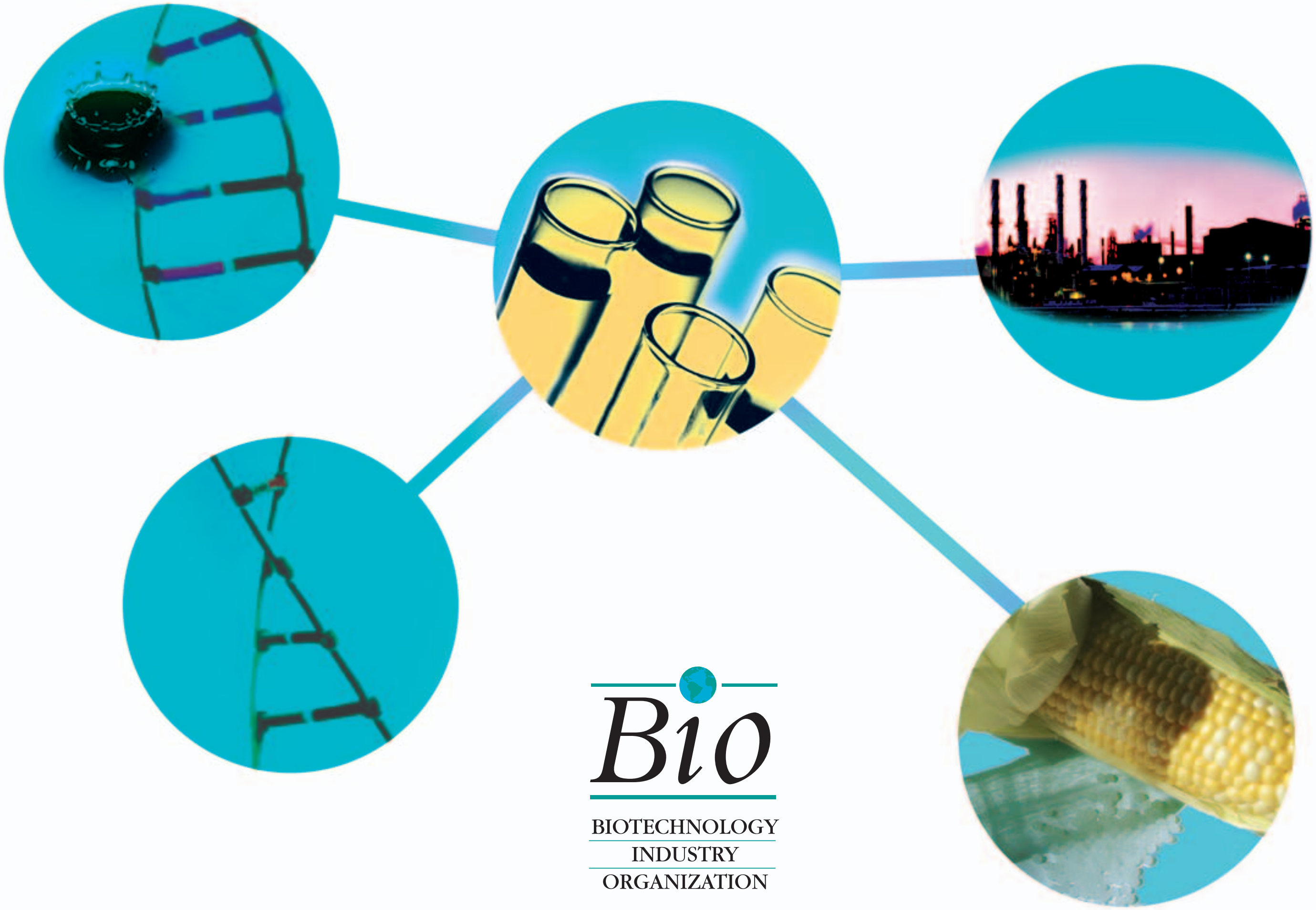
New Biotech Tools for a Cleaner Environment

Industrial Biotechnology for Pollution Prevention, Resource Conservation, and Cost Reduction



BIOTECHNOLOGY
INDUSTRY
ORGANIZATION

www.bio.org

New Biotech Tools for a Cleaner Environment

Industrial Biotechnology for Pollution Prevention, Resource Conservation, and Cost Reduction

Bio
BIOTECHNOLOGY
INDUSTRY
ORGANIZATION

AJW
Inc.

Biobased Products for a Cleaner Environment

www.bio.org

Foreword

Industrial biotechnology, the third wave of biotechnology, holds immense promise for transforming a wide variety of industrial processes by preventing pollution, reducing costs, conserving natural resources, and delivering innovative products to improve our quality of life. It is also creating new markets for traditional agricultural crops and crop residues as renewable feedstocks, chemical intermediates, and energy sources.

Members of the Biotechnology Industry Organization (BIO) Industrial and Environmental Section believe that sustainable development cannot be achieved without continuous innovation, improvement, and use of clean technologies and "green" chemistry to make fundamental process changes to reduce pollution levels and resource consumption. Industrial biotechnology uses the techniques of modern molecular biology (genomics, proteomics, and bioinformatics) to develop new biobased processes that reduce environmental impacts while improving efficiency in numerous industrial sectors. No matter what stage of industrial production–inputs, manufacturing process, or final product–industrial biotechnology is providing innovative new tools, techniques, and know-how to enable companies to move beyond regulatory compliance to the proactive pollution prevention and resource conservation strategies that are the hallmarks of industrial sustainability.

> "Sustainable development is a compelling moral and humanitarian issue. But sustainable development is also a security imperative."
>
> – U.S. Secretary of State Colin L. Powell, July 12, 2002

These new tools, however, cannot help move us toward a more sustainable future unless government policymakers, corporate leaders, and nongovernmental organization (NGO) leaders comprehend their value, support their adoption, and take proactive steps to incorporate them in a wide array of manufacturing processes.

In 2001, the Organisation for Economic Co-operation and Development (OECD) prepared a trailblazing report that presented 21 real world case studies in which biotechnology was applied to existing industrial processes. The OECD report found that industrial biotechnology more than delivered on its promise to transform and modernize.

We have attempted to build on the 2001 OECD study by asking the next obvious question: **What if industrial biotechnology were more widely used?** In posing this question we have attempted an initial–but limited–analysis of the potential environmental and resource conservation benefits that may accrue to certain industrial sectors. This analysis can–and should–be expanded in numerous directions. For example, greater use of industrial biotechnology will have multiple upstream and downstream consequences. We believe that further study will show these to be overwhelmingly beneficial. Nevertheless, quantifying the benefits and addressing trouble spots before they become problems necessitates additional work.

