Chapter 1

The Bioeconomy: A New Era of Products Derived from Renewable Plant-Based Feedstocks

Peter Nelson, Elizabeth Hood, and Randall Powell

1.1 Introduction

The first two decades of the 21st century will be marked as the turning point when large investments, technology breakthroughs, and new strategic alliances set the stage for the eventual widespread replacement of fossil feedstocks with renewable, plant-based alternatives for the production of fuels, chemicals, and energy. This is not a new idea, as humankind in the pre-industrial era utilized plant-derived chemicals such as proteins, sugars, and cellulose as the primary feedstocks to make a range of necessary materials and industrial products. However, as non-renewable fossil resources now become increasingly scarce, expensive, and produce negative environmental impacts, the need has never been so great to develop and expand agriculture and forestry as the source of sustainable feedstocks to serve a growing global population. Ultimately, renewable resources must feed, clothe, shelter, fuel, and provide for material goods for the planet’s inhabitants, while also addressing vexing environmental problems including climate change, pollution, access to clean water, and long-term soil health.

In the 20th century, incredible technological improvements in agriculture and forestry were made. These advances included dramatic yield increases, drought tolerance, insect resistance in agricultural crops, and new production methodologies such as conservation tillage, which builds soil health and requires less energy. These productivity and environmental improvements offer much promise for a future bioeconomy in which agriculture and forestry will provide the predominant feedstocks for much more than food, feed, and fiber. Agricultural successes such as the Green Revolution have dramatically increased global crop yields, reduced hunger in the developing world, and expanded access to nutritious foods, but are still heavily dependent upon fossil-derived energy and chemicals. Fortunately, agricultural and forestry-based companies and institutions are now collaborating in new ways with industries traditionally dependent on fossil fuels to expand the use of renewable raw materials in a range of manufactured goods.
Over the coming decades, this will lead to a more sustainable, closed-loop-systems-based approach to the production of food, energy, and materials. This biobased transition requires development and integration of a range of technologies encompassing energy, process efficiency, environmental compatibility, and even more advanced agricultural production systems. The increasing application of biotechnology tools—previously focused on human health—to improve agricultural crops and practices, enable clean manufacturing processes, and provide sustainable products is the essential catalyst for this transition.

A renewable “bioeconomy” is now starting to become a reality, but the concept is not new. In the early days of the 20th century, industrial and agricultural leaders such as Henry Ford and George Washington Carver were proponents and practitioners of the use of plant-derived materials in a range of nonfood products. These innovators demonstrated the commercial utility of renewable biobased feedstocks in hundreds of products, such as automotive composites, glues and adhesives, dyes and inks, plastics, and, of course, biofuels. Unfortunately, the rapid emergence of petroleum as an available and inexpensive feedstock, albeit with unrecognized long-term environmental consequences, drove manufacturers to develop fossil-based rather than renewable products as the initial outputs of the Industrial Revolution. A century later, as the true costs of fossil fuels are realized, renewable feedstocks are re-emerging at commercial scale, largely through innovative partnerships across the value-chain linking agriculture, biotechnology, and the chemical process industries in new ways.

Evidence of this transition has become increasingly apparent over the last 30 years as some organizations began decoupling themselves from traditional businesses to focus on agricultural biotechnology. A leading example is Monsanto Company, which has aggressively divested its mainstay fossil-based chemical manufacturing business to focus on the commercial opportunity to develop new agricultural biotechnology traits in commodity crops such as corn, cotton, and soybeans. Major agricultural commodity companies such as Archer Daniels Midland (ADM) and Cargill have also expanded chemical and fuel product offerings based upon their plant-based raw material resources. More recently, a number of multinational chemical companies— notably Dow and DuPont—are pursuing biobased product platforms, with initial commercial products now entering the marketplace. Increasingly, many traditional agricultural commodity companies, fossil-based chemical companies, and newer industrial biotechnology firms are partnering to integrate knowledge of biobased feedstocks, new conversion processes, and operational expertise in order to solve future challenges related to energy and useful materials.

The transition to a photosynthesis-based bioeconomy offers commercial opportunity, resource and environmental sustainability, and more equitable global economic development than has been the recent case with fossil resources. However, more intensive agricultural and forestry utilization, and the accompanying deployment of technology must be the products of clear strategic planning and sustainable development practices.

If managed correctly, the transition to a renewable-based economy can create new rural and urban opportunities, offer unique environmental solutions, and create wealth. The new economy based on renewable agricultural and forestry raw materials and clean processes will also serve as a major catalyst for realignment of some of the world’s largest companies and institutions, creating many new partnerships across the value-chain. This is an exciting time in which entrepreneurial companies as well as established industries can innovate new farm-to-factory supply chains and establish an early position in the emerging bioeconomy.

Although there are multiple technology platforms and an expanding portfolio of biobased raw materials, which will comprise a future biobased economy, this book will focus on biochemical processing technologies, applied primarily to sugar, starch, and lignocellulosic
1 The Bioeconomy: A New Era of Products Derived from Renewable Plant-Based Feedstocks

biomass feedstocks. This platform will be a significant game changer, lend itself to a wide range of potential chemical products, and provide opportunities for new players in the supply chain.

In particular, sugars derived from lignocellulosic biomass represent an abundant feedstock resource that does not compete with food and feed supplies. Commercially viable processes for converting lignocellulosic biomass to biobased products must address two overriding issues: efficient nonseasonal feedstock supply and logistics, and cost-effective deconstruction of cellulose and hemicellulose polymers to fermentable simple sugars. Feedstock supply and cost issues are being addressed by new crops, new harvesting/storage practices, and decentralized processing models. Technology issues to access sugars (and lignin) within lignocellulosic feedstocks are being addressed through new pretreatment options, genetically modified fermentation organisms, biotechnology-enhanced plants, and plant-based enzyme production systems. The development and commercialization of these new technologies and the requisite biobased supply chain will be profiled in this publication. Despite the early stage and dynamic nature of the industrial bioprocessing industry, the authors hope that the current status and perspectives presented will prove beneficial to the diverse industry stakeholders.

