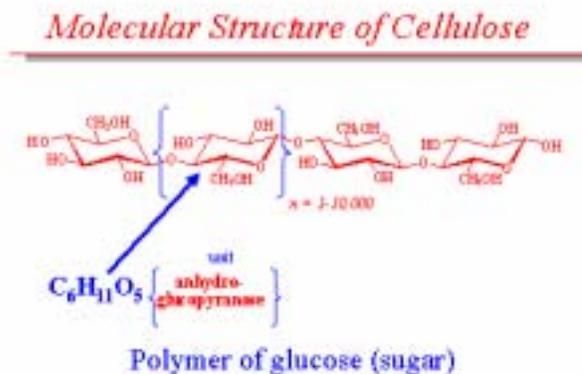


Figure 1 Cellulose structure

Bioconversion

The term bioconversion is used in several ways. One definition limits the term to the conversion of organic wastes to methane via a biological process involving living organisms (also known as anaerobic digestion). This process does not lend itself very well to the biorefinery concept, as the biomass is converted to the simple one carbon compound, methane. Further refining of methane may yield hydrogen, but few other products are easily or economically produced. This is but one example of bioconversion.

Here we consider bioconversion to be the use of biological processes to transform biomass materials from one form to another. Such conversions involve the use of enzymes, microbes or other biological agents, alone or in combination. It is important to note that in the 'biorefinery' the bioconversion processes involve the use of both physical and chemical methods. For example, the current process for "cracking" corn involves, steeping the corn kernels (a biological process), followed by grinding and separation, followed by conversion of the corn starch by thermostable alpha amylase in a jet cooking step at 100 C (a combination of biological and thermal processes), followed by treatment with a second enzyme to produce a 95% glucose syrup. In another example, the hemicellulose fraction of a lignocellulosic material such as corn stover (wheat and rice straw, as well) can be separated by a thermo-chemical treatment prior to use of enzymes to convert the cellulose fraction to glucose. It is interesting to compare the process of anaerobic digestion that yields methane to the "biorefinery" process that yields ethanol. Anaerobic digestion employs, for the most part, complex biomass that is converted directly by microorganisms. In what may be called the current "biorefinery concept", the biomass is "pretreated" to produce simple sugars. This is so because the organism used for centuries to make ethanol, the yeast, *Saccharomyces cerevisiae*, does not secrete the enzymes required to convert complex biomass to sugars. The yeast must have glucose in order to make ethanol. The current lignocellulose-based biorefinery concept is based on the corn-milling model in which the biomass is converted to glucose

Definition of Biorefinery

The term "biorefinery" has been used to describe the, as yet unrealized, manufacturing paradigm for converting "lignocellulosic biomass and" to valuable products. The biorefinery is analogous to the petroleum refinery in that in it the biomass is "cracked" into separated components and each is converted to a separately marketed product. A biorefinery, then, is as a processing unit that refines biomass. This definition includes existing processing plants wherein grains (corn, wheat, barley and sorghum) and sugar cane are converted to starch, sugars, ethanol, organic acids and polymers. It is important to note that this definition of a biorefinery does not limit the method of conversion of crops to "bioconversion" alone. The biorefinery of the future is likely to integrate both bioconversion and chemical "cracking" technologies. In addition to ethanol, it is envisioned that in the future many valuable bio-based products will be produced from low value biomass. The concept is illustrated in Figure 4.