Although this report is written with a U.S. audience in mind, it does have global ramifications. Nothing illustrates this better than the rapid industrial expansion that is going on in China, India, and other parts of the world. Industrial transformation can take a long time while new technologies are developed, tested, deployed, and adopted. However, as environmental and global competitive pressures increase, time without action is no longer a luxury but becomes a liability. We hope that corporate leaders will be inspired by this report to explore the possibilities of using biotechnology in their own companies and that policymakers will be similarly motivated to look for incentives to increase the uptake of industrial biotechnology processes that accelerate achievement of environmental compliance goals.

This report is published by the BIO Industrial and Environmental Section and does not necessarily reflect the views of all BIO members. The mention of specific companies and trade and product names does not constitute an endorsement. BIO thanks the members of its Industrial and Environmental Section; EuropaBio; the U.S. Environmental Protection Agency (EPA); and others who contributed data, gave input, and reviewed this report.

> “When enthusiasts talk of sustainable development, the eyes of most people glaze over. [Their arguments] usually depend on people giving up the comforts of modern economy to achieve some debatable greater good. . . . What is needed is an industry that delivers the benefits without the costs. And the glimmerings of just such an industry can now be discerned.
>
> “That industry is based on biotechnology. At the moment, biotech’s main uses are in medicine and agriculture. But its biggest long-term impact may be industrial.”
>
> —***The Economist***, “Saving the World in Comfort,” March 27, 2003, editorial.

TABLE OF CONTENTS

Report Objectives 7

Executive Summary 8

1. Introduction 10

2. What Is Industrial Biotechnology? 13

3. Safely Harnessing Genetically Enhanced Microorganisms 18

4. A Brief History of Pollution Prevention 19

5. Methodology 20

6. Case Studies and Projections: Industrial Biotechnology for Pollution Prevention 24

- 6.1 Pulp and Paper Production and Bleaching 23
- 6.2 Textile Finishing 31
- 6.3 Plastic and Chemical Production. 37
- 6.4 Fuels Production 42
- 6.5 Pharmaceutical and Vitamin Production 61
- 6.6 Additional Examples of Industrial Biotechnology in Action. 49
- 6.7 Future Research Needs 50

7. Policy Considerations 52

8. Conclusions 55

Snapshots 57

Appendix 61

- Appendix I: History of Industrial Biotechnology 61
- Appendix II: Opportunities for Biobased Plastics. 64
- Appendix III: Some Examples of Industrial Enzymes and Their Uses 68
- Appendix IV: Some Tools in the Genomic, Proteomic, and Bioinformatics Toolbox 70
- Appendix V: Additional Information About the Performance of Select Industrial Biotechnology Processes 71
- Appendix VI: References 72

About the Preparation of this Report . . . . **inside back cover**

TABLE OF FIGURES

Figure 1: Simplified Flow Diagram: Integrated Mill (Chemical Pulping, Bleaching, and Paper Production) 25
Figure 2: Typical Bleaching Plant Showing Chemical Bleaching Process 27
Figure 3: Projection for Reduction of Chlorine in Wastewater w/ Biotech Process 28
Figure 4: Projection for Reduction of Energy Consumption in Pulp Production/Bleaching with a Biotechnology Process 28
Figure 5: Typical Textile Processing Flow Chart. 33
Figure 6: Projection for Reduction of Energy Consumption in Textile Finishing with a Biotechnology Process 34
Figure 7: Projection for Reduction of Water Consumption in Textile Finishing with a Biotechnology Process 34
Figure 8: Recent Case Study Cargill-Dow 38
Figure 9: Projection for Reduction in Petroleum Consumption in Plastics Production with a Biotechnology Process 39
Figure 10: Ethylene Products 41
Figure 11: BiotechnologyExample 48
Figure 12: Market Share of Vitamin B_2 for Production, by Method of Production 48
Figure 13: Biological versus Traditional Processing: Analysis of Resource Usage of Antibiotic Intermediate Processing 48

Table 1: Consumer Products Made with Industrial Biotechnology 16, 17
Table 2: Cases by Sector and Country 20
Table 3: Environmental and Cost Benefits from the Use of Biotechnology: Selected Cases 21
Table 4: Resources and Pollution Comparison for Pulp and Paper Production 29
Table 5: Resources and Pollution Comparison for Textile Finishing 35
Table 6: Resources and Pollution Comparison for Plastics and Chemical Production 40
Table 7: Resources and Pollution Comparison for Fuel Production. 45
Table 8: Resources and Pollution Comparison for Pharmaceutical and Vitamin Production. 47

Report Objectives

1. Provide context for industrial biotechnology.

This report discusses the evolution and recent blossoming of industrial biotechnology, development of pollution prevention policy, and increasing potential for industrial biotechnology to offer new and transformative ways to prevent pollution and sustain development.

2. Quantify potential pollution prevention benefits achieved by applying certain industrial biotechnology processes to entire sectors within the United States.

This report applies performance outcomes reported in the original OECD case study report to industrial sectors within the United States. Data for these sectors was drawn from EPA and other publicly available databases. Extrapolations were then made from the OECD case studies across several discrete industry sectors in order to illustrate the largest potential magnitude of benefits.

3. Educate stakeholders about industrial biotechnology.

Industrial biotechnology is already reducing pollution and manufacturing costs in some industry sectors. It holds great promise to further reduce pollution and the consumption of raw materials if deployed more broadly; this, in turn, can reduce the cost of producing goods and may lead to better products. Because industrial biotechnology can utilize many renewable feedstocks, such as corn and other agricultural crops and crop residues, it may provide new sources of income for farmers. This report aims to deliver information on these powerful new biotechnology tools to the public, policymakers, NGOs, the press, and corporate America. All of these groups have a stake in a cleaner future and need to be informed about the latest technological developments that are available to improve our world.

4. Inspire a wider inquiry into industrial biotechnology.

The Industrial and Environmental Section of BIO, its members, and some national policymakers possess greater familiarity with the current and potential uses for industrial biotechnology than the target audience for this document. From that familiarity comes our optimism about the possible benefits that can be derived from greater industrial biotechnology use. BIO strongly believes that as an understanding of this field spreads, so, too, will the general sense of enthusiasm about this powerful technology. At the same time, we can not expect that reaction on the strength of this document alone. Industrial biotechnology encompasses a multitude of products and processes. Each will need to endure the scrutiny of potential customers, policymakers, NGOs, and the public. Our expectation is that this report will inform as well as raise questions. We invite those whose interest is aroused, but whose questions are not satisfied, to join with BIO in future research dialogues and other efforts to widen the inquiry into industrial biotechnology's current and potential benefits.

Executive Summary

Industrial biotechnology is one of the most promising new approaches to pollution prevention, resource conservation, and cost reduction. It is often referred to as the third wave in biotechnology. If developed to its full potential, industrial biotechnology may have a larger impact on the world than health care and agriculture biotechnology. It offers business a way to reduce costs and create new markets while protecting the environment.

