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Research and Development Needs for a Fully Sustainable Biocommodity Industry

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Lignocellulosic biomass provides a low-cost, uniquely sustainable resource for large-scale production of organic fuels and chemicals that can have low environmental impact while providing important economic and strategic advantages. Conversion costs must be competitive for these benefits to be realized, and biological processing routes can take advantage of emerging tools in modern biotechnology to dramatically improve economics. For example, significant advances have been made in biological conversion of lignocellulosic biomass into ethanol, and the private sector is working to apply the technology commercially. Raising the substantial capital needed is challenging for first-of-a-kind commodity projects, but understanding the fundamental principles governing bioprocessing steps will accelerate the rate of application. In addition, improved knowledge of cellulose and hemicellulose hydrolysis grounded in fundamental principles will facilitate improvements that are vital to the cost reductions needed to achieve competitiveness in an open market and to develop a range of sustainable biocommodity products. Premature attempts to force technological applications without building technical and economic foundations will be inefficient in resource allocation and will often fail.

Introduction

Lignocellulosic biomass, hereafter referred to as "biomass", includes agricultural (e.g., corn stover) and forestry residues (e.g., pulp and paper sludge), a substantial fraction of municipal solid waste (e.g., waste paper and yard waste), and ultimately herbaceous (e.g., switchgrass) and woody (e.g., poplar) crops grown to support large-scale uses (*1*). In this paper, we show that such low-cost raw materials are competitive in price with petroleum and can be biologically converted into a wide range of organic fuels and chemicals at a scale that can have tremendous environmental and economic benefits. Furthermore, biomass is the only known sustainable resource for production of such products that are so important to our lifestyle. Thus, while the sustainability of producing and using fuels and chemicals derived from fossil sources may be improved in terms of environmental impact, biomass provides the only resource for making such products that can also offer sustainability in terms of resource availability.

Although biomass will undoubtedly be the only option for making organic fuels and chemicals that can minimize greenhouse gas release and reduce our vulnerable dependence on petroleum, their cost must be competitive with petroleum-derived products to realize widespread use now. Given that petroleum refining has matured from limited production of lamp oil to large-scale manufacture of a broad spectrum of products with over a century of experience, it is important to be realistic about the magnitude of this challenge (*2*). Nonetheless, biological processing of biomass has capitalized on the powerful emerging tools of modern biotechnology to make substantial progress in this direction despite limited research funding for such a low-value product (*3*), and significant opportunities have been identified to further reduce bioprocessing costs to compete with conventional products (*4,5*). Consequently, the technology is competitive now in some applications, and further cost reductions are imminently possible.

Premature attempts to commercialize bioprocesses will fail without the political will to provide consistent support for incentives or other market measures or the ability to select and adequately finance projects with economic merit. Of course, a crisis atmosphere could arise that produces unrealistic quests for instant solutions to issues such as severe climate change, cartel reductions in petroleum availability, or other festering problems that receive little attention now. However, because a hasty response will fail without a proper foundation, patience is needed to develop a solid technology base that will support low risk scale-up of cost-effective technologies that can transform biomass into a range of high volume commodity products and propel our society into a new era of resource and environmental sustainability with or without crises. We will attempt to present the background and a framework for such a metamorphosis.

The Biomass Resource and Refining to Biocommodities

Biomass has been shown to provide an abundant resource that would be more than adequate to produce quantities of organic chemicals equivalent to total current use (*6*). Although subject to more speculation, biomass could also potentially make a major impact on transportation fuels (*7*). As shown in Figure 1, biomass costing $42/ton is equivalent to petroleum at about $6.25/barrel on a weight basis, or approximately $13/barrel in terms of equivalent energy content (3,*8*). Because biomass from waste sources or from improved energy crops is expected to be available at costs less than this, its cost should not be a major impediment to the manufacture of fuels and commodity chemicals. Rather, the primary challenges are to insure a match between biomass supply and demand and to develop low cost processes that are competitive. The emerging fields of biotechnology and bioprocessing provide the powerful tools needed to reach such a goal.