1.2 Market Opportunity for Biofuels and Biobased Products

Liquid biofuels including corn-based ethanol, as well as advanced biofuels such as biobutanol or cellulosic ethanol, are assured of a growing market over the next 50 years. As petroleum costs escalate with diminishing supplies, liquid transportation fuels will still be preferred due to energy density, safety, and distribution infrastructure, with increasing growth of biofuels between now and 2035 (IEA, 2008). The biofuels market represents the largest and most consistent demand from which to build a strong sugar and biomass supply chain from field to factory.

The global biofuels market is already estimated to be $150 billion per year (UN, 2009). According to one report focused on the United States market:

Rapid growth in the consumption of renewable fuels results mainly from the implementation of the US Renewable Fuel Standard (RFS) for transportation fuels and State renewable portfolio standard (RPS) programs. Biofuels production will grow over the next two decades, though is likely to fall short of the 36 billion gallons of RFS target in 2022. However, it may exceed expectations for 2035 including fuels from cellulosic ethanol, renewable diesel, and first generation biofuels. (Newell, 2009)

Beyond biofuels, companies are increasingly targeting higher value biobased chemical products and biomaterials.

Liquid fuels are the ultimate commodity chemicals, representing the highest volume, but lowest value products whether produced from fossil or renewable feedstocks. In the United States, the petroleum-based liquid fuels industry and related energy services account for approximately 67% of petroleum consumed, with an overall industry value of $350 billion dollars. In contrast to commodity fuels, the goods and services resulting from the higher-value plastics, coatings, resins, and related consumer products utilize only 7% of petroleum consumed while resulting in an approximate $255 billion impact (Frost, 2005). Cargill and McKinsey & Company estimate that there is a potential to produce up to two-thirds of chemicals from biobased materials representing over 50,000 products, a $1 trillion annual global market (Jarrel, 2009).
Commercial examples of higher value biobased products are emerging with increased frequency, as profiled in Chapter 12 of this review. By 2007, internal corporate investment in research and development related to biobased chemicals and biomaterials was as much as $3.4 billion, which far outpaced biofuels. This was due primarily to internal research and development investments from a few large pharmaceutical companies, which was in contrast to the United States Government’s continued focus during the same time period on liquid transportation biofuels (Lundy et al., 2008). While some biobased products are direct replacements for fossil-derived materials, others possess novel properties unique to their biogenic origin. An interesting example is Canadian-based EcoSynthetix (www.ecosynthetix.com) that is producing a starch-based coating product for the paper industry that outperforms its competitive products by requiring less water and heat in production, while exhibiting superior ink adhesive properties. This product is competitive with its petroleum-based counterpart when the price of oil is as low as $30 per barrel. Recent grants from United States Department of Energy (DOE) to support biomass work have not just focused on biofuels. For example a sizable $600 million round of funding awarded in late 2009, included support for Myriant Technologies’ succinic acid project and Amyris Biotechnology’s process to produce a range of biobased products to complement their biofuel program. It is expected that this trend will continue with both public and private investment focused on a range of high-value biomaterials and chemicals, as opposed to exclusively on biofuels.

1.3 Feedstocks

1.3.1 Biobased Feedstock Availability and Issues

Globally, ample supplies of renewable feedstocks are available for developing a robust and profitable biobased products industry, including agricultural crops, residues, and forestry materials, as well as future sources such as algae. Lignocellulosic biomass is globally dispersed and can be found in many forms, including agricultural crop and processing residues, forestry resources, dedicated energy crops such as miscanthus and switchgrass, and municipal solid waste. In the United States alone, resources associated with agriculture and forestry were calculated at 1.3 billion dry tons per year of biomass potential (Perlack et al., 2005). There are additional chapters in this volume that provide detailed information from a variety of perspectives on the availability of lignocellulosic biomass.

It is important to note that the theoretical availability of biomass does not necessarily mean that it is economically feasible or environmentally viable to collect. For example, many primary row crop regions in the United States would produce excellent yields of perennial bioenergy crops, but the economics do not currently support substitution. The availability of agricultural crop residues must also be carefully considered. Crop residues include sustainably removable materials left after harvesting primary crops such as corn and wheat. Such residue availability has often been calculated based on 1:1 corn stover-to-grain ratios provided in the “Billon-Ton Report” published by the United States Department of Agriculture (USDA) and DOE (Perlack et al., 2005). Corn stover is widely considered a prime candidate for bioprocessing, although the actual availability within a working farm system, as well as collection incentives to farmers, may not be understood adequately. Additionally, regional (and global) variables affecting crop residue supply are acknowledged in the Billion Ton Report. For example, in northern climates, corn stover, the stalks and residues left after harvesting the grain, does not degrade quickly due to the cold winter temperatures. This sometimes creates a problem in that there is too
much stover for field preparation activities for the next spring. As corn yields increase due to biotechnology, this problem may increase and it will be necessary to remove stover. This is not the case in southern climates, as stover degrades quickly in the wet, relatively warm winters and is counted on by the farmer as a valuable source of organic matter in the soil.

Rice straw is another potential crop residue source that is widely available. In this case it would be an environmental benefit to remove the straw because currently it must be burned or otherwise disposed of every year to avoid diseases in the following year’s rice crop. It would be a great benefit for air quality and the farmer to develop a market for this straw in a biomass application. In California, there has been much work, with limited success, in trying to develop markets for rice straw as a reaction to the Rice Straw Burning Reduction Act of 1991 (AB1378). Projects included the development of construction products and packaging materials from rice straw. Unfortunately, the straw is high in silica, which damages existing harvesting and handling equipment, making it impractical to develop a widespread harvesting system. However, if alternative technologies could extract higher value silica products, economics might support the development of more robust harvesting systems.

The use of wheat straw in biomass processing and biomaterials has potential, as the straw is already harvested in the United States and globally for use in animal bedding and for other applications. Over the last two decades, wheat straw has been used for composite construction materials, filler materials in plastics, and in the development of cellulosic ethanol. Iogen (www.iogen.ca) has based its cellulosic ethanol demonstration plant on wheat straw as a major raw material. The company is planning its first commercial facility in Saskatchewan that will utilize cereal straw feedstocks.

In the near term, especially in the United States, corn cobs may represent the most accessible crop residue for early commercial lignocellulosic processing. Harvesting of corn cobs in a one-pass system is feasible and is being developed as a component of the United States’ corn ethanol industry. There is already an existing market in some regions for corn cobs at approximately $80.00 per ton, to be used in the production of chemicals such as furfural. Companies such as POET Biomass, a division of POET (www.poetenergy.com), and DuPont Danisco Cellulosic Ethanol, LLC (www.ddce.com) are developing conversion technologies specifically targeting corn cobs as feedstocks for biochemical conversion using enzymes. There is also significant work by major equipment companies, including CNH America LLC. (www.cnh.com) and Deere & Co. (www.deere.com), on one-pass harvesting systems for corn cobs.