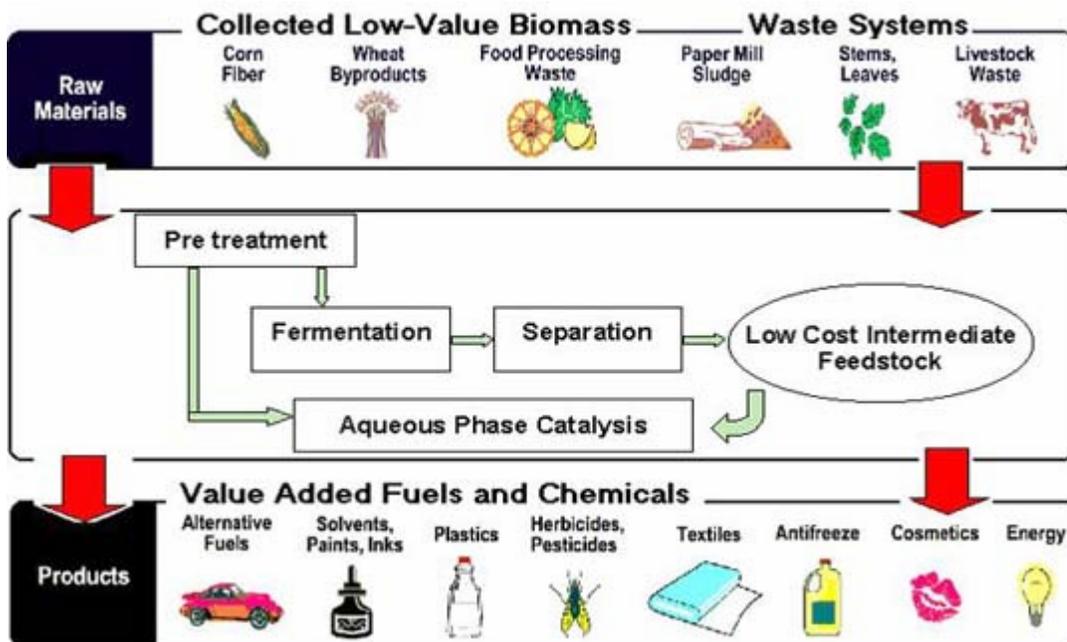


Figure 4. Bioproducts from low value biomass derived feedstocks

The history of the existing corn wet-milling industry may be indicative of how the biorefinery of the future will evolve. Initially the corn wet milling industry produced starch as the major product. As technology developed and the need for higher value products drove the growth of the industry, the product portfolio expanded from various starch derivatives such as glucose and maltose syrups to high fructose corn syrup. Later, fermentation products derived from the starch and glucose such as citric acid, gluconic acid, lactic acid, lysine, threonine and ethanol were added. Many other by-products, such as corn gluten, corn oil, corn fiber and animal feed are now being produced. The lignocellulosic biomass-based refineries may begin in a similar way with ethanol as their primary product. Since the majority of lignocellulosic material, including that in corn stover, is cellulose (glucose polymer), the production of ethanol from the glucose is likely to be the first product. Current technology development aims to engineer yeast or bacteria to convert xylose and arabinose to ethanol. An alternative to converting the hemicellulose to ethanol by means of engineered microbes is to employ new technology to convert the five-carbon sugars from hemicellulose to value-added products, via fermentation and/or catalytic conversion. Biorefineries of the future may produce another stream of value-added products from lignin. Technology development will be driven by the need to develop valuable products from every component of the biomass. Lignin makes up 18% of the corn stover and 80-100 million tons of stover/year may be available for conversion to ethanol; so that as much as 18 million tons of lignin could be available for production of new products. To date the only significant use of lignin is as a combustion fuel for power generation.

One view of the biorefinery is as a locally owned and operated independent entity devoted primarily to products for local markets and fuels for captive use within the biorefinery using one or a limited number of crops. We think it more likely, however, that bioconversions and biorefineries of the future may be integrated with the chemical, food, nutraceutical and pharmaceutical industries. In fact, such integration may be essential to the economic viability of biomass-based fuel production.

II. Bioconversion, microbial biodiversity and conversion of lignocellulosic feedstocks

The first bioconversion process was probably ethanol production. Taking a very broad view of the technology that is employed today to make ethanol one can conclude very little progress has been made in the last century although the cost of producing fuel ethanol has been cut in half over the last twenty years. Ethanol production involves grinding grain, adding water, adding yeast, incubation, decanting and distillation. A few enzymes have been added and some strain improvement of the yeast has occurred. During the last three decades a significant effort to employ cellulases to convert cellulose to glucose for yeast fermentations has not yet reached commercial application on a wide scale. The number of different microorganisms and enzymes that have been studied for this application is not large. Many have questioned whether we have fully exploited the biodiversity that exists in the microbiological world in biomass conversion and in other areas as well.