Cellulosic biomass is made up of about 40 to 50% cellulose, 25 to 30% hemicellulose, 10 to 18% lignin, and lesser amounts of minerals, solubles, protein, and other components (*1*). Acids or enzymes can hydrolyze cellulose to glucose sugar while five sugars (arabinose, galactose, glucose, mannose, and xylose) are usually produced when acids or enzymes act on hemicellulose. As illustrated in Figure 2, these sugars can be fermented to various products such as ethanol and other alcohols, organic acids, glycols, and aldehydes, or the fermentation products or sugars themselves can be chemically transformed into products, opening up more possibilities (3,*9*). Lignin can be chemically converted into phenolics, aromatics, dibasic acids, and olefins or can be burned for heat and electricity for the conversion process, for export, or for both. Although not typically considered now, the high protein content in many types of biomass could be recovered for food or feed applications, extending the impact of biomass use.

The spectrum of biorefinery products made possible by the diverse structure of biomass can provide synergies analogous to modern petroleum and grain processing operations (*2*, *6*). Manufacture of fuels such as ethanol will support large-scale operations that achieve economies of scale, lowering costs as long as additional feedstock transportation costs are less than the incremental savings due to nonlinear scale up of capital and some operating costs. Portions of the resulting low cost sugars can be processed into lower volume, higher value chemicals and materials, potentially increasing profitability if the margins are greater. In addition, excess heat or power derived by burning lignin can be sold at a lower price than possible in a dedicated power plant, allowing biomass power to compete in deregulated utility markets. Biological processing of biomass to commodity products through such an approach has recently been termed "biocommodity engineering" to distinguish the unique features of this emerging discipline from more typical current applications of biotechnology to high-value, low-volume health care products (*8*).

Sustainability and Other Benefits of Biocommodity Products

Sustainable development can be defined as meeting the needs of the present without compromising the ability of future generations to meet their needs (*10*). Thus, petroleum is not a sustainable resource because it is finite and contributes carbon dioxide and other greenhouse gases that could lead to global climate change. Furthermore, it can be argued convincingly that burning of fossil resources as fuel squanders a valuable resource for making chemicals by future generations, and although the environmental consequences of fossil resource use can be improved for some chemicals, fossil-based technologies cannot address overall sustainability. On the other hand, biomass offers a unique sustainable resource from both a supply and impact perspective when low impact crops are used, fossil resources are not required during biomass production and processing, and environmentally benign products are made (*5, 11*).

By definition, all organic products are ultimately derived from biomass, with petroleum being a depletable biomass reservoir. Thus, biomass is the only sustainable resource for making organic products, as well as the only source of human food either directly as fruits, vegetables, and grains or indirectly as animal feed. On the other hand, heat, mechanical energy, electricity, and hydrogen could be derived by many other sustainable technologies such as wind, hydropower, ocean thermal energy, photovoltaics, and nuclear power. This unique match of biomass to providing food, feed, and organics coupled with the large demand for these products and limitations in biomass availability suggests that priority for biomass utilization in a rational world should be given to production of food, feed, and organic chemicals and fuels, in that order.

Some clarification is worthwhile about the sustainable use of biomass. Several studies have shown that very little fossil energy is needed to plant, grow, harvest, and transport biomass and ship final products to their markets. Furthermore, burning the lignin in the feedstock can provide more than enough heat and electricity to process biomass to ethanol (*7, 12–14*). Thus, the ratio of energy available from bioethanol to fossil energy inputs is significant. However, because far more energy is contained in ethanol than is required to make it, bioethanol itself could be used to fuel vehicles for planting, harvesting, and transportation operations while other inputs such as fertilizer could be derived from sustainable sources instead of the fossil sources commonly assumed in such studies. This is analogous to the fact that tankers burn petroleum to cross the oceans and still deliver much more than they consume at a low cost. Thus, provided the crops employed have little impact on soils, biomass-derived products such as ethanol are renewable.