Another potential source for lignocellulosic biomass is dedicated energy crops, both perennials and annuals. Perennials include crops such as miscanthus and switchgrass which have recently been the focus of attention by crop biotechnology and cellulosic ethanol companies. Perennials offer options to farmers and land owners for use of marginal land that is currently in pasture or other use. These crops sequester carbon in their root systems, as well as utilize relatively small amounts of inputs such as fertilizers and pesticides. The economics of producing these crops does not lend itself to replacing prime row crops, but their production may be part of farm-based crop diversification strategies in the future or as part of a program to utilize marginal and unproductive farm land.

Annual crops include sweet sorghum and forage sorghums, both of which require minimal inputs and produce significant biomass. In the case of sweet sorghum, a large sugar content in the crop can be easily converted to ethanol or other biobased products with current technology, while the bagasse could serve as feedstock for lignocellulosic conversion technologies.

Markets for these crops are being developed for biopower applications, even as other higher value uses are being commercialized. There is a growing market in Europe and in certain
regions in the United States for densified wood and energy crop pellets and briquets for home heating, industrial use, and co-firing with coal. The latter use is increasingly being driven by regulatory requirements directed toward renewable power generation and greenhouse gas reduction. Forestry and wood-processing residues and byproducts, as well as short-rotation woody crops, also represent important biomass feedstocks. Collectively referred to as “woody biomass,” these resources are often advantaged by an existing year-round harvesting and collection infrastructure. A detailed analysis of all of the crops, trees, and residues is provided in this volume.

1.3.2 Characterization of Lignocellulosic Feedstocks

Woody and herbaceous biomass, or lignocellulosic biomass, primarily comprises three major components—lignin, cellulose, and hemicellulose—along with lesser amounts of minor and trace constituents. Cellulose and hemicellulose are polysaccharides or sugar polymers composed of repeating monomer sugar units bonded together into long chains, much like rail cars are coupled together to form a train. Combined with lignin, these biopolymers comprise the structural components of plant matter and are produced by the photosynthetic process, whereby atmospheric carbon dioxide (CO$_2$) is absorbed by the plant, chemically transformed, and “fixed” into these other useful chemical materials.

Lignin is a natural polymer found in all plant materials, which combines with cellulose and hemicellulose to provide structural strength to the plant. It is not a sugar polymer, but rather an aromatic polymer, meaning its component phenylpropyl molecular units contain the highly stable benzene-ring chemical structure, which is also the basis for many commercially useful materials produced from petroleum. The aromatic chemical structure also imparts a high caloric value to the lignin molecule, which is valuable for combustion (heat) and also chemical transformations. The lignin polymer can have significant variability in its chemical structure, often differing based upon the biomass source.

Cellulose and hemicellulose are referred to as carbohydrates because they are aliphatic polymers composed only of carbon, hydrogen, and oxygen. Cellulose is the most abundant biopolymer on earth and is made of six carbon or C-6 glucose (sugar) monomers. Cellulose obtained from wood pulp, cotton, and other plants has been used for centuries to produce paper and cardboard, as well as derivative products. Often referred to as dietary fiber, it is not digestible by humans, but with recent technology developments, it can now be commercially hydrolyzed by chemical, enzymatic, or biological processes to its monomer sugars, which can then be readily utilized as feedstocks for bioprocessing. Yeast fermentation of glucose to ethanol (mostly for beverages) has been practiced for centuries, and other natural and genetically modified organisms can convert glucose to various useful chemical molecules.

Hemicellulose is a polymer primarily composed of various five carbon or C-5 sugar monomers with some C-6 sugars as well. Unlike cellulose, it is an amorphous polymer with little structural strength and is easily hydrolyzed to its monomeric sugars with acid/base or enzymes. Unfortunately, C-5 or xylose sugars cannot be fermented using natural yeasts. However, aggressive research and development programs are developing new organisms and genetically modified yeasts to utilize these readily available C-5 sugars as bioprocessing feedstocks, as described in Chapter 8 of this volume.

Fractionation, or separation, of petroleum into its component constituents has been the key methodology to develop high value petrochemical end products. A similar biobased example
is corn wet milling, in which the corn kernel is separated into its different components, from which value-added products are produced. As noted above, lignocellulosic biomass feedstocks possess comparable compositional diversity, and several leading technology developers are pursuing fractionation, or separation, of these components in order to facilitate more efficient and targeted downstream conversion of each component to value-added products. Historically, lignocellulose fractionation originated in the pulp and paper industry, where processes were designed to remove hemicellulose and “de-lignify” wood pulp in order to obtain a purified cellulose fraction for paper manufacturing (Agenda 2020 Technology Alliance, 2006). More recent approaches have used a combination of physical and thermal pre-processing followed by aqueous and/or solvent extractions, to afford substantially purified fractions of hemicellulose, lignin, and cellulose for further processing that is specific to each component. As a supporting technology, lignocellulose fractionation may prove to be extremely valuable as an integrated component of biochemical processing, providing sugars for fermentation and also a purified lignin stream as an aromatic chemical platform feedstock. Developmental and commercial lignocellulosic fractionation technologies are fully described in Chapter 12 of this volume.

1.3.3 The Role of Agricultural Biotechnology

In order to provide sustainable food, fuel, and material needs of humans, it will be necessary to dramatically increase the yields of agricultural crops and forest resources, as well as develop crops with specific attributes for biomass feedstocks. Currently, biotechnology traits used to reduce farmers’ costs and increase profitability are widely deployed in canola, corn, cotton, soybeans, and sugarbeets, predominantly in the United States. However, more than 13 million farmers in 25 countries currently grow agricultural biotechnology crops. In 2008, the global biotechnology crop area grew by 9.4%, or 26.4 million acres, to reach a total of 309 million global acres. Between 2007 and 2008, the United States alone increased its biotechnology crop acreage from 143 million acres to 154 million, phenomenal growth considering that the first biotechnology crops were not introduced until the mid-1990s (ISAAA, 2008).