Estimates of the microbiological diversity that is uncharacterized range from 90 to 99%. This is an enormous untapped resource for new organisms and new information about how lignocellulosic materials are recycled in nature. It is logical to predict that the application of such new technologies as genomics, proteomics and metabolomics will result in the discovery and/or construction of new microorganisms and new enzymes to improve bioconversion of biomass. (Metting et al. this volume).

The current state of the art for lignocellulosic conversion can be characterized as “in development” and it employs basically the same paradigm established centuries ago. There has been a huge effort to develop pretreatment processes to convert the biomass to be compatible with the ethanol-producing organism. *Saccharomyces cerevisiae* does not produce extracellular enzymes, so it cannot grow on any biomass, including starch, and cannot use sugars other than glucose. Both yeast and *Zymomonas* have been engineered to convert five-carbon sugars to ethanol. However, these engineered fermentation organisms cannot meet the requirements for rapid and efficient conversion of sugars derived from lignocellulosic materials on a commercial scale. The new technologies, i.e. genomics, proteomics and metabolomics, will enhance our capability to examine the limitations of these and other engineered organisms and to improve bioconversion of biomass.

Using an approach analogous to the starch processing industry (wherein amylases are used to convert starch to glucose), current research is directed at engineering cellulase enzymes to be used directly to convert cellulose to glucose. Unfortunately, cellulose

resembles starch only in that both are composed of glucose. The nature of the structure of a glucose polymer with beta 1,4 bonds, as occurs in cellulose, results in an extremely rigid and crystalline polymer. Three different enzymes are required to completely hydrolyze cellulose to glucose. The process involves an endoglucanase activity to cleave bonds randomly within the polymer, an exoglucanase activity that cleaves off disaccharide units called cellobiose and an enzyme activity to hydrolyze cellobiose to two glucose molecules. Improving the specific activities of all three enzymes is desirable and requires comparable improvements in all three activities as these enzymes work in concert to achieve cellulose hydrolysis. DOE has large contracts with the two largest industrial enzyme producers (Genencor International and Novozymes) to develop improved cellulase systems. A process for simultaneous conversion of the biomass to sugars and fermentation uses cellulases and yeast together. This process has had little commercial success due to the high cost of cellulases. Even with improvement in specific activity or other efforts to lower the cost of the enzymes, the problem of the physical structure of the cellulose remains. A combination of chemical and biological treatments will be necessary for the ideal lignocellulosic “cracking” process similar to the use of high temperature and thermostable alpha amylase in starch processing.

On the other hand, a completely new paradigm may be required for the lignocellulosic biorefinery. After all, the current yeast-based paradigm has been practiced for hundreds of years. This new paradigm may emerge from study of as yet unexamined microbiological diversity. For example, among the filamentous fungi, there are numerous single organisms that produce cellulase, hemicellulase and ligninase enzymes extracellularly. These organisms can convert lignocellulosic materials to sugars, ethanol, carbon dioxide and biomass. In the future, pretreatment processes may involve a solid-state fermentation step that replaces, supplements or augments the yeast-based glucose-to-ethanol process. There are already examples of filamentous fungi being used with biomass by-products of corn processing such as distillers grains (composed of hemicellulose and cellulose) for direct conversion to organic acids. This may be the first example of the diversification of products from the dry mill ethanol plants and may lead to application of the technology to other cellulose rich biomass in these plants.

III. Bioconversion on the farm and century-scale impacts on petroleum use and carbon sequestration

Bioconversion of crop residues to produce fuel or energy at the farm scale is rarely practiced in the USA. There are a few examples of the use of anaerobic digestors to produce methane. While ethanol is not produced on individual farms, many dry mill ethanol plants have been built by farmer cooperatives in the Midwest. Even were the financial incentives present, there are significant technical obstacles to bioconversion of crop materials on the farm. Each farm would have to install fermentors, acquire and practice fermentation technologies, install collection and distillation technologies to produce methane and ethanol as fuel. Farm equipment and transportation vehicles that run on methane or 100% ethanol are not readily available. The concept of a self-sustaining farm operation, however idealistic, is unlikely to succeed when costs of fuel

production are nearly equal or less than the market value of the product. Small farms are disappearing and large commercial operations are driven to maximize profit; self-sustaining operation is not, necessarily valued. The low cost of petroleum derived fuel is an obstacle to use of bioconversion technologies on the farm.