While bioethanol clearly can be made with little, if any, fossil fuel inputs, the energy balance for some polymeric products has been shown to be less favorable than for fossil fuel options (*15, 16*). In this case, aerobic fermentations were employed to make viscous materials that require far more energy input than the anaerobic technologies applied for lower viscosity ethanol manufacture, and energy intensive separations were needed for product recovery. In addition, fermentation sugars were derived from corn, a feedstock that requires more fuel and fertilizer to produce than biomass, and fossil sources are used to power the process. On the other hand, use of biomass sugars for fermentation and lignin to generate power in the process would reduce fossil fuel use and improve sustainability, although additional biomass inputs could be needed to meet the high-energy demands of this technology. This study illustrates that it can be misleading to assume that all biomass-based technologies are sustainable and that careful analysis is needed to insure that the process is properly configured and uses an appropriate raw material. These results also support the idea that petroleum should be saved to manufacture products for which it is so uniquely suited and not squandered on uses for which there are sustainable alternatives.

Biomass conversion offers many other important benefits in addition to sustainability. These include disposal of solid organic wastes, reduced trade deficits, improved domestic security, creation of rural agricultural and manufacturing employment, and better air quality. However, because these attributes have been described extensively elsewhere, the reader is referred to such sources (*1, 5, 7, 8, 11*).

Research Progress

In the early 1980s, evaluations of biomass conversion to ethanol were conducted to discover a quick fix that would ameliorate the high price of petroleum (*3*). Although biomass conversion was found to not yet be competitive with making ethanol from corn, primarily because the mixture of five sugars released in hemicellulose hydrolysis could not be converted to ethanol at high yields or used for other products, these studies were used to develop a common basis for comparison of bioethanol technologies and to define research priorities (*17*). These results, coupled with a policy shift to funding long-term, high-risk research, led to targeting enzymatic hydrolysis of cellulose to glucose because high yields and competitive costs were feasible through the application of modern biotechnology. Although directed at bioethanol, all of the key steps through hemicellulose and cellulose hydrolysis are applicable to the production of biomass sugars ('biosugars') that can be used to make many other products.

Technoeconomic evaluation models have been updated periodically to track steady research progress in lowering the cost of bioethanol from about $4.60/gal in the 1980 timeframe to a value competitive with ethanol from corn now (*5, 14, 17*). However, these cost projections are measures of research progress based on a number of needed assumptions and simplifications, and processing costs will be sensitive to variabilities in feedstock costs, project financing approach, technology used, and other factors that require more detailed estimates. Nonetheless, they show that bioethanol can be competitive.

Two advances were instrumental to reducing the cost of bioethanol by about a factor of four over the past 20 years (*5*). First, improvements were made in our ability to make biosugars from cellulose and hemicellulose by 'overcoming the recalcitrance of biomass.' These advances were achieved through optimizing dilute acid biomass pretreatment to improve sugar yields from hemicellulose and to increase the recoverability of glucose in subsequent cellulose digestion by enzymes. In addition, better cellulase enzymes that improve glucose release and reduce the use of expensive enzymes along with process integration to improve rates, yields, and concentrations were important.

A second improvement category, 'overcoming the diversity of biomass sugars' by genetically modified organisms, was critical to realizing competitive costs. Prior to this, ethanol yields from all five biomass sugars were inadequate, disposal costs of unused sugars were too high to be competitive, and markets for alternative products from these sugars were not sufficient to support large-scale bioethanol manufacture regardless of other improvements. But now a new class of genetically modified organisms makes it possible to derive revenue from all sugars, with the importance of this breakthrough recognized by the awarding of U.S. Patent 5,000,000 (*18, 19*). Conversion of biosugars to products other than ethanol will also require that high product yields be achieved from all five sugars in biomass, although unused sugars could be converted to bioethanol.

Challenges in Commercializing Biosugar Technologies

Attempts to apply bioethanol technology before it was possible to ferment all sugars at high yields were doomed because revenues were insufficient to cover costs. However, with the improvements discussed, the cost of making bioethanol and many other products from biosugars is now projected to be competitive, and firms are pursuing market applications. Although some express frustration that commercial processes are not yet in operation, it is important to realize that significant hurdles must still be overcome. Unfortunately, promising technology is not sufficient in itself, and the steps to commercializing commodity products in particular are demanding and slow.