To date, the vast majority of commercialized agricultural biotechnology-derived crops have focused on genetic “input traits,” which add value to the farmer and/or environment by reducing the production costs of the farm operation. Examples include Roundup™ Ready soybeans that are resistant to the herbicide glyphosate, allowing soybean farmers to more widely adapt conservation tillage practices. There are other examples related to insect and herbicide resistance. In addition to input traits in commodity crops, plant biotechnology has developed new crops for bioenergy and pharmaceutical applications with enhanced “output traits,” which allow the crop to produce certain characteristics desired by food, health, or industrial customers. While the value proposition for input traits is directed to the farmer, output traits are directed to those making products from the crops and ultimately to the consumer. Output traits allow crops to have higher protein and other nutritional properties, stronger fibers, specific oil profiles, novel health benefits, and to produce new products within green plants. In short, output traits enhance the value of the plant as a feedstock for the production of plant-based products. Not all of these technology improvements are created through gene transfer. Some use mutation, breeding, and other novel techniques to create new crop performance.

Numerous examples of enhanced crop products have been commercialized or are in development for food, feed, and industrial applications, as summarized in Table 1.1. In the mid-1990s, Monsanto Company had a designer fiber unit that attempted to match specialized end uses for
Table 1.1. Selected plant biotechnology companies and products.

<table>
<thead>
<tr>
<th>Company</th>
<th>Brand</th>
<th>Trait</th>
<th>Crops</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceres, Inc.</td>
<td>Blade</td>
<td>Improved biomass characteristics, yields</td>
<td>Switchgrass, biomass sorghum, sweet sorghum and other biomass crops</td>
<td>Advanced biofuels, biobased chemicals, and biopower</td>
</tr>
<tr>
<td>Dow AgroSciences</td>
<td>Nexera</td>
<td>High oleic/low linolenic fatty acids</td>
<td>Canola and sunflower</td>
<td>Food—no trans fats and low in saturated fat</td>
</tr>
<tr>
<td>Dow AgroSciences (Mycogen Seeds)*</td>
<td>Supercede HE High Energy</td>
<td>40% more oil than No.2 yellow corn</td>
<td>Corn</td>
<td>Animal feed—increases energy in metabolism</td>
</tr>
</tbody>
</table>
| DuPont/Pioneer®                | Partnership with Bunge | Low linolenic soybeans                                    | Soybeans                                   | Food/feed, future products include high-oleic and Omega-3
| Edenspace Systems Corporation  |                        | Improved biomass characteristics and plant-made enzymes    | Switchgrass and corn                       | Biomaterials and advanced biofuels             |
| Infinite Enzymes, LLC.         |                        | Plant-made industrial enzymes                              | Corn                                       | Green chemicals and advanced biofuels          |
| Mendel Biotechnology           | Bioenergy Seeds        | Improved biomass characteristics, yields                   | Miscanthus and other biomass crops         | Advanced biofuels and biopower                |
| Metabolix                      | Mirel                  | Plant-based plastic and chemicals                          | Switchgrass                                | Biomaterials and bioenergy                     |
| Monsanto                       | Vistive                | Low-linolenic soybeans                                    | Soybeans                                   | Food/feed, reduce trans fats, increase shelf life and oil stability |
| Syngenta Seed                 | Quantum™ Phytase       | Phytase                                                    | Corn                                       | Animal feed ingredient                         |
| Syngenta Seeds                |                        | Cellulase                                                  | Corn                                       | Plant production system for cellulase used in green chemistry/cellulosic ethanol |
| Targeted Growth Inc.           |                        | Ricinoleic acid                                            | Camelina                                   | Green chemistry/biomaterials                   |
| Syngenta Seeds                | Amylase and cellulase (under development) |                     | Corn                                       | High amylose corn for conventional ethanol production |
| aGrooms, 2006.                |                        |                                                            |                                            |                                                 |
cotton with specific, genetically engineered characteristics in a cotton variety. Other examples include products for reagent use that ProdiGene, Inc. commercialized. Trypsin (trade name TrypZean), beta-glucuronidase, and avidin are all sold by Sigma Chemical Co. Significant research is also being conducted to improve the fatty acid profile in camelina, a crop pioneered by United States producer groups in the Great Plains and companies such as Targeted Growth, Inc. (www.targetedgrowth.com). Targeted Growth, Inc. began a breeding program for camelina in 2005, employing a three pronged approach: classical and molecular breeding, mutation breeding, and transgenics (Panter, 2008). Other companies, such as Linnaeus Plant Sciences (www.linnaeus.net), are seeking to change the oil profile of the crop for various novel biobased product applications.

Researchers are also working to adapt modern biotechnology tools to the development of new bioenergy crops. Examples of these include miscanthus, switchgrass other herbaceous crops, and short rotation woody crops. Companies working in this area include Ceres, Inc. (www.ceres.net); Chromatin, Inc. (www.chromatininc.com); Edenspace Systems Corporation (www.edenspace.com); Infinite Enzymes, LLC (www.infiniteenzymes.com), Mendel Biotechnology, Inc. (www.mendelbio.com), and Metabolix (www.metabolix.com). For both large multinational biotechnology firms and small boutique trait developers, a key hurdle is navigating a confusing and costly regulatory environment. A streamlined approach to getting crops deregulated and into commercial applications will have to be coordinated to attract the significant capital needed to grow this part of the industry.

1.3.4 Biomass Agricultural Equipment Development

As discussed in this chapter and the subsequent chapters in the volume, there is significant activity in the development of biomass feedstocks, conversion processes, and end-use applications. Increasingly, there is also investment by major farm equipment manufacturers in developing biomass harvest systems such as one-pass corn cob harvesters or systems to remove tree residues in harvesting. Noteworthy projects include commercial scale harvesting demonstrations of corn cobs by POET Energy and switchgrass by Genera Energy, LLC. (www.generaenergy.net). Equipment manufacturers actively engaged in biomass development activities include AGCO (www.agcorp.com); CLAAS (www-claasofamerica.com); CNH America, LLC. (www.cnh.com); Deere & Company; and Vermeer Corporation (www.vermeer.com). The involvement of these prominent companies in both agriculture and forestry-based biomass development addresses another major link in the new supply chain and promises innovative solutions for farmers and processors.