Were all the farms in the USA to 'bioconvert' the large volumes of available residual crop biomass in order to produce their own power, a significant reduction in petroleum usage would result. Take, for example, the State of Iowa with 40 Million metric tons of corn stover (Sheehan et al., 2003). Processed at the farm, with a yield of 6.1 liters of ethanol and 0.035 liters of oil per tonne of stover, would provide 244 million liters of diesel fuel and 1.4 million liters of oil, eliminating the need for substantial amounts of fossil-derived fuels and the costs of transporting them to the farm. Over a period of 100 years this would be 24.4 billion liters of diesel fuel and 140 million liters of oil. For the USA the total would be at least 244 billion liters of diesel and 1.4 billion liters of oil.

If all the farms in the USA were to use bioconversion to produce their own power, the reduction of the use of petroleum might be significant if large volumes of residual crop biomass were converted. For example, if all the available corn stover in Iowa (40 Million metric tons (Sheehan et al., 2003) were collected at each farm and processed at the farm 6.1 liters/mt (244 Million liters) of diesel fuel and 0.035 liters/mt (1.4 million) of oil per metric ton would be saved as transportation costs would be eliminated. Over a period of 100 years this would be 24.4 billion liters of diesel fuel and 140 million liters of oil. For the USA the total would be at least 244 billion liters of diesel and 1.4 billion liters of oil.

The direct impact of on-farm bioconversion activities on soil carbon sequestration is worth exploring. Removal from the fields of all available corn stover in Iowa (an unlikely scenario) for conversion to ethanol or other products would leave none for incorporation into soil for carbon sequestration purposes (Sheehan et al., 2002). Rosenberg and Izaurrealde, 2001 concluded that significant amounts of carbon can be sequestered by employing various crop production practices. In the USA conservation tillage/ residue management has the potential of sequestering 3.5 to 10.7 Pg C over a 100-year period (Lal et al., 1998). The data on corn stover suggests that the impact on carbon sequestration might be significant. In the extreme case example (shown in Table 1), all available stover collected in the 10 producing States for 90 years would result in a loss of 1.4 Pg carbon. If the total projected to be sequestered in US croplands is 3.5 to 10.7 Pg C, the resulting impact over a 90-year period of stover removal from the fields ranges from a 10 to 40% reduction of the total carbon that might be sequestered from appropriate crop production practices in the USA

Table 1 Carbon lost with 100% collection of available corn stover

| | |
|--|---|
| USA Conservation tillage/residue management potential carbon sequestration (Lal et al., 1998) | 0.035 to 0.107 Pg/year or 3.5 to 10.7 Pg/100 years |
| Carbon lost in Iowa, 100% corn with no till, 100% available residue collection (Sheehan et al. 2002) | 0.14 Pg/90 years |
| Carbon loss for USA Corn no till, 100 % available residue Collection (10 states x Iowa's value) | 1.4 Pg/90 years |

The possible reduction in total carbon that might be sequestered in corn producing soils is only part of the potential impact of residue removal on carbon. Use of the stover to produce ethanol and bioproducts would have positive impacts on the balance of greenhouse gases. These impacts are discussed below.

VI. Local Biorefineries

One concept of the biorefinery is of a local processing unit designed to separate and refine agricultural crops. The whole crop is separated into its anatomical and chemical components, the idea being that the most valuable upgraded products could be economically transported to distant markets while the less valuable products could be used locally as feed and fuel.

The selection of the plant species to be grown for biorefineries is based on the utility of the whole crop for commercial purposes and, of course, on its adaptability to the location. In Europe wheat and rapeseed are seen as suitable plant species. In the USA there is a well-established industry to convert corn to value-added products, the corn wet-milling industry. In part, the success of the industry is based on economies of scale. Other crops useful for bioconversion are sorghum and sugar cane.

Some economic analyses done in Europe suggest that small, local wheat biorefineries producing baking flour, starch, gluten, feed and straw products could be profitable using traditional harvesting methods. At this small scale, however, most of the proposed products that could be prepared from wheat or corn would be too expensive to compete with products already on the market. The only hope is to use size, location and flexible production methods to develop niche markets. The production of tailor-made raw materials for further processing or products for direct sale is pre-commercial, requiring creation of markets.