Because economies of scale are important for most commodity processes, biorefineries must be large, and total capital costs become very high. Thus, large sums of capital must be raised, a very demanding task, from three typical sources of support: venture capital, equity, or project. Venture capital often expects a higher rate of return on investment than is possible for new commodity products. Internal equity financing is possible for large companies, but hurdle rates can be too high to accommodate contingencies and other margins for first-of-a-kind technology. Project financing offers lower rates of return for debt holders, but the demands on project certainty and longevity are significant.

In any financial arrangement, uncertainty and risk for biocommodity projects must be minimized (*20*). This can require that contracts be in place for an adequate supply of biomass to the plant over much of its financial life. Often, contracts are needed for all off-take over the project life. In addition, the feedstock quality typically must be demonstrated to satisfy process needs throughout the operating year, including the effects of storage, and product and coproduct quality must meet market specifications. Finally, the engineers and contractors responsible for engineering, procurement, and construction may be required to provide process guarantees for yield and quality.

Meeting these and many other requirements to mitigate uncertainty and risk is demanding for a first-of-a-kind project. Long term feedstock and off-take agreements result in higher costs for raw materials and lower product selling prices to make these arrangements attractive, squeezing profit margins. In addition, those accepting risk through process guarantees take measures to protect themselves from losses. Such firms would prefer to scale up by no more than a factor of 10 from one scale to the next, but successive scale up strategies of this type are too expensive and risky for most operators to afford. Thus, in addition to normal contingencies to cover unexpected occurrences such as bad weather, a contingency will also be applied in case the process does not perform as well at a large scale as it did in smaller systems, and extra equipment is often included to insure that poorly understood streams can be processed. Technologies and equipment with established commercial performance will also be employed wherever possible to reduce risk even though such equipment may be more costly or less effective than more advanced but less practiced options. Beyond that, other contingencies are applied for new technologies to compensate for unknowns that often occur with new technologies.

The overall effect of all of these contingencies and safety factors is to drive the capital costs far higher and to squeeze profit margins more than is apparent from costing the core technology alone (*4*). We could view the cost structure as a series of concentric rings, with the center circle representing the cost of the technology itself as pictured for a fully mature process. Surrounding that circle would be a ring representing normal contingencies typical of any project The sum of these two circles is what we would expect to pay based on the process concept and laboratory performance data. However, additional cost rings need to be included to account for performance margins, extra equipment, and contingencies for the new technology unknowns discussed above, adding significantly to the cost. As a result, the total capital cost of the new technology will undoubtedly be far more than anticipated in the early stages or than one would expect once performance and equipment are well established as the same technology matures. Contractual requirements for feedstock and off take squeeze the profit margin, reducing returns on capital. Unfortunately, the difference between the true technology costs and those including risk coverage can be so great as to stop commercialization despite the substantial promise for the long term. The cost gap that develops as new technology moves from the laboratory bench to commercial use is often called the "Valley of Death" and can terminate its use despite tremendous promise and low cost potential.

The nature of commodity products presents an additional challenge for market entry (*6*). The good news is that a large market has been established that one can sell into as long as price and performance requirements are met. However, it is difficult to establish a competitive advantage beyond price, and those already in the market will likely have the upper hand in terms of equipment that is partially or fully (cash cow) paid-for. Thus, financiers will often expect that the total product cost including cash costs and capital amortization for new entries must be less than the cash costs for existing technologies to insure survival in a price war. It can also be required that the margin between revenue and cash costs must be more than is needed to cover debt service, adding even more to the challenges of financing the project. Finally, first-of-a-kind projects have no reference point for benchmarking, reducing the comfort level for many financial institutions.

Some measures can be taken to help compensate for uncertainty and risk associated with application of new biocommodity technologies (*21*). First, waste biomass can be used at little if any cost to the project. Additionally, it may be possible to integrate the facility into an existing process such as a biomass power plant to take advantage of some existing equipment, reducing capital costs, as well as in-place infrastructure and permits. Use of low-cost debt funding, particularly as tax-free government bonds, can lower interest rates and capital amortization. Higher value coproducts such as chemicals from lignin could also improve revenues for initial operations. However, in spite of the advantages such measures can afford, it is still likely that government support will be essential to implement technology for the first time.