1.4 The Biochemical Technology Platform

Biomass or components of biomass can be used as feedstocks by molecular modification of the constituents, a process often referred to as bioprocessing. There are three distinct technology platforms for these molecular transformations—chemical, thermochemical, and biochemical. Each platform has specific characteristics for commercial processing, including range of feedstocks and products, co-products, cost, scale, and stage of technology development.

The focus of this book is on the biochemical technology platform that utilizes enzymes and microorganisms to effect molecular transformations, often with incredible energy efficiency and product specificity. Biochemical processing, sometimes referred to as the “sugar” or
Plant Biomass Conversion

carbohydrate platform, seeks to convert C-6 and C-5 sugars derived from biomass through fermentation processes to biofuel and biobased chemical products.

In the United States and globally, much recent biochemical platform R&D has focused on the development of pretreatment systems and enzymes that can depolymerize cellulose and hemicellulose into monomeric sugars to allow yeast fermentation to “cellulosic” ethanol. As a second-generation biofuel, ethanol derived from lignocellulosic feedstocks eliminates the food-fuel issue associated with sugar/starch feedstocks and has also been shown to have a much more favorable net energy balance and lifecycle GHG reduction than corn (starch-based) ethanol. Also within the biochemical platform, other research is developing new bacterial organisms and genetically modified yeasts to convert both C-6 and C-5 sugars to other biofuel and chemical products (see Chapters 11 and 12 in this volume), with perhaps the most advanced efforts directed at butanol, an important industrial chemical and possible second-generation biofuel, and succinic acid, a multifunctional platform chemical.

Significant progress has been made in developing biochemical technologies to use lignocellulosic feedstocks. The overall process requires several steps, including feedstock pretreatment, depolymerization, sugar fermentation, and distillation/product isolation. Several pretreatment methodologies have been developed, generally combining heat, pressure, and chemical reaction to make the cellulose and hemicellulose polymers more accessible to enzymatic and microorganism attack (as described in Chapter 9 in this volume). Pretreatment processing must be designed to minimize introduction or formation of contaminants that would be toxic to the downstream fermentation organisms.

While significant hydrolysis of the hemicellulose can occur during pretreatment, cellulase and other enzymes must be added to convert the more recalcitrant cellulose to its component C-6 sugars and complete conversion of hemicellulose to C-5 sugars. Remarkable advancements in cellulase enzyme cost and effectiveness have been made in the last 5 years and are continuing (see Chapter 10 in this volume). Novel approaches to enzyme production are also being developed, for example:

A major technical challenge in making cellulosic ethanol economically viable is the need to lower the costs of enzymes needed to convert biomass to fermentable sugars. The expression of cellulases and hemicellulases in crop plants and their integration with existing ethanol production systems are key technologies that will significantly improve the process economics of cellulosic ethanol production. (Sainz, 2009)

While C-6 sugars are readily fermented to ethanol by natural yeasts, current R&D programs seek to develop new organisms that can effectively convert the C-5, as well as the C-6 lignocellulosic sugars to ethanol and other chemical products. Some R&D programs are pursuing organisms that can both hydrolyze cellulose and hemicellulose and ferment the resulting mixed sugars to ethanol, referred to as consolidated bioprocessing. These efforts will be more fully described in other Chapters throughout this volume.

1.5 Investment and Major Players

Despite the recent global economic downturn, $16.9 billion was invested in new biofuels in 2008 (UN, 2009) and the cleantech sector emerged as the leading investment category for venture capitalists in 2009. Recognizing the complexities of introducing new biobased
technologies, strategic partnerships are becoming a preferred route to commercial products in the biobased supply chain. This is leading to a business environment that includes direct investments in entrepreneurial ventures, as well as many strategic partnerships and joint ventures, often leveraging existing competencies and assets. Table 1.2 summarizes key biobased product companies and their investors/partners.

<table>
<thead>
<tr>
<th>Company</th>
<th>Feedstock/Product</th>
<th>Investors/Partners</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abengoa Bioenergy</td>
<td>Corn ethanol and experimental lignocellulosic biomass fuels and chemicals</td>
<td>DOE</td>
</tr>
<tr>
<td>Amyris Biotechnology</td>
<td>Development of advanced biofuels and chemicals from sugar-based feedstocks including sweet sorghum and sugar cane.</td>
<td>DAG Ventures, Khosla Ventures, Kleiner Perkins, TPG Ventures, Total</td>
</tr>
<tr>
<td>Butamax Advanced Biofuels</td>
<td>Biobutanol, sugarbeets</td>
<td>DuPont, British Petroleum</td>
</tr>
<tr>
<td>Catchlight Energy LLC.</td>
<td>Feedstocks, supply chain, technology licensing and deployment</td>
<td>Joint ventures between Chevron &amp; Weyerhauser</td>
</tr>
<tr>
<td>Coskata</td>
<td>Wood, MSW</td>
<td>Khosla Ventures, Great Point Ventures, Advanced technology Ventures, General Motors, Globespan</td>
</tr>
<tr>
<td>Dupont Danisco Cellulosic Ethanol, LLC.</td>
<td>Corn cobs, switchgrass</td>
<td>DuPont, Danisco, Genera Energy (University of Tennessee),</td>
</tr>
<tr>
<td>Dupont Tate&amp;Lyle</td>
<td>Sugar</td>
<td>DuPont, Tate&amp;Lyle</td>
</tr>
<tr>
<td>Elevance Renewable Sciences</td>
<td>Oilseeds</td>
<td>Cargill Inc., Materia Inc., California Institute of Technology, TPG Growth, TPG Biotechnology Partners</td>
</tr>
<tr>
<td>Gevo Development LLC.</td>
<td>Biobutanol, other biobased products.</td>
<td>Cargill, ICM, Khosla Ventures, Virgin Fuels, Burrill &amp; Company, Malaysian Life Sciences Capital Fund</td>
</tr>
<tr>
<td>Iogen Corporation</td>
<td>Wheat straw, other feedstocks, cellulosic ethanol</td>
<td>Royal Dutch Shell, Goldman Sachs, Volkswagen, Petro-Canada, Government of Canada, DSM</td>
</tr>
<tr>
<td>Mascoma Corporation</td>
<td>Biomass feedstocks, cellulosic ethanol</td>
<td>Khosla Ventures, Flagship Ventures, General Catalyst, Kleiner Perkins, Vantage Point, Atlas Ventures, Pinnacle Ventures</td>
</tr>
<tr>
<td>Range Fuels</td>
<td>Wood and other biomass feedstocks, cellulosic ethanol</td>
<td>Passport Capital, BlueMountain, Khosla Ventures, Leaf Clean Energy Company, PCG Clean Energy &amp; Technology Fund</td>
</tr>
<tr>
<td>Verenium Corporation</td>
<td>Wood, sugarcane bagasse</td>
<td>British Petroleum, Khosla Ventures, Braemar Energy Ventures, Charles River and Rho Ventures</td>
</tr>
</tbody>
</table>
Significant investments were made in advanced biofuels and green chemistry by a range of biotechnology, petroleum, and chemical companies in 2008 and 2009. Funding directed toward developing biobased chemicals has risen steadily since 2004 and reached $3.4 billion in 2007 in the United States (Lundy et al., 2008). From 2004 to 2009, major investments were made by large multinational petroleum and chemical companies, including Chevron, DuPont, Dow, Dutch Royal Shell, and Exxon Mobil. Venture capital investment also grew substantially, with the cleantech sector moving into a leadership position through the economic downturn of 2008–2009. As an example, new funds were announced by leading cleantech investor Khosla Ventures (www.khoslaventures.com), as well as Finistere Ventures (www.finistereventures.com).