Rudimentary industrial biotechnology actually dates back to at least 6000 B.C. when Neolithic cultures fermented grapes to make wine, and Babylonians used microbial yeasts to make beer. Over time, mankind's knowledge of fermentation increased, enabling the production of cheese, yogurt, vinegar, and other food products. In the 1800s, Louis Pasteur proved that fermentation was the result of microbial activity. Then in 1928, Sir Alexander Fleming extracted penicillin from mold. In the 1940s, large-scale fermentation techniques were developed to make industrial quantities of this wonder drug. Not until after World War II, however, did the biotechnology revolution begin, giving rise to modern industrial biotechnology.

Since that time, industrial biotechnology has produced enzymes for use in our daily lives. For instance, meat tenderizer is an enzyme and some contact lens cleaning fluids contain enzymes to remove sticky protein deposits. The applications for enzymes are increasing every day, especially in the manufacturing sector. In the main, industrial biotechnology involves the microbial production of enzymes, which are specialized proteins. These enzymes have evolved in nature to be super-performing biocatalysts that facilitate and speed-up complex biochemical reactions. These amazing enzyme catalysts are what make industrial biotechnology such a powerful new technology.

Today, the application of biotechnology to industrial processes is not only transforming how we manufacture products but is also providing us with new products that could not even be imagined a few years ago. Because industrial biotechnology is so new, its benefits are still not well known or understood by industry, policymakers, or consumers. This report includes analysis of only five industrial sectors to illustrate the potential to use industrial biotechnology for pollution prevention, energy savings, cost reduction, and other process improvements. It is intended to introduce readers to the possibility of pollution prevention and other benefits from greater use of industrial biotechnology. Our hope is that this information will inspire more interest in understanding, developing, and adopting these new industrial biotechnology processes.

Many biocatalytic tools are becoming available for industrial applications because of the recent and dramatic advances in biotechnology techniques. In many cases, the biocatalysts or whole-cell processes are so new that many chemical engineers and product development specialists in the private sector are not yet aware that they are available for deployment. This is a good example of a “technology gap” where there is a lag between availability and widespread use of a new technology. This gap must be overcome to accelerate progress in developing more economic and sustainable manufacturing processes through the integration of biotechnology. In addition, public officials in the environmental policy apparatus in the United States seem only vaguely aware of the existence of these new biotechnology tools and their ability to "green" the industrial landscape.

In 2001, OECD investigated the use of industrial biotechnology processes in 21 case studies. The results of these case studies were released in a first-of-its-kind report and showed that biotechnology invariably led to a reduction in either operating costs, capital costs, or both and to a more sustainable process–a lowered ecological footprint in the widest sense–by reducing some or all energy usage, water usage, wastewater production, and greenhouse gas production.[1] The report further highlighted examples of reducing toxic chemicals and other environmental benefits. The distribution of the 21 OECD case studies is shown in the following table:

Members of the BIO Industrial and Environmental Section concluded that additional study of this issue was appropriate and necessary. This study takes the next step by asking the question: **What if industrial biotechnology were more widely used?** Our methodology included taking a specific case study performance described in the OECD report and applying it unilaterally to analogous industrial sectors in the United States in order to extrapolate outcomes data. We believe that, for the purposes of illustration, it is valid to consider adoption of a technology across industry sectors in order to develop a sense of the largest magnitude of potential benefits.

Cases by Sector and Country

Industry/ Sector	Pharma	Fine Chemicals	Bulk Chemicals	Food & Feed	Textiles	Pulp & Paper	Minerals	Energy
Austria						1		
Canada						2		2
Germany	2			1	1			
Japan		1	1	1				
Netherlands	1			1			1	
S. Africa							1	
UK		1	2					1
USA			1					

Our analysis indicates significant pollution prevention and suggests that cost savings, as well as reduced consumption of raw materials and energy, could be achieved if industrial biotechnology were more widely used in the future. The report also draws on the literature regarding policy hurdles and other factors influencing the decision of companies to adopt industrial biotechnology processes. Some of the results are the following:

- Biotechnology process changes in the **production and bleaching of pulp for paper** *reduce the amount of chlorine chemicals necessary for bleaching by 10–15%.* If applied across the industry, these process changes could *reduce chlorine in water and air as well as chlorine dioxide by a combined 75 tons per year.* Biotechnology processes *cut bleaching-related energy uses by 40%*–a savings that can create additional pollution reductions. The biotechnology process also *lowers wastewater toxicity.*
- Biotechnology process changes in the **textile finishing sector** *reduce water usage by about 17–18%, cost associated with water usage and air emissions by 50–60%, and energy demand for bleaching by about 9–14%.*
- Biotechnology process changes in **plastics production** replace petrochemical feedstocks with feedstocks made from organic material such as corn or even corn stovers, thereby *reducing demand for petrochemicals by 20–80%.* Because these bioplastics are biodegradable, their use could also *reduce plastics in the waste stream by up to 80%.* Waste burdens are reduced partly because disposable food service

---

[1] OECD, *The Application of Biotechnology to Industrial Sustainability,* Paris, France (2001): 10.

items such as plates, cups, and containers can be composted along with the food waste, eliminating the need for separation. These bioplastics can be used to make products ranging from clothing to car parts, all of which can be composted instead of disposed in landfills or incinerators.

- Biotechnology process changes allow for **bioethanol production** not only from corn but from cellulosic biomass such as crop residues; *bioethanol from cellulose generates 8 to 10 times as much net energy as is required for its production. It is estimated that one gallon of cellulosic ethanol can replace 30 gallons of imported oil equivalents*. The closed-loop nature of *using cellulosic biomass to produce bioethanol can contribute substantially to the mitigation of greenhouse gas emissions* and can help provide a partial solution to global warming.
- Biotechnology process changes in the **nutriceutical and pharmaceutical sector** during the production of riboflavin (vitamin B_2) *reduce associated carbon dioxide emissions by 80% and water emissions by 67%*. Changes in the production of the antibiotic cephalexin *reduce carbon dioxide emissions by 50%, energy demand by 20%, and water usage by 75%*. The market share of the biotechnology method of vitamin B_2 production increased from 5% in 1990 to 75% in 2002.