R&D Implications for Commercializing Biocommodity Products

Contingencies built into capital costs to meet process guarantees coupled with requirements for feedstock and product contracts and safe profit margins are major hurdles for new products. These requirements are even more challenging for new routes to commodities that must compete immediately with established technologies that have benefited from substantial learning curves. Although operation of integrated operations at a near-commercial scale can overcome many of these obstacles, capital and operating costs are so high and the risk so great that financing such operations is almost impossible, at best. However, improving our ability to predict performance of large-scale systems and further reductions in costs can be invaluable in overcoming these obstacles.

Improving the Accuracy of Process Scale Up

Commercial processes will not necessarily duplicate the laboratory systems often used to gather data at a scale many orders of magnitude smaller. For example, dilute acid hydrolysis of biomass may be performed manually in a simple batch laboratory operation. However, because finding suitable commercial equipment for solids handling is often challenging, the sequence of (1) adding acid to biomass, (2) mixing to insure uniform distribution, (3) allowing time for acid to fully penetrate pores, (4) pressurizing the resulting material to reaction conditions, (5) heating directly or indirectly, (6) holding the heated acidified biomass for a set reaction time, and (7) rapidly cooling the material to quench the reaction and prevent degradation of the sugars released, will be far more complex (*14*). The question then becomes how to predict the performance of commercial systems. For example, process engineers may need data on diffusivity of acid in biomass, solid/liquid mixing results, biomass heat transfer constants, and other design information typically not considered in conversion versus reaction time data gathered in a simplified laboratory setup. Armed with insufficient information, safety margins must be applied to insure that the project cannot fail, typically at considerable cost.

The importance of developing a fundamental understanding of technology to support its application has been described in the book *Pasteur's Quadrant* by Donald Stokes (*22*). The point is made that Vannevar Bush established a dichotomy between basic and applied science during World War II in which basic research is directed at understanding the scientific basis of phenomena without an application in mind, while applied research is viewed as using technology without trying to understand it. However, Stokes presents the case that research can be viewed in terms of a two-dimensional matrix that considers applications in one dimension and the quest for fundamental understanding in the other. In this context, pure basic research as classically defined would emphasize knowledge without concern for use, while pure applied research would favor use without concern for understanding. In general terms, Stokes favored consideration of both elements—applications and understanding—in a sector labeled "Pasteur's quadrant" in honor of the great scientist who laid the foundations of microbiology with a view to applications such as curing disease. In this mode, applications benefit from an improved fundamental understanding that illuminates cause-and-effect relationships.

Similarly, biomass research can benefit from an emphasis on developing fundamental principles that support commercial applications. Thus, for example, it is important to understand the impact of key process parameters on performance rather than simply gathering data on concentration versus time profiles for hydrolysis, fermentation, and other biomass operations. We need to predict such things as how fast acid or other hydrolysis chemicals diffuse through biomass, how such chemicals must be dispersed to penetrate the material, how long biomass must be soaked in such chemicals, how rapidly biomass can be heated by direct or indirect means, how recombinant organisms behave when grown in large-scale fermentors, how key nutrients must be provided at a large scale, and how shear rate affects performance in large scale fermentations. There are countless such questions that need to be addressed in a clear and convincing way to comfort engineers and investors financially responsible for projects costing tens to hundreds of millions of dollars. Failure to build confidence in such information will likely result in lost opportunities to apply technologies that have considerable promise for low-cost applications.

Advancing Biocommodity Technologies to Reduce Costs

Although cost projections show that bioethanol is presently competitive with ethanol from corn, incentives are required for ethanol from either feedstock to compete financially in the current fuel market. Furthermore, risk mitigation for the application of new technology for making ethanol or other new products from biomass can drive up costs and impede market entry, as discussed above. However, several studies have shown that additional cost reductions are feasible that would make bioethanol competitive as a pure fuel in the open market, drastically expanding the impact of the technology and its benefits (*4*, *5*). Many of the same advances are also applicable to other products that can be derived from biomass, thereby improving their competitiveness as well.