Partnerships among established global producers in the agriculture, biotechnology, chemical, and petroleum sectors are becoming commonplace. An early example was the Cargill-Dow, LLC venture started in 1997, which is now NatureWorks, LLC (www.natureworksllc.com) (wholly owned by Cargill), which invested approximately $1 billion to commercialize corn-based polyactic acid (PLA). British Petroleum and DuPont have formed Butamax Advanced Biofuels, LLC (www.butamax.com) to commercialize biobutanol as an advanced biofuel, while British Petroleum is also investing in Verenium and other advanced cellulosic biofuels businesses. More recently, Exxon Mobil announced in 2009 a $600 million investment to produce biofuels from algae in a joint venture with Synthetic Genomics founded by human genome pioneer J. Craig Venter (Mouawad, 2009). Royal Dutch Shell PLC increased its investment to $60 million in 2009 in Codexis (www.codexis) to explore biofuels production (Gold, 2009) while continuing to partner with Canada-based Iogen (www.iogen.ca). DuPont has formed Dupont Danisco Cellulosic Ethanol, LLC (www.ddce.com) to commercialize cellulosic ethanol and is in a joint venture with sugar company Tate & Lyle (called Dupont Tate & Lyle Bioproducts) to produce 1,3-propanediol (www.duponttateandlyle.com). These are a few of the hundreds of new business divisions, companies, and partnerships being developed globally to pursue renewable fuels and chemicals.

Major venture capital funders such as Khosla Ventures (www.khoslaventures.com) and Burrill & Company (www.burrillandco.com) announced new funds in 2009 that will focus on biofuels and related technologies, including two new funds totaling $1 billion by Khosla Ventures. Khosla Ventures has led investment in numerous advanced biofuels companies, including Amyris (www.amyris.com), Coskata (www.coskata.com), Gevo (www.gevo.com), LS9 (www.ls9.com), Mascoma (www.mascoma.com), Range Fuels (www.rangefuels.com), and Verenium (www.verenium.com), providing strong strategic direction and momentum to the industry at a crucial time. Coskata has also received investment from General Motors, another example of the cross-industry, strategic investments made in this space between 2005 and 2009. Incorporating the forestry sector, Catchlight Energy is a joint venture between Chevron and Weyerhaeuser dedicated to combining the strengths of the two organizations to commercialize biofuels (www.catchlightenergy.com).

The formation of domestic and foreign strategic alliances has grown from 532 new industrial biotechnology alliances in 2004 to 1,367 new alliances in 2007. Patent and trademark activity has intensified as firms seek to protect, commercialize, and license their new discoveries and brands. Trademark registrations in particular have shown strong growth, increasing from 197 new registrations in 2004 to 1,027 in 2007, reflecting the increasing prominence of biobased brands as the field moves from early discoveries to the commercialization of innovative technologies and products (Lundy et al., 2008).

The Federal Government’s significant investments since 2000 have helped many of the early companies develop technologies, improve processes, and leverage private investment, as
Table 1.3. Selected USDA and DOE grants (2002–2009) for biomass projects.

<table>
<thead>
<tr>
<th>Year</th>
<th>Program</th>
<th>Total Funding</th>
<th>Awarded Projects</th>
<th>Partial List of Recipients</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>Biomass R&amp;D Joint</td>
<td>$79,350,000.00</td>
<td>8 awards</td>
<td>Broin &amp; Associates (now POET), Cargill, DuPont, Abengoa, National Corn Growers Association, Iowa Corn Promotion Board</td>
</tr>
<tr>
<td>2003</td>
<td>Biomass R&amp;D Joint</td>
<td>$23,803,802.00</td>
<td>19 awards</td>
<td>Dartmouth (Mascoma), University of Florida (now partnering with Buckeye Technologies), Pure Vision Technology, Metabolix, Cargill, ADM</td>
</tr>
<tr>
<td>2004</td>
<td>Biomass R&amp;D Joint</td>
<td>$26,357,056.00</td>
<td>13 awards</td>
<td>Rohm &amp; Haas Co., Weyerhaeuser Company</td>
</tr>
<tr>
<td>2005</td>
<td>Biomass R&amp;D Joint</td>
<td>$12,626,931.00</td>
<td>11 awards</td>
<td>Samuel Robert Noble Foundation</td>
</tr>
<tr>
<td>2006</td>
<td>Biomass R&amp;D Joint</td>
<td>$17,492,507</td>
<td>17 awards</td>
<td>Increasing focus on feedstock development: Ceres Inc., SUNY, Edenspace Systems</td>
</tr>
<tr>
<td>2007</td>
<td>Biomass R&amp;D Joint</td>
<td>$18,449,090.00</td>
<td>21 awards</td>
<td>GE Global Research, Ceres Inc., Agrivida Inc.</td>
</tr>
<tr>
<td>2007</td>
<td>DOE Commercial Scale Biorefinery</td>
<td>$385,000,000.00</td>
<td>6 awards</td>
<td>Abengoa Bioenergy, BlueFire Ethanol, Broin Companies (now POET), Iogen, Range Fuels</td>
</tr>
<tr>
<td>2008</td>
<td>DOE Small Scale Biorefinery</td>
<td>$200,000,000.00</td>
<td>7 awards</td>
<td>Verenium, Lignol Innovations, ICM, UT/Genera</td>
</tr>
<tr>
<td>2009</td>
<td>DOE Advanced Biorefinery</td>
<td>$564,000,000.00</td>
<td>19 awards</td>
<td>ADM, Amyris Biotechnology Inc., Elevance Renewable Sciences, BioEnergy International LLC (Myriant)</td>
</tr>
</tbody>
</table>

summarized in Table 1.3. For example, the recent $564 million DOE investment in advanced biorefinery projects leveraged a private investment of $1.3 billion. The Obama Administration is continuing to invest heavily in advanced biofuels, regional innovation clusters, renewable energy jobs, and biotechnology.