An example of the creation of such a market is fuel ethanol in the USA. The local corn-based biorefineries that exist in the USA today are dry mill ethanol plants, established in response to legislative actions and supported by the state and federal governments to provide ethanol as an additive to gasoline. Many of these biorefineries are cooperatives owned by the corn producers and transportation costs have governed their location near the sites of crop production. These ethanol plants use grain, mostly corn, as their biomass source. Grains are 2 to 5 times more dense than plant stems. Switching to less dense biomass such as corn stover or straw would raise transportation costs considerably. Transportation costs are based on weight, distance and density. Using today's technology would cost the biorefinery 2 to 5 times as much for stover as for grain. This factor may encourage the growers and local biorefineries to invest in the development of new technology to begin stover processing at the farm, or even in the field integral with harvesting, to reduce the bulk density of the materials to be transported. It is even possible that in the future crop residual biomass may be processed then pumped from the production site to the biorefineries like oil from the well to the petroleum refinery.

Dry Mill Ethanol Process

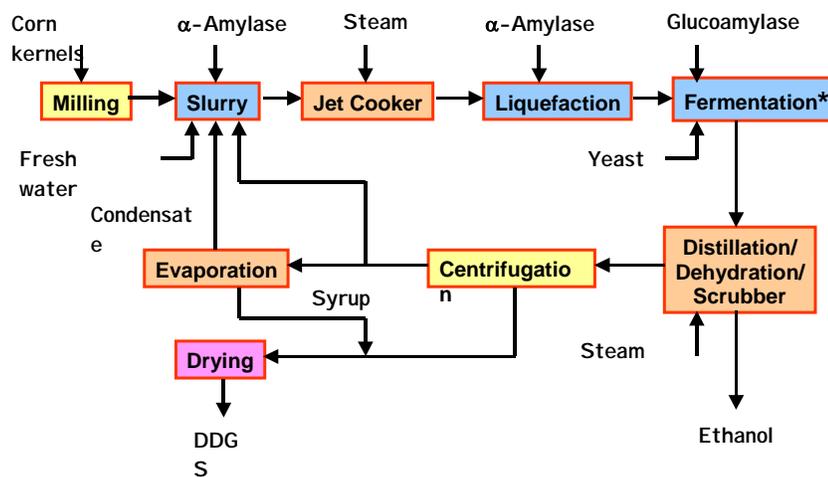


Figure 5 Dry Mill Ethanol Process Scheme

V. Large Consolidated Biorefineries and Century-scale Impacts on Energy and Climate Change Mitigation

The current biomass conversion industry in the USA has two business types: the local dry mill ethanol plant and the huge consolidated corn wet mill. This latter type has developed as the result of a product line expansion from cornstarch to its derivatives such as: glucose and high fructose corn syrup and to fermentation products derived from glucose including ethanol, citric acid, lactic acid and, more recently, platform molecules for the synthetic fiber industry. The three major corn wet milling companies are Archer Daniels Midland (ADM), Cargill and Tate and Lyle, A.E. Staley Manufacturing. Each of these companies is continuing to expand its list of biomass derived products. Cargill has

teamed with Dow to produce polylactide, a new platform molecule used to produce a new green plastic using lactic acid derived from corn. Dupont, Genencor and A.E. Staley are collaborating to develop a biological route to produce 1,3 propanediol, the platform molecule from which the synthetic polymer 3GT is made. In this case the partners intend to provide an alternative to the current petroleum-based manufacturing process. These examples suggest that the corn wet milling industry will continue to diversify its products in the future. Other, biobased platform molecules are expected to add to the list in the next few years. The business models vary. For example, Cargill and Dow formed a separate company, Cargill-Dow, to manufacture the starting material, lactic acid and the polymer product, polylactide. The product is manufactured at a Cargill corn wet milling plant located in Blair, NE to take advantage of the cheap starting material glucose derived from corn starch. A.E. Staley appears to be taking the route of partnering with the polymer manufacturer Dupont which it serves as supplier of the 1,3 propanediol. This company has also developed technology to produce lactic acid, the raw material for polylactide. Their strategy appears to be to supply the raw material for the new platform molecules. ADM appears to be taking a similar approach as they are manufacturing lactic acid and are likely to acquire and implement technology to supply raw materials to end users such as Dupont, Dow and Cargill-Dow.