Biobased technologies are just beginning to be used in forestry, pulp and paper, chemicals and plastics, mining, textile production, and energy sectors. The sectors examined in this report may account for up to 40% of energy use, 50% of industrial pollution, and are also a significant contributor to greenhouse gas emissions. With accelerated diffusion of industrial biotechnology into these sectors, rapid and dramatic environmental improvements are possible. In many cases, *use of industrial biotechnology processes can also reduce the risk of toxic chemical spills and chemical exposure accidents*. This risk reduction is in part due to the dramatic reduction in the use, storage, handling, and transportation of hazardous chemicals.[2]

SOME INDUSTRIAL BIOTECH APPLICATIONS BY INDUSTRIAL SECTORS:

- Biological Fuel Cells
- Fine and Bulk Chemicals
- Chiral Compound Synthesis
- Synthetic Fibers for Clothing
- Pharmaceuticals
- Food Flavoring Compound
- Biobased Plastics
- Biopolymers for Automobile Parts
- Bio-Ethanol Transportation Fuel
- Nutritional Oils
- Oil and Gas Desulphurization
- Leather Degreasing
- Bio-hydrogen
- Biopolymers for Plastic Packaging
- Coal Bed Methane Water Treatment
- Chem/Bio Warfare Agent Decontamination
- Pulp and Paper Bleaching
- Biopulping (paper industry)
- Specialty Textile Treatment
- Enzyme Food Processing Aids
- Metal Ore Heap Leaching
- Electroplating/Metal Cleaning
- Rayon and Other Synthetic Fibers
- Metal Refining
- Vitamin Production
- Sweetener Production (high fructose syrup)
- Oil Well Drill Hole Completion (non-toxic cake breakers)
- Road Surface Treatment for Dust Control
- Textile Dewatering
- Vegetable Oil Degumming

Given the wide scope of industrial biotechnology in terms of business sectors it would be futile for this report to attempt to address every question. In fact, this document should inspire more questions than it answers. For example, what are the life cycle benefits of greater use of xylanase to replace chlorine? Or what protocols should be in place to ensure the proper handling of each industrial biotechnology waste product? We simply do not know. We have some information, but not complete answers, in many cases. What we do know is that this document should encourage enough interest so that corporate, government, and NGO entities will join our future efforts to frame questions and find answers and solutions so that greater economic and environmental benefits can be achieved.

---

[2] Hitzmann, Bernd, "Identification of Substitutional Potentials of Chemical Production Procedures by the Use of Biotechnical/Genetic Methods for Risk Prevention," (English version), The Federal Environmental Agency, Berlin, Germany (August 2001).

1. Introduction

The application of biotechnology to industrial processes is not only transforming how we manufacture products but is also providing us with new products that could not even be imagined a few years ago. Because industrial biotechnology is so new, its benefits are still not well known or understood by industry, policymakers, or consumers. This report includes analysis of only five industrial sectors to illustrate the potential to use industrial biotechnology for pollution prevention, energy savings, cost reduction, and other process improvements. It is intended to introduce readers to the possibility of pollution prevention and other benefits from greater use of industrial biotechnology. Our hope is that this information will inspire more interest in understanding, developing, and adopting these new industrial biotechnology processes.

Pollution control usually means adding equipment at the end of a process to capture or transform pollutants after they have been created. Devices ranging from a car's catalytic converter to a wastewater treatment plant to scrubbers on a power plant are technologies that are designed to manage pollution once it has already been created by everyday activities. American industry spends billions of dollars yearly on technology systems to manage waste and capture polluting effluent and emissions. **The more sustainable and less expensive alternative is preventing pollution in the first place.**

Biotechnology, bio-tech-nol-o-gy **(noun) 1: The application of scientific and engineering principles to the processing of materials by biological agents to provide goods and services.**

—OECD.

From the beginning, industrial biotechnology has integrated product improvements with pollution prevention. Nothing illustrates this better than the way industrial biotechnology solved the phosphate water pollution problems of the 1970's caused by the use of phosphates in laundry detergents. Biotechnology companies developed enzymes that remove stains from clothing better than phosphates, thus enabling replacement of a polluting material with a non-polluting biobased additive while improving the performance of the endproduct. This innovation dramatically reduced phosphate-related algal blooms in surface waters around the globe, and simultaneously enabled consumers to get their clothes cleaner with lower washwater temperatures and concomitant energy savings.

Industrial biotechnology is one of the most promising new approaches to pollution prevention and reduced resource consumption. Often referred to as the third wave in biotechnology, industrial applications of biotechnology are already successfully transforming traditional manufacturing processes and show promise as a tool for achieving sustainable industrial development. Generally, sustainable development means continuous innovation, improvement, and use of clean technologies or green chemistry to make fundamental changes in pollution levels and resource consumption. An industrially sustainable process should, in principle, be characterized by

- significant reduction or elimination of waste or polluting emissions and
- lower consumption of energy and nonrenewable raw materials.

Industrial biotechnology achieves these goals in part by using specialized biocatalysts and/or renewable carbohydrate feedstocks (i.e., sugars and starches from any kind of agricultural crop or crop residue) to reduce process temperatures and duration, consumption of raw materials and energy, and generation of wastes. The overall costs of production often fall as well.

A 2001 OECD report, *The Application of Biotechnology to Industrial Sustainability,* examined 21 cases where traditional industrial processes were replaced with or modified by a biotechnology process. The report found that industrial biotechnology processes invariably led to less expensive and more environmentally friendly processes. Interestingly, OECD found that cost reduction and improvements in product quality were usually the primary forces driving the decision to incorporate a biotechnology process. In one case, a company adopted an industrial biotechnology process because it had no other economic option for environmental compliance.

These findings lead to the next logical question: **What if industrial biotechnology were more widely used?** The OECD case study report was the beginning of an effort to answer that sweeping question. With this analysis, the BIO Industrial and Environmental Section takes the next step.

Our report expands on the original OECD case studies in order to better understand the magnitude of potential economic and environmental benefits. Using the OECD case studies as a starting point, our report speculates on the potential for pollution prevention and energy savings if certain industrial biotechnologies were to advance from an early stage of individual process modifications to become standard in specific industrial sectors.

Many of these biotechnology applications would reduce industrial pollution by substituting a biotechnology process for a traditional industrial process. In a chemical synthesis, an enzyme might replace a toxic chemical that is difficult and expensive to manage. The amount of energy consumed could be reduced by condensing a complex set of chemical reactions at high temperatures to a few reactions at much lower temperatures. Industrial biotechnology might lead to the development of an innovative endproduct that replaces an existing product that is less environmentally friendly or simply less desirable. Industrial biotechnology is beginning to be deployed in several important industrial sectors including forestry, pulp and paper, chemicals and plastics, mining, textile production, and energy.

> “One of the most attractive aspects of bioproducts is the potential to reduce the generation of hazardous and toxic wastes associated with the manufacture of fossil-based products. Most biological processes require natural catalysts (e.g., enzymes) and solvents (water) and produce few or no toxic or hazardous byproducts. In most cases, solid wastes and effluents from these processes are biodegradable or can be recycled or disposed of without excessive treatment processes.”
>
> – Energetics, Incorporated, Report for the Department of Energy, “Industrial Bioproducts: Today and Tomorrow,” Columbia, MD (2003): 15.

This report explores the impact of those changes and draws on the literature regarding benefits and hurdles to deployment in order to develop a set of findings, recommendations, and suggested areas for additional research. The report is intended for corporate leaders and policymakers and it aims to inspire them to take further action to adopt industrial biotechnology. The general public and the NGO and agriculture communities should also find the results in this report to be thought provoking and encouraging.