On the feedstock side, substantial investment is occurring in the development of dedicated energy crops and crop-based synergies such as enhanced traits or downstream processability. These initiatives include the commercialization of plant-made enzymes by Syngenta and startup companies, and the commercialization of dedicated energy crops by companies such as Arbogen, Ceres, and Mendel Biotechnology.

1.6 The Role of the Farmer

An essential component of the value chain for biobased products is the alignment of companies seeking to commercialize biobased products with feedstock providers, namely the farmers, logistics, and preprocessing producers. All too often biobased products industry proponents tout the ability of biorefineries to revitalize rural regions without understanding the overall value proposition or fully considering the vital linkages necessary with the farmer. Three
primary models have emerged for companies and processors to access lignocellulosic biomass, as described below (Nelson, unpublished).

1. **Farm gate**—In this model, farmers are paid a set price and/or contracted price for biomass baled and delivered to the factory, storage site, or made available at field for pickup. Generally, this price is between $30 and $70 per dry ton according to most publications. In discussions with farmers, it is clear that this model will require a guaranteed long-term contract that includes one or more of the following: an independent ability to market carbon credits, a contract price (especially for perennial energy crops) indexed to corn or petroleum, and a guaranteed price floor. The Biomass Crop Assistance Program (BCAP) authorized in the 2008 Farm Bill was recently released, which will provide assistance to farmers producing biomass crops within this scenario.

2. **Access fee/land rental**—In this model, farmers are essentially land owners, similar to the pulp and paper industry, in which companies pay to have dedicated energy crops produced and the companies handle the planting and harvesting. Although the farmers may have some role in maintenance, they are essentially operating as absentee land owners. This model is not considered viable in major row crop farming regions, but may be of interest to small, part time farmers or those that own marginal land.

3. **Value-added farmer participation**—In this model, farmers participate in a value-added enterprise, possibly formed as a cooperative, in which their biomass production includes some component of preprocessing, logistics, and/or value-added processing or service to the end clients. As an example, a University of Tennessee-sponsored program through its subsidiary company Genera Energy, LLC (www.generaenergy.net) has formed a biomass processing cooperative to support scale up of switchgrass in East Tennessee. In the United States, the development of farmer-owned businesses to process biomass into pellets or briquettes to cofire with coal or other biopower applications may serve to establish a reliable supply chain for lignocellulosic biomass destined for future higher-value applications, other than combustion. Show Me Energy Cooperative LLC. of Centerview, Missouri (www.goshowmeenergy.com) is a great example. Show Me Energy has over 400 farmers who own part of the cooperative and are supplying waste straw and dedicated energy crops to their pellet operation.

Logistics and storage considerations for commercial lignocellulosic feedstock supply are not insignificant. For example, within each of these models, some scenarios envision biomass materials being baled and stored at the fields for delivery throughout the year to the processing facility. It remains to be seen whether off-season on-field storage of lignocellulosic crops will be accepted by high production commercial row crop farming operations. For a given project or program, the successful model must involve farmers and supporting logistics providers as more than an afterthought. To attract serious, large-scale farmers who can professionally deliver large volumes of biomass as well as invest in the supporting infrastructure will require new business models that make a compelling case to each participant in the supply chain.

### 1.7 Opportunities for Rural Development

A pressing need exists for rural development to provide jobs and long-term sustainable opportunities in rural areas in the United States and across the world. In the United States, poverty is consistently higher in rural as opposed to urban areas, with over 500 rural counties defined as being in “persistent poverty.” Agriculture is often a significant economic sector in these regions, but its role as a job and local wealth creator has declined in recent years (Cowan,
2002). New biobased feedstocks may offer the opportunity to grow, process, and transport lignocellulosic biomass for new products and rebuild these local agriculture-based economies.

The conversion of lignocellulosic biomass to biobased products promises to have significant impact on rural communities. The low bulk density of lignocellulosic biomass dramatically changes logistics and processing dynamics. Grain crops such as corn and soybeans can be economically transported via barge and rail for remote processing and consumption, whereas at least the first phase of commercial lignocellulosic feedstock processing will necessarily be located in close proximity to the harvested biomass due to transport economics. This is especially true for herbaceous biomass such as processing and crop residues and dedicated energy crops, while forestry materials or densified feedstocks may be transported longer distances. Most models indicate that the viable transport radius of harvested herbaceous energy crops around a rural biorefinery or preprocessing facility is approximately 25–50 miles. This will necessitate smaller decentralized biorefineries across rural areas that will at least incorporate preprocessing and/or initial refining of lignocellulosic biomass substrates.

To give an example of what this opportunity can mean for rural regions, the corn ethanol industry can be examined at its high growth period from 2006 to 2008. One report summarized the economic impact during this period as follows:

The industry spent $12.5 billion on raw materials, other inputs, goods and services to produce an estimated 6.5 billion gallons of ethanol during 2007. An additional $1.6 billion was spent to transport grain and other inputs to production facilities. Within the corn ethanol industry, new jobs are created as a consequence of increased economic activity resulting from ongoing production and construction of new capacity supported the creation of 238,541 jobs in all sectors of the economy during 2007. These include more than 46,000 jobs in America's manufacturing sector – American jobs making ethanol from grain produced by American farmers (Urbanchuk, 2008).