Three different approaches have been applied to show the low-cost potential of biomass: sensitivity studies built around existing economic analyses (*14*, *23*), allowable cost projections (*24*), and advanced technology scenarios (*4*). Each shows that biomass can be converted into ethanol at costs that could compete in the open market, but because a summary of each has been presented previously (5), the former two will not be discussed here. However, a few key points are presented below about the advanced technology study because it is relevant to other products that could be made in a biorefinery.

The most expensive processing steps for converting biomass to ethanol or other products are pretreatment, which contributes about one third of the cost, and biological conversion of cellulose to glucose and fermentation of glucose and other sugars to ethanol, collectively representing almost 40% of the total (*4*). Three technology scenarios were investigated to improve these costs. The first was built on a published base-case process that was believed to be achievable with existing technology. A second case, termed advanced technology, was defined to combine features of existing commercial products for other feedstocks and to represent technology judged to have the features most likely for a mature process, analogous to the evolution from early petroleum processing to modern refining technology. The third case, called best technology, envisioned the ultimate potential for R&D advancements for processing biomass, a state that provides an idea of the upper end of improvements.

To summarize, this analysis showed that attaining the advanced technology scenario could achieve costs of about $0.50/gal, a level that would compete with conventional fuels in the open market, while the best possible technology case could cost as little as $0.34/gal. The advanced technology pretreatment approach was patterned after some of the promising features of flowthrough hot water only systems with high yields, short residence times, and use of little if any chemicals for hydrolysis. The advanced biological system also employed a consolidated bioprocessing operation that combined the operations of enzyme production, cellulose hydrolysis, and fermentation of all sugars in one step. Although other configurations could no doubt realize similar costs, the point was that advanced processing technologies, and not simple yield improvements alone, are essential to realizing competitive costs. By similar reasoning, it is expected that novel conversion configurations will also be essential to reducing the cost of making other products from biomass.

Development of advanced process configurations is challenging, and progress is slowing as we approach the final targets. However, advances to date have been largely by trial-and-error, and more efficient routes will accelerate the next steps. In particular, our knowledge of the mechanisms for many of biomass conversion systems is limited, and more emphasis on understanding the fundamental principles governing biomass conversion would provide a platform to help define and apply such advancements, reducing costs for both. This approach would be synergistic with supporting applications of current technologies.

Conclusions

In addition to traditional, vital uses for production of food and feed, biomass is the only sustainable resource for production of organic fuels and chemicals, and because many of these biomass products provide powerful environmental, economic, and strategic benefits, biomass provides a unique combination of sustainable benefits from both a resource and an environmental perspective. Thus, development and commercialization of new processing technologies that targets these important applications merits priority.

Hemicellulose and cellulose in biomass can be broken down to release sugars that can be fermented or chemically reacted into many commodity products. The lignin portion can be burned to provide heat and electricity to power the conversion process and for export, while biomass protein could be recovered for food and feed applications. The minerals in biomass could also be employed for commercial products. Tremendous progress has been made in reducing the cost of biological processing of biomass to ethanol and other commodity products, to the point where many are receiving commercial attention. However, significant challenges remain in applying such technologies due to their inherently high capital costs, the low value of commodity products, and uncertainty for first time commercial uses. Thus, only projects that are economically and technically viable will be successful, and improving our fundamental understanding of bioprocessing technology is vital to support low-cost scale up to commercial operations and to provide a foundation for technological improvements. In addition, more attention must be devoted to advancing technologies that promise to radically reduce the cost of pretreatment and biological processing to achieve competitiveness in an open market without subsidies, with applied fundamental research also being important to this quest.