The main point of analysis for this report is an initial assessment of the potential of industrial biotechnology for pollution prevention. To develop a context for this analysis, in Chapters 2 and 3 we present a description of industrial biotechnology and a discussion of the safe handling of genetically enhanced microorganisms, and in Chapter 4 we present a brief history of pollution prevention.

In Chapter 5, we describe the method used to develop the analysis. We present the analysis in Chapter 6, including a review of the OECD case studies, information about the application of industrial biotechnology in each of five sectors, and a section outlining further research needs. Then in Chapter 7, we review the policy considerations derived from a literature review and discuss potential policy drivers in the United States for increased reliance on industrial biotechnology. The report concludes that as a result of recent technological advances, industrial biotechnology could revolutionize environmental protection strategies, as well as the whole industrial landscape.

This report is the beginning of an effort to answer the sweeping question: **What if industrial biotechnology were more widely used?**

What does this mean for our future? The sectors examined in this report may account for up to 40% of energy use, 50% of industrial pollution, and are also a significant contributor to greenhouse gas emissions. With accelerated diffusion of industrial biotechnology into these sectors, rapid and dramatic environmental improvements are possible. Bioprocessing reduces–and in some cases eliminates–industrial waste, businesses will spend less on cleanup, disposal, and control of pollution. Bioprocessing primarily uses renewable agricultural products, such as corn, corn stover, wheat straw, rice straw, and other materials, as raw feedstocks and it could provide new markets for these agriculture crop residues.[3] Industrial biotechnology is on the leading edge of the development of a renewable carbohydrate economy that could replace a petroleum-based economy.

---

[3] Although industrial biotechnology processes can use any agricultural feedstock including genetically modified crops, the main focus of industrial biotechnology is to develop processes that might work on *any* agricultural feedstock.

2. What Is Industrial Biotechnology?

Industrial biotechnology builds on the technological advances pioneered in health care. It uses the same **genomic, proteomic, and bioinformatic techniques** used in medical biotechnology.

These techniques are most often applied in the world of microorganisms. By working in concert with nature, industrial researchers discover new ways to enable cleaner production of industrial raw materials, intermediates, and consumer goods.

Rudimentary industrial biotechnology dates back to at least 6000 B.C. when Neolithic cultures fermented grapes to make wine, and by 4000 B.C. Egyptians were making leavened bread using yeast. Babylonians used microbial yeasts to make beer, and yogurt and vinegar production was documented in China in early times. The production of wine through fermentation has long been well established in many parts of the world. These examples are, in essence, rudimentary forms of industrial biotechnology where microorganisms were used to catalyze or perform biochemical reactions for humans.

Over time, our ability to work with these microorganisms has grown. The early Chinese used certain molds as topical treatments for skin infections. In the 1800s, Louis Pasteur proved that fermentation was a result of microbial activity. In 1897, the German scientist Eduard Buchner discovered that specialized proteins, called enzymes, were responsible for converting sugar to alcohol in yeast. Buchner's discoveries about the function of enzymes were a key element in transforming the crude applications of fermentation for making cheese, wine, and bread into modern industrial biotechnology. In 1928, Sir Alexander Fleming discovered that penicillin could be extracted from mold, and in the 1940s, large-scale fermentation techniques were developed to make industrial quantities of this wonder drug.

Despite the existence of these early applications, scientific understanding of microbial fermentation at the molecular level is fairly recent. A more detailed history of the business of industrial biotechnology is found in Appendix I. This progress in our scientific understanding of microbial systems launched the field of industrial biotechnology.

The post World War II biological revolution that led to a deeper understanding of the chemical basis for cellular function also produced the recent explosive development of healthcare, agriculture, and industrial biotechnology. Modern industrial biotechnology involves working with nature to maximize and optimize existing biochemical pathways that can be used in manufacturing. The biotechnology revolution rides on a series of related developments in three fields of study of detailed information derived from the cell: genomics,[4]

---

[4] "Genomics is the scientific study of a genome and the roles that genes play, alone and together, in directing growth and development, and in controlling and determining biological structure and function." "Well Defined: Brush up on your 'Omics'," *Chemical and Engineering News,* (Dec 8, 2003): 20.

proteomics,[5] and bioinformatics.[6] As a result, scientists can apply these new techniques to a large number of microorganisms ranging from bacteria, yeasts, and fungi to marine diatoms and protozoa.

All living systems, including microorganisms, produce enzymes that function as biocatalysts. Buchner's discovery of yeast enzymes opened the door to the discovery of a panoply of these amazing proteins. Enzyme biocatalysts perform myriad chemical functions in living cells. In humans and other living things, enzymes help digest food, turn the information in DNA into proteins, put molecules together to form new compounds, and perform other complex biochemical functions. Since World War II, industrial biotechnology has produced enzymes for use in our daily lives. Meat tenderizer is an enzyme and some contact lens cleaning fluids contain enzymes to remove sticky protein deposits. The applications for enzymes are increasing every day, especially in the manufacturing sector.

Many of these enzymatic functions are similar to the steps taken in manufacturing to process raw materials, such as wood pulp and plant fiber, and turn them into finished products such as paper and textiles. However, nature's enzyme-based processes operate at lower temperatures and produce less toxic waste and fewer emissions than conventional manufacturing processes. They may also use less purified raw materials because enzymes have precise chemical selectivity. Today's enzymes also work on materials derived from common agricultural feedstocks such as corn, corn stover, wheat straw, rice straw, and other agriculture residue to turn them into useful biobased products such as bioplastics and bioethanol.

George Washington Carver is considered the father of biobased products. His groundbreaking work at the beginning of the 20th century was meant to achieve the diversification of the agricultural economy of the southeastern United States by freeing it from the constraints of a cotton monoculture. Like the petroleum supplies of today, cotton in the late 19th and early 20th century was vulnerable to supply interruptions–in the form of boll weevil infestations–that no one could control. Carver sought to develop solutions to monoculture cotton by using agricultural feedstocks as raw materials to make industrial products. His early research resulted in the development of 325 biobased products based on the peanut and 108 based on the sweet potato; these products ranged from the obvious, like peanut butter, to an array of soaps and creams, dyes and paints, nitroglycerin, axle grease, detergents, and plastics. Today's modern biotechnology allows us to build on and realize Carver's dream of creating a truly biobased economy.

Industrial biotechnology companies use many specialized techniques to find and improve nature's enzymes. Information from genomic studies on microorganisms is helping researchers capitalize on the wealth of genetic diversity in microbial populations. Researchers first search for enzyme-producing microorganisms in the natural environment and then use DNA probes to search at the molecular level for genes that produce enzymes with specific biocatalytic capabilities. Once isolated, such enzymes can be identified and characterized for their ability to function in specific industrial processes. If necessary, they can be improved with biotechnology techniques.