Despite its significant rural economic impact in the United States, it is generally recognized that starch-based ethanol is an important, but ultimately limited, first-generation biofuel. As such, its economic impact on rural communities may have been largely realized. Furthermore, the germplasm, production inputs, and processing of corn are controlled by a relatively small number of multinational companies such as DuPont Pioneer, Monsanto and Syngenta on the seed side, and ADM, Bunge, and Cargill on the processing side, leaving little room for entrepreneurial technology developers and farmer value participation.

Fortunately, the fully realized bioeconomy will require diverse and flexible feedstocks and technologies to produce a comprehensive range of biobased products, as well as biofuels. The multiproduct “biorefinery” will increasingly utilize more globally abundant lignocellulosic feedstocks to produce both commodity and value-added products. As a result, the lignocellulosic processing opportunity is substantially larger in terms of volume, and the low bulk density will dictate that processing be located in proximity to feedstock production. In contrast to corn and other grains with fully developed food-centric supply chains, the lignocellulosic feedstock supply chain is largely undeveloped and unconsolidated.

A recent comprehensive United States study concluded that in a 98-county area in the Mid-South Mississippi Delta region, lignocellulosic feedstock processing utilizing 10% of cropland, 25% of idle lands, 25% of conservation reserve program land, and 15% of pasture land would support a biomass industry valued at over $8 billion annually. This industry would create 25,000 new jobs within a decade and 50,000 jobs by 2030 in the study area alone (Tripp et al., 2009).
1.8 Environmental Benefits

The environmental benefits of biobased products and related technologies are just beginning to be fully understood. For example, studies have shown that the life cycle analysis for cellulosic ethanol produced from certain dedicated energy crops has a 90% reduction in greenhouse gas (GHG) emissions compared to petroleum gasoline (Farrell et al., 2006). Case studies have shown that energy and water use for biobased processes decreased 10–80%, while the use of petrochemical solvents was reduced by 90% or eliminated completely (OECD, 2001). Additional benefits can be found in product recyclability, air emissions, and reduced overall energy consumption from locally sourced foods, materials, and fuels. However, sustainable crop production is necessary to avoid soil and water depletion, as described in Chapters 6 and 7 of this volume.

1.9 Economic Comparison of the Biochemical and Thermochemical Technology Platforms

According to a recent report by the International Energy Agency (IEA), the thermochemical and biochemical routes have comparable potential energy yields, converting dry biomass at about 20 GJ/ton to about 6.5 GJ/ton of biofuels, for an overall conversion efficiency of about 35%. The report further projects potential ethanol yield of about 80 gallons/dry ton from biochemical processing and a synthetic diesel yield of 53 gallons/dry ton from thermochemical conversion. Experience with each platform, utilizing biomass feedstocks, is limited to pilot and precommercial scale at present, so accurate production cost information remains to be confirmed (see Chapter 14 in this volume). Furthermore, leading private-sector technology developers do not generally publish proprietary process cost information. IEA has estimated production costs of second-generation biofuels to be in the range of $3.02–3.79/gallon for ethanol and at least $3.79/gallon for synthetic diesel, comparable to the wholesale petrochemical fuel prices when crude oil is in the range of $100–130/bbl. The IEA report concludes that there is presently not a clear commercial or technical advantage between the platforms for the production of biofuels and that widely fluctuating crude oil prices impart high risk to investment in second-generation biofuels (IEA, 2008). The IEA report does not take into account the value of biobased products and the benefit of added flexibility of diverse end product applications.

1.10 Conclusions and Future Prospects

The bioeconomy represents a disruptive technological, social, and economic change that will be realized over decades, not years. The opportunities—as described in this volume—are many, as are the challenges. These will be met and exploited by a diverse combination of traditional food-based agribusiness, the fossil-based fuel and chemical industries, entrepreneurs, financiers, and farmers.

The market for biobased products is potentially higher value than for biofuels, and biochemical processing technologies likely offer more value-added specialty chemical product options than thermochemical technologies. Sugars derived from globally abundant and dispersed...
1 The Bioeconomy: A New Era of Products Derived from Renewable Plant-Based Feedstocks

Lignocellulosic feedstocks would serve as the predominant raw materials for rural biorefineries, which in turn could transform declining rural economies and create new “local” supply chains for energy, liquid transportation fuels, and other products. Positive environmental impacts from the use of renewable feedstocks, lower intensity manufacturing, and more efficient local supply and consumption would be significant.

A vision for plant-based renewable resources was published in 1998 (http://www1.eere.energy.gov/biomass/pdfs/technology_roadmap.pdf). This document was the result of a workshop comprising industry and trade group representatives assembled to discuss what it would take to convert the US industrial base to a more sustainable economy. The goals were modest by most standards: 10% of bio-based products and 40% of fuels would be from plant-based sources by the year 2050. Over a decade later, progress down this path has been slow at best. More aggressive goals than those stated in the 1998 document have been set in the US 2007 Energy Independence and Security Act—36 billion gallons of renewable transportation fuels per year (~20–30% replacement) to be reached in 2022. Because corn-starch-based ethanol is nearly maximal at 9 billion gallons per year (~25% of the grain crop), the balance of the ethanol should be derived from lignocellulosic biomass.

The ultimate requirement to replace finite fossil feedstocks with renewable resources is perhaps best described by Italian Chemist and Holocaust survivor Primo Levi in his 1975 chronicle of the elements (Levi, 1975):

> Carbon, in fact, is a singular element: it is the only element that can bind itself in long stable chains without a great expense of energy, and for life on earth (the only one we know so far) precisely long chains are required. If the elaboration of carbon were not a common daily occurrence, on the scale of billions of tons a week, wherever the green of a leaf appears, it would by full right deserve to be called a miracle.

> Man has not tried until now to compete with nature on this terrain, that is, he has not striven to draw from the carbon dioxide in the air the carbon that is necessary to nourish him, clothe him, warm him, and for the hundred other more sophisticated needs of modern life. He has not done it because he has not needed to: he has found and is still finding (but for how many more decades?) gigantic reserves of carbon already organized, or at least reduced. Besides the vegetable and animal worlds, these reserves are constituted by deposits of coal and petroleum: but these too are the inheritance of photosynthetic activity carried out in distant epochs, so that one can well affirm that photosynthesis is not only the sole path by which carbon becomes living matter, but also the sole path by which the sun’s energy becomes chemically usable.

The chapters of this volume describe the current state of the transformation to a renewable and sustainable bioeconomy and suggest the opportunities that await its realization.

References