The large corn wet milling industry is not driven primarily by a need for fuels and power. Each of the major corn wet milling companies manufactures ethanol as an alternative to higher value products as markets dictate. At this time these companies have no commercial reason to reduce the price of ethanol, although this may happen as an indirect consequence of the development of higher value products such as vitamins and other nutraceuticals. Such high value products are already in development. In the future these biorefineries may also produce fermentation commodity bioactive compounds for animal and human therapeutic needs. The obstacles to such development are not lack of facilities or know-how. Rather, it is the difficulty of meeting regulatory requirements and entering completely new markets.

Operators of the dry mill ethanol plants which are devoted primarily to a single product, are motivated to find ways to improve the efficiency of ethanol manufacture and to adding the technology that will allow production of higher value products. For example, research is underway to produce higher value products from the low value residual distillers grains. Addition of more sophisticated fermentation and separation technologies will be required for significant additions to product diversity. Significant obstacles exist: most significant is the large capital investments required.

The most significant impact of biorefineries on energy, greenhouse gases and climate change GHC in this century is likely to come from the conversion of lignocellulosic materials to ethanol. Other bioproducts are not likely to be manufactured on a scale any larger than what is now contemplated for corn stover. In this paper we have examined some hypothetical energy and emissions data for conversion of corn stover to ethanol and for the production of polylactide, a bioproduct that will likely be produced in the biorefineries of the future.

a. Example I: Ethanol from corn stover in the USA

i. Energy from corn stover

Estimates of how much corn stover is available vary from 60 to 100 million tons/year and it is estimated that the total ethanol that could be produced is 4 to 9 billion gallons /year. For the purpose of this examination, we have used 100 million tons/year corn stover. Electricity is a co-product of ethanol production generated at the rate of 2.28 kWh per gallon of ethanol or 68, 692 MJ of electricity per hour. The energy value for ethanol and the co-product electricity is about 6×10^{11} MJ/year. This is equivalent to about 98 million barrels of oil. (1×10^{18} joules=163 million barrels of oil equivalent)

ii. Impact on GHG production

Carbon emission data from a hypothetical stover-to-ethanol plant has been estimated (Sheehan et al., 2002). Using a figure of 9×10^7 g CO₂ per hour and assuming use of all available corn stover (100 million tons/year for 100 years), the total emission to the atmosphere would be 10×10^{15} grams of carbon dioxide or 2.73 Pg carbon. The estimate for the USA is about 1.8 Pg C/year (this estimation is for 2010 and future year could be much higher in some of scenarios) or 180 Pg C accumulating in 100 years. Corn stover production would contribute 2% to the total. Further analysis of the overall impact of the use of corn stover to produce fuel ethanol on GHG production has been documented (Sheehan et al., 2002).

iii. Life cycle analysis (LCA) of impacts on energy and GHG mitigation for corn stover derived ethanol

Sheehan et al.(cited above) reported the results of an LCA analysis of GHG emission from corn stover as compared to gasoline. The life cycle analysis integrated soil science, agronomy, and process engineering using the Century model, soil erosion RUSL WEQ, ORIBUS model and ASPEN PLUS process simulator to assess all of the “cradle to grave” impacts of producing ethanol from stover. The analysis used Iowa as example. In one scenario assuming all Iowa farmers switch to continuous production of corn and use “no till” methods production of 3 billion gallons of ethanol per year from corn stover is possible. Every mile fueled with ethanol requires only 5% of the crude oil that would be consumed in a mile fueled with conventional gasoline. This is a 20-fold reduction in reliance on crude oil. The stover conversion process generates both ethanol and electricity and requires a small amount of non-renewable energy for feedstock production, transport, conversion, distribution and delivery to the end user. Because of the electricity generation, the conversion process actually produces a negative flow of non-renewable energy usage of -0.109 MJ per mile driven for E100 as compared with 5.84 MJ non-renewable energy per mile for gasoline. This leads to a 102% reduction in use of non-renewable energy. A comparison of life cycle non-renewable energy flow for E85 (85% Ethanol blend) indicates that corn stover-derived ethanol stacks up against