---

[5] "Proteomics studies all of an organism's proteins or proteome. This can contain thousands of proteins, which, even within a given organism or cell, can vary depending on cell or tissue type, disease state, and other factors." *Ibid.*

[6] "Bioinformatics derives knowledge from computer analysis of biological data. These can consist of the information stored in the genetic code, but also experimental results from various sources, patient statistics, and scientific literature." Nilges, Michael, and Jens P. Linge, "Bioinformatics," Unité de Bio-Informatique Structurale, Institut Pasteur, *available at http://www.pasteur.fr/recherche/unites/Binfs/definition/bioinformatics_definition.html* (last visited Mar 21, 2004).

Once an enzyme is isolated and improved, it is produced in commercial quantities using contained stainless steel fermentation tanks, systems similar to those that produce therapeutic human proteins or bulk yeast for the brewing industry. Whole-cell systems, including genetically enhanced microorganisms (e.g., bacteria or yeast improved through gene shuffling), are sometimes used directly to manufacture enzymes and other products. In whole-cell systems, a microorganism is engineered to synthesize a special product through fermentation or in a culture medium.

Scientists are also using proteomics and bioinformatics to increase enzyme output rates in microorganisms to improve productivity. Genetic enhancements can be used to enable common microorganisms to produce enzymes that would otherwise come from other microorganisms that are too expensive or too finicky to cultivate in industrial quantities. Biotechnology enables scientists to maximize the effectiveness and efficiency of enzymes by customizing their specificity, improving catalytic properties, and broadening the conditions under which they can function. As a result, such bio-engineered enzymes are more compatible with existing industrial processes.

Biocatalytic tools are becoming available for industrial applications because of the recent and dramatic advances in biotechnology techniques. In many cases, the biocatalysts or whole-cell processes are so new that many companies are not aware that they are available. This is a good example of a technology gap where a lag occurs between availability and widespread use of a new technology. This gap must be overcome to accelerate progress in developing more economic and sustainable manufacturing processes through the integration of biotechnology. In addition, public officials in the environmental policy apparatus in the United States seem only vaguely aware of the existence of these new biotechnology tools and their ability to "green" the industrial landscape.

There is some overlap among healthcare biotechnology, agriculture biotechnology, and industrial biotechnology. However, industrial biotechnology is primarily separate and distinct from agriculture biotechnology. Agriculture biotechnology involves developing improvements to agriculture crops. Industrial biotechnology may use crops or crop residues but is primarily concerned with biochemical conversion of these feedstocks into intermediates and consumer products. These intermediates and consumer products are mostly chemicals, plastics, and fuel and are not involved in the food chain. Other industrial biotechnology processes that involve chemical synthesis and manufacturing are concerned with replacing toxic chemicals with biological catalysts or processes. Some products made with the help of industrial biotechnology are consumed by humans, such as flavorings, sweeteners, vitamins, and antibiotics. These products are the same as finished products made with chemicals but are made in a more environmentally friendly manner when industrial biotechnology is used in their manufacture.

Examples of products made with industrial biotechnology are given in Table 1. The following are some examples of industrial biotechnology that are not examined here but that may be encountered in daily life; additional examples are included in Appendix III:

- Proteases, which are enzymes used to remove protein impurities (such as food and grass stains) from our clothes, are essential components of modern laundry detergents. Enzymes were added to detergents to replace polluting phosphates and to boost cleaning power.
- Glucose oxidase and other enzymes are replacing potassium bromate as an antioxidant for flour in baked bread because of concerns about the carcinogenicity of bromate.

Table 1: Consumer Products Made with Industrial Biotechnology

CONSUMER PRODUCT	OLD MANUFACTURING PROCESS	NEW INDUSTRIAL BIOTECH PROCESS	BIOTECH ENABLING TECHNOLOGY	CONSUMER BENEFIT
Detergent	Phosphates added as a brightening and cleaning agent	Addition of biotechnology enzymes as brightening and cleaning agents ■ Proteases remove protein stains ■ Lipases remove grease stains ■ Amylases remove starch stains	Genetically enhanced microbes or fungi engineered to make enzymes	■ Elimination of water pollution from phosphates ■ Brighter, cleaner clothes with lower temperature wash water ■ Energy savings
Bread	Potassium bromate, a suspected cancer-causing agent at certain levels, added as a preservative and a dough strengthening agent	Addition of biotechnology enzymes to ■ enhance rising ■ strengthen dough ■ prolong freshness	Microorganisms genetically enhanced to produce baking enzymes (directed evolution and recombinant DNA)	■ High-quality bread ■ Longer shelf life ■ No potassium bromate
Polyester Bedding	Polyester* produced chemically from petroleum feedstock *any synthetic fiber	Biotech polyester (PLA) produced from corn starch feedstock	Existing bacillus microbe used to ferment corn sugar to lactic acid; lactic acid converted to a biodegradable polymer by heating; polymer made into plastic products and polyester	■ PLA polyester does not harbor body odor like other fibers ■ Biodegradable ■ Not made from petroleum ■ Does not give off toxic smoke if burned
Vitamin B_2	Toxic chemicals, such as aniline, used in a nine step chemical synthesis process	One-step fermentation process uses vegetable oil and glucose as a feedstock	Genetically enhanced microbe developed to produce vitamin B_2 (directed evolution)	■ Biologically produced without chemicals ■ Greatly reduces hazardous waste generation and disposal
Stonewashed Blue Jeans	Open-pit mining of pumice; fabric washed with crushed pumice stone and/or acid to scuff it	Fabric washed with biotechnology enzyme (cellulase) to fade and soften jeans or khakis	Textile enzymes produced by genetically enhanced microbe (extremophiles and recombinant DNA)	■ Less mining ■ Softer fabric ■ Reduced energy consumption ■ Lower cost
Paper Bleaching	Wood chips boiled in a harsh chemical solution then bleached with chlorine to yield pulp for paper making	Enzymes selectively degrade lignin and break down wood cell walls during pulping	Wood-bleaching enzymes produced by genetically enhanced microbes (recombinant DNA)	■ Reduces use of chlorine bleach and reduces toxic dioxin in the environment ■ Cost savings due to lower energy and chemical costs

CONSUMER PRODUCT	OLD MANUFACTURING PROCESS	NEW INDUSTRIAL BIOTECH PROCESS	BIOTECH ENABLING TECHNOLOGY	CONSUMER BENEFIT
Ethanol Fuel	Food and feed grains fermented into ethanol (a technology that is thousands of years old)	Cellulase enzyme technology allows conversion of crop residues (stems, leaves, straw, and hulls) to sugars that are then converted to ethanol	Genetically enhanced organism developed to produce enzymes that convert agricultural wastes into fermentable sugars (directed evolution, gene shuffling)	Renewable feedstock ■ Reduces green house gas emissions ■ Increases domestic energy production ■ Is more energy efficient to produce than old process
Antibiotics	Chlorinated solvents and hazardous chemicals used to produce antibiotics through chemical synthesis	One-step biological process uses direct fermentation to produce antibiotic intermediate	Genetically enhanced organism developed to produce the key intermediate of certain antibiotics (recombinant DNA)	■ 65% reduction in energy consumption ■ Overall cost savings
Contact Lens Solution	Surfactants and/or saline solutions (do not remove protein deposits) used to clean lenses	Protease enzymes remove protein deposits from the contact lens	Genetically enhanced microbes engineered to make protease enzymes (directed evolution)	■ More effective contact lens cleaning ■ Less eye irritation and fever infections