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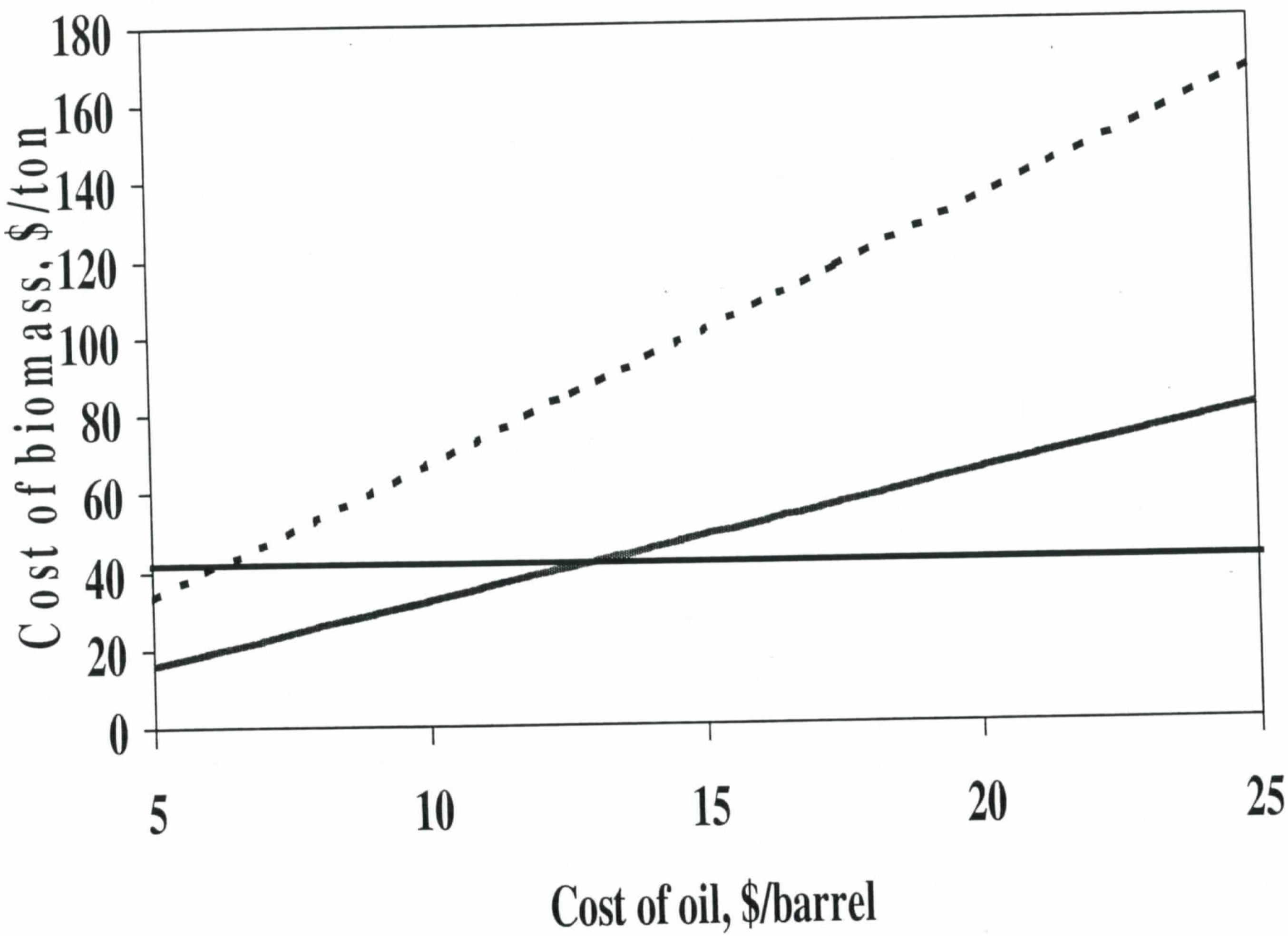
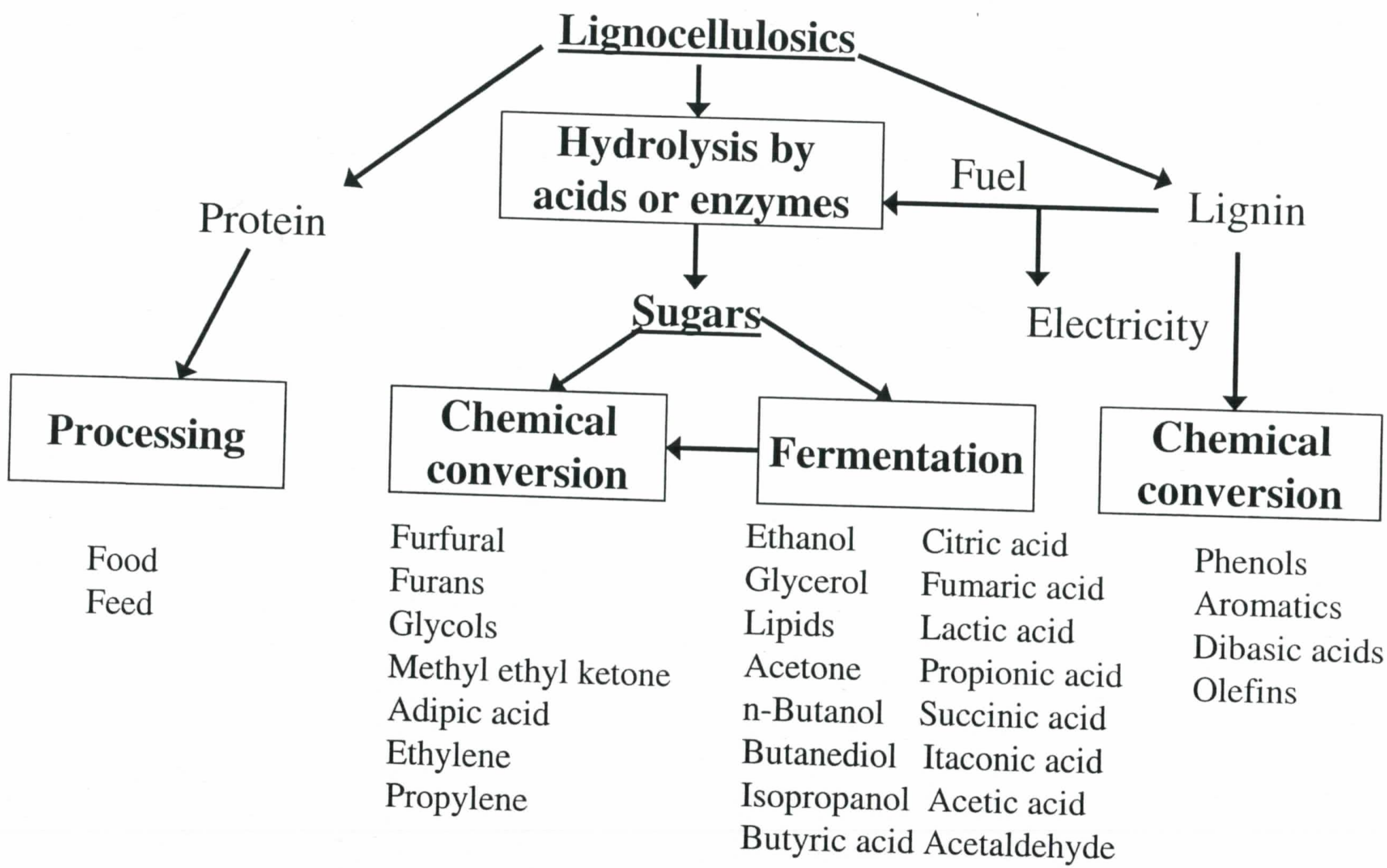
Figure Captions

Figure 1. Cost of biomass versus cost of petroleum based on mass (dashed lines) or energy content (solid line), with the horizontal line indicating biomass costing $42/ton (3, based on reference 8).

Figure 2. A biorefinery concept for conversion of cellulose, hemicellulose, lignin, and protein in biomass into fuels, chemicals, materials, heat, power, food, and feed (3, based on reference 9).



Cost of biomass, $/ton
180
160
140
120
100
80
60
40
20
0
5
10
15
20
25
Cost of oil, $/barrel


Lignocellulosics
Hydrolysis by acids or enzymes
Protein
Fuel
Lignin
Sugars
Electricity
Processing
Chemical conversion
Fermentation
Chemical conversion
Food
Feed
Furfural
Furans
Glycols
Methyl ethyl ketone
Adipic acid
Ethylene
Propylene
Ethanol
Glycerol
Lipids
Acetone
n-Butanol
Butanediol
Isopropanol
Butyric acid
Citric acid
Fumaric acid
Lactic acid
Propionic acid
Succinic acid
Itaconic acid
Acetic acid
Acetaldehyde
Phenols
Aromatics
Dibasic acids
Olefins