ethanol made from other biomass feedstocks, 1.15 MJ for corn stover, 1.23 MJ for woody biomass and 1.86 MJ for herbaceous biomass. Ethanol production from corn grain, on the other hand, requires 3.95 MJ per mile. There is up to a 4-fold reduction in consumption of non-renewable energy for ethanol derived from biomass instead of corn grain. In a biorefinery, the requirement for non-renewable energy for manufacturing other products can be greatly reduced when they are co-produced with ethanol from stover.

The impact on soil carbon depends on the amount of stover collected and is a function as well of time. Therefore the CO₂ emission varies over time as reported by Sheehan et al. (2002). The total GHG reduction (or avoided) per mile driven over 90-year projected profile is shown in Figure 6. Gasoline emits 385 CO₂ equivalents (eq.) per mile, At the maximum allowable removal of stover (an average 40% removal to prevent soil erosion), the ethanol life cycle actually has a negative cycle flow of -24 CO₂ eq.,--- 106% lower emissions of GHG as compared to gasoline. Previous research by Wang et al. (1999) also demonstrated 79-118% reduction in GHG emissions and 82-92% reduction in fossil energy use for woody and herbaceous biomass.

Since soil carbon content varies over time, so does the total GHG reduction. as is shown in Fig 6. The GHG reduction peaks 15 years after introduction of stover-driven ethanol, and gradually declines thereafter as the soil system seeks a new state of equilibrium.

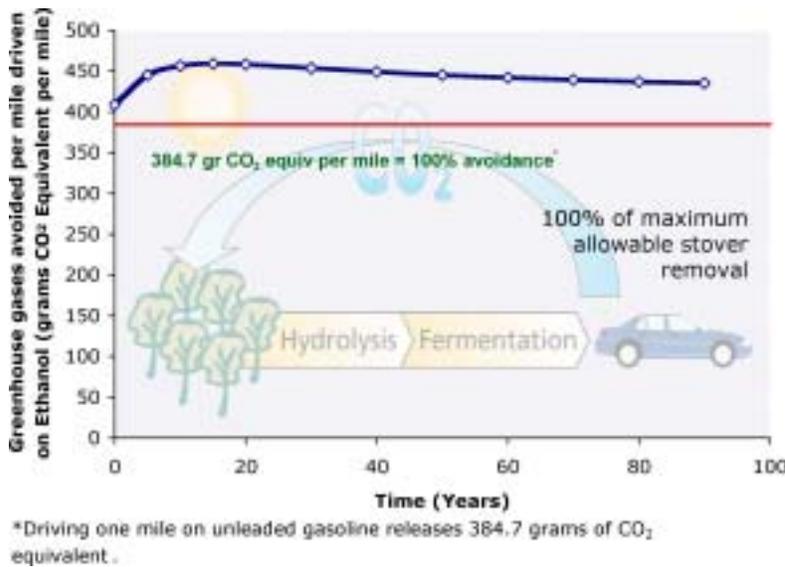


Figure 6 Avoided Emission of Greenhouse Gases over Time for Displacement Gasoline by E100. (Sheehan et al. 2002 Figure 155)

iv. Century-scale impacts on GHG mitigation

In the DOE's Vision for Bioenergy and Biobased Products in the United States (October 2002), the goals for bioenergy transportation fuels from biomass, are to increase significantly from 0.5% of US transportation fuel consumption in 2001 (0.147 quads) to