- High-fructose corn syrup, the sweetener in colas and other soft drinks, is made with the help of enzymes. Before the process of enzyme hydrolysis for starches was created, acid was used to chemically react with corn to turn it into an intense sweetener. Now, enzymes have replaced the acid, and corn can be processed into many valuable ingredients for food and industrial products with less harm to the environment.
- Enzymes are used for hide degreasing in the leather industry and, instead of petroleum-based solvents, for metal cleaning in the electroplating industry.
- Enzymes are used to produce ascorbic acid from glucose and in degumming processes during the production of cooking oils.

Industrial biotechnology is creating the potential for a new industrial revolution because it offers innovative tools derived from nature that can be put to work to reduce environmental impacts and costs while yielding superior goods and services. The development of new tools and strategies is critically important if we are to move toward a more sustainable system of industrial production in the future.

3. Safely Harnessing Genetically Enhanced Microorganisms

New methods and models for managing microorganisms are developing along with the industry. It will be necessary for corporate and governmental policies and procedures to continue to evolve in order to ensure the continued safe handling of biotechnology materials in industrial settings. To our knowledge, the best review of this topic compiled to date is *Biosafety in Industrial Biotechnology* (see references). The preface of that book notes that "unlike other modern industries, such as chemical and nuclear, where regulation has followed from incidents or accidents, modern biotechnology has been subject to close scrutiny and regulation from its inception."

Today, industrial biotechnology mainly uses microorganisms–usually yeasts, bacteria, or fungi–to produce industrial enzymes or as part of whole-cell production systems. In many cases, these microorganisms are genetically engineered or enhanced to perform the specialized tasks required in manufacturing. Because these microorganisms are used in contained, closed-loop fermentation systems under well-controlled conditions in industrial facilities, chances are minimal for unintentional release of live genetically enhanced microorganisms into the environment. It is important to note that most of this work is being done by enzymes. Industrial biotechnology researchers and companies have had a very good record of safety and stewardship in this regard for the past 35 years.

OECD correctly notes that the microorganisms used for industrial bioprocessing or for production of industrial enzymes are carefully selected to avoid the use of pathogens. Industrial biotechnology production facilities are also subject to environmental regulations such as the New Substances Notification Regulations of Environment Canada, the Toxic Substance Control Act in the United States, and similar regulations in other countries. Occupational health regulations also impose rules on the handling of microorganisms in the workplace, and, in most cases, microorganisms are inactivated by sterilization after they have performed their assigned production tasks. The resulting material is usually heat treated or dried, and then composted. These practices vary by country and regulation, but every effort is made to ensure safe and proper handling. This two-step process (sterilization and composting) breaks down the DNA and protein components. The resulting material has high organic value; for example, in Denmark the composted biomass is sought by local farmers who apply it as a top-grade fertilizer.[7]

BIO's statement of ethical principles states that it will "strive to optimize the cost efficiencies and environmental advantages associated with using biotechnology while protecting human health and the environment." In addition, members of the BIO Industrial and Environmental Section believe in and practice proper stewardship during production and handling of these microorganisms for industrial use. The section's bylaws specifically state that the activities of the section shall include efforts to

- promote safe experimental and industrial practices within the biotechnology industry that protect and serve public interests and maintain the integrity of the environment and other living organisms,
- gather and promote the exchange of information on industrial and environmental biotechnology and the responsible growth of the industry, and
- encourage environmental stewardship through the promotion of industrial sustainability.

BIO and its members are proud of their record of safely handling industrial biotechnology materials. We invite others to both examine that history and join us in discussing these issues as our industry continues to grow and evolve.

---

[7] Novoymes, "Using surplus materials as fertilizer," (Nov 2000) available at *http://www.novozymes.com* (last visited Mar 16, 2004).

4. A Brief History of Pollution Prevention

As the concept of "triple bottom line" accounting takes hold, companies are increasingly evaluating their own performance in terms of the economic, societal, and environmental impact of their activities. As a result, there is a growing reliance on pollution prevention to increase a company's sustainability profile and help it to decrease negative environmental, social, and economic impacts of a given manufacturing process.

A byproduct of industrial processes, pollution includes discharges to air, land, and water. Pollution prevention works at the front end of an industrial process to stop pollution from forming; pollution control targets the tail end of the process and manages pollution once it has been formed. Sometimes referred to as source reduction, pollution prevention is achieved by using raw materials more efficiently, substituting less harmful substances for hazardous materials, eliminating toxic substances from the production process, and other measures.

Although the concept of pollution prevention has been around for decades, it was established as a national objective in the United States by the Pollution Prevention Act (PPA), which was signed into law in 1990. PPA requires EPA to promote source reduction as opposed to source control and treatment. This strategy was meant to lead industry to implement process changes that prevent pollution from occurring rather than cleaning up pollution at the end of an industrial process.

Two of the primary drivers of pollution prevention are cost reduction and risk management. By implementing pollution prevention practices, companies often reduce their operational, waste disposal, and compliance costs.[8] Companies can also minimize their liability by reducing the wastes that are regulated. An added benefit is reducing the potential for workplace exposure to hazardous materials. As a result, companies can improve workers safety and decrease the potential liability associated with handling toxic materials.

PPA focused industry, government, and public attention on reducing the amount of pollution through cost-effective changes in production, operation, and raw materials use. However, "opportunities for source reduction are often not realized because of existing regulations, and…focus on treatment and disposal."[9]

After PPA was implemented, some data-reporting requirements, such as the Toxics Release Inventory used for this report, were modified and updated. EPA also proposed creating the Environmental Leadership Program, which would provide incentives for companies to develop and implement pollution prevention practices.

Currently, such practices do not provide direct release from regulatory mandates or sanctions. Companies that pursue pollution prevention programs do so for various other reasons. Most are seeking the benefits of increased productivity, efficiency, and cost savings. Other goals include enhancing public image and, in some cases, lowering the burden of overall regulatory compliance or potential liability.

Industrial biotechnology processes provide a potent pollution prevention tool. We believe that regulators, other policymakers, industry, and other stakeholders should explore opportunities to create policy mechanisms to encourage the adoption of these environmentally beneficial tools.

---

[8] National Pollution Prevention Roundtable, *What are the Economic Incentives for Pollution Prevention?,* available at *http://www.p2.org/about/nppr_p2.cfm* (last visited Mar 2, 2004).