4% of US transportation fuel consumption in 2010 (1.3 quads), 10% in 2020 (4.0 quads) and 25% in 2030 (9.5 quads). Assuming GHG reduction is 409 grams CO₂ eq per mile for stover-derived ethanol, and a fuel vehicle efficiency of 25 miles/gallon, the resulted reduction of GHG as CO₂ eq from projected biomass ethanol targets is 0.160 Pg, 0.493 Pg and 1.17 Pg annually as shown in Table 2. Over 100 years, the projected reduction of GHG as Carbon eq from projected biomass ethanol targets is 13 Pg (C) using 2020 targeted ethanol goal. This could contribute about 6 % reduction of total USA GHG emission (using projected total USA carbon emission 2.1 Pg C in 2020). One may question whether we have the sustainable biomass feedstock to reach the 43 billion gallons of ethanol target in 2020. If we use all the available biomass feedstocks including corn stover, woody and herbaceous biomass, and assuming enhanced biomass yield (improvement of plant growth and continuous corn production) and enhanced ethanol conversion yields (improved pretreatment and enzymatic hydrolysis and fermentation microorganisms), a ethanol capacity of 48 billion gal/year may be a feasible. The figures in this projection are based on ethanol that will be cheap enough to require no help from the government in finding a market. It could, perhaps, be used in much higher percentages in gasoline than it is today, Technology might be developed that would allow ethanol to be used alone. Future use of ethanol would not depend on its oxygenating properties or on the social advantage of its origin in renewable raw materials. With a low enough ethanol price it might be used as a feedstock for ethylene production, instead of the reverse situation which now prevails. Ethylene is a key building block in the petrochemical industry. It is the raw material for polyethylene and other large-volume commodity polymers and for a number of basic organic chemicals. Significant reductions in GHG emission and non-renewable energy use in producing these chemicals may be achieved.

Table 2. Goals for Bioenergy (Biofuels) and Potential GHG reduction

| | Current (2001) | 2010 | 2020 | 2030 |
|---|----------------|--------------|---------------|---------------|
| Projected transportation fuel (quads) | | 32.5 | 40 | 47.5 |
| Projected Gasoline (billion gallons) | 130 | 387 | 476 | 565 |
| Biomass share of demand for transportation fuel | <1% | 4% | 10% | 20% |
| Quads/year | 0.147 | 1.3 | 4.0 | 9.5 |
| billion gallons of ethanol/year | 1.76 | 15 | 48 | - |
| Reduction of GHG emission CO₂ eq Pg/year for E100 | 0.018 | 0.160 | 0.493 | 1.170 |
| Reduction of GHG emission C eq Pg/year for E100 | 0.005 | 0.044 | 0.134 | 0.319 |
| Reduction of GHG emission C eq Pg/100 years for E100 | 0.497 | 4.368 | 13.439 | 31.917 |

b. Example II: Polylactide from corn

Polylactide is an example of the type of new product that may be made in the biorefinery of the future. This product is made by a microbial conversion of glucose (from corn

starch) to lactic acid. Polylactide is produced as a granule and is used to manufacture new biodegradable polymers with properties that are equivalent and sometimes superior to petroleum derived synthetic fibers. How much of this product may be manufactured in this century is difficult to predict. The volume predicted for the early years of 2000 was 300 million lbs/year with markets predicted to increase to 500 million in 10 to 20 years. One might project the market for such a product to reach 1 billion lbs by 2100. The accumulated total biomass required to manufacture polylactide for the next 100 years would be considerably less than 50 million tons. The associated impacts on GHG are small as compared to those from the large-scale manufacture of cement, iron or even corn stover to ethanol. Bioproducts such as polylactide and microbial 1,3 propanediol derived polymers may have an impact on GHG if the numbers of these products increases rapidly so that there are hundreds of these processes operating at a comparable scale.

VI. Summary

The US Department of Energy (DOE) has set ambitious goals to reduce the use of oil, and thus reduce GHG. One approach to meeting these goals is the use of renewable biomass to produce fuel and energy in biorefineries. Here we have provided some basic information and case studies regarding the potential impact of GHG reduction and energy for future bioconversion and biorefineries.

To meet the DOE renewable energy goals using biomass, billions of pounds of biomass must be converted. Corn stover has been identified as a biomass of sufficient volume to be allow these goals to be met if the needed technology can be developed and installed. There are major challenges in reducing production costs in biorefineries posing great opportunities for fundamental science and engineering research. New research may lead to dramatic shifts from the way we currently conceive and practice biomass production and conversion. For example, biomass may be conveyed via pipelines to address the problem of transportation costs, and there may be a switch from the yeast paradigm to a multi-organism approach to biomass conversion to fuels and chemicals.

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