[9] EPA, "Pollution Prevention Act: 42 U.S.C. 13101 and 13102, s/s et seq. (1990)," available at *http://www.epa.gov/region5/defs/html/ppa.htm* (last visited Mar 16, 2004).

5. Methodology

In 2001, OECD released a report called *The Application of Biotechnology to Industrial Sustainability*.[10] This report was developed by the OECD Task Force on Biotechnology for Sustainable Industrial Development to assess how widespread the use of industrial biotechnology was in 2000–2001 and to assess the real-world experiences of 21 companies worldwide that furnished case study data. The purpose of the report was to use these case studies to help answer questions regarding the costs and benefits of industrial biotechnology and to describe the factors that affected decisions by companies to use this technology. The OECD report provided a useful basis for this document because it examined numerous industrial sectors in nations with a range of economic resources and regulatory circumstances. Despite the varied settings where industrial biotechnology was used, the OECD found generally consistent results. The report found that industrial biotechnology processes invariably led to less expensive and more environmentally friendly processes. The distribution and the environmental and cost benefits of the 21 OECD case studies are shown in Tables 2 and 3.

This report's analysis begins with the OECD report and goes on to address the question: **What if industrial biotechnology were more widely used?** The analysis in this report takes the performance results of several OECD case studies in the pharmaceutical, chemical, paper, textile, and energy sectors and assumes that they are applied across the board in similar industry sectors within the United States. In addition, information on bioplastics is drawn from the OECD report and from other sources.

An important simplifying assumption of our analysis is that performance achieved through the application of a process in a case study can be extrapolated across the entire sector in the United States. For example, where a case study showed environmental benefits at a pulp and paper plant, our results assume that the same performance would be achieved across the U.S. pulp and paper industry. The purpose of this report is to develop a sense of the best-case scenario of the maximum potential environmental benefit that could be achieved.

Table 2. Cases by Sector and Country[11]

Industry/ Sector	Pharma Chemicals	Fine Chemicals	Bulk & Feed	Food	Textiles & Paper	Pulp	Minerals	Energy
Austria						1		
Canada						2		2
Germany	2			1	1			
Japan		1	1	1				
Netherlands	1			1			1	
S. Africa							1	
UK		1	2					1
USA			1					

The decision to employ the simplified analysis is the result of data and resource limitations. Much of the data necessary to do a finer analysis are not available–they are either gathered in an aggregated form or held as competitively sensitive information. It is also used in service of the larger objectives for this document: namely, to provide a sense of industrial biotechnology's maximum potential, and to stimulate interest in and support for more robust analysis of the topics touched on here.

---

[10] OECD, "The Application of Biotechnology to Industrial Sustainability," (2001).

[11] *Ibid,* 12. Also part of a presentation at BIO 2002 by Dr. Mike Griffiths of OECD.

Table 3. Environmental and Cost Benefits from the Use of Biotechnology: Selected Cases[12]

Case/ Sector	Energy	Raw Materials	Waste to Air	Waste to Water	Operating Cost
1/Pharma	same	-75% (non-renewable)	-50%	-66%	-50%
2/Pharma			-90%	-33%	-90% (env. related)
3/Pharma	elec +, steam -		-80%	-80%	considerable reduction
4/Food & Feed	same				-43%
6/Chem	-80%		down	down	down
7/Chem		down	down	down	-54% (raw material)
8/Chem	down		down		down
10/Food & Feed	-70%			-80%	-40%
11/Food & Feed		-50% (ground-water)			-30% (ground-water)
12/Textile	-15%	down (water)		down	-9%
13/Pulp & Paper	-30%–40%	down		down	
16/Pulp & Paper		-35% (CI_2), -65% (CIO_2)		down	
17/Minerals		down (recycle)		down	
18/Minerals	down		down		down
21/Energy				down	increased productivity

The widespread uptake of this technology will not occur at the same speed in all sectors. We believe, however, that making projections across industry sectors is valid since there are many existing examples of entire industrial sectors using a technology. In some cases, this sector wide uptake is based on economic considerations, in some it is based on technology availability and in others it is based on legal regulatory requirements. For instance, virtually all paper pulping operations using the Kraft pulping process and virtually all coal-fired power plants use sulfur dioxide scrubbers. We further acknowledge that in some cases, industrial biotechnology may be used in only part of a given sector. Nevertheless, projecting for a whole sector is a valid means of highlighting what is possible in the future.

For example, more than 90% of riboflavin (vitamin B_2) is currently produced with a biotechnology fermentation process that replaced a conventional chemical process that employed several highly toxic chemicals. In large part this transformation of standard production techniques was possible because A) the biotechnology-based process was less expensive and B) the pharmaceutical and vitamin industries are accustomed to, and structured for, rapid turnover of capital stock and processing techniques. Such rapid penetration of biotechnology in sectors less situated for rapid transformation is less likely.

At the same time, because biotechnology has so many potential industrial applications, its uptake may occur differently–but with equally dramatic results–in other sectors. For example, nearly every aspect of papermaking from pulping wood to de-inking recycled paper could benefit from existing enzyme-based processes. So, instead of a single biotech process permeating the industry, one could envision

---

[12] *Ibid*, 44.

the complete conversion of a single paper plant from chemical to biotechnology-based production.

The authors recognize that industrial plant age, technology availability, and cost are but three factors that can result in performance variability. Studies of technology uptake suggest that diffusion of technology into the broad economy can take decades or longer as individual companies and governments experiment with, deploy, and then adopt new technology Rapid changes, however, can occur as a result of traditional fossil fuel feedstock cost increases, changes in environmental regulations, or other factors. A presentation by Barbara Miller of Dow Chemical Company describes the diffusion of technology and is included in Appendix II. In addition, this report does not attempt to quantify the costs associated with adoption of biotechnology processes. As is also discussed by Miller, disruption and capital costs would be associated with uptake of these processes. This is an area for further research.

Pollution prevention performance for specific processes is derived from the OECD case studies and applied to U.S. industry sector data obtained from EPA and other public sources. In some cases, more recent data is now available than was used in assembling this report. Additional assumptions are included in the footnotes

We use examples drawn only from OECD case studies measuring pollution reduction in a manner matching reasonably well with the data available from EPA and other public sources. Our analysis is also limited because industrial biotechnology does not have a discrete North American Industrial Classification System (NAICS) code that would allow for the collection of broad categories of data regarding its usage. It became apparent during our investigation that the formulation and adoption of such a code for the biotechnology sector in general and for discrete biotechnology sectors in particular would contribute to more accurate assessments of costs and benefits.

More analysis is needed by federal agencies to draw out additional empirical information about possible environmental benefits in this rapidly expanding field. This report considers only a few of the many industrial biotechnology process available today. It does not examine either upstream or downstream benefits. Because industrial biotechnology presents such a broad array of potential intersections with existing industrial activities one could easily speculate that the potential benefits of significant industrial biotechnology diffusion would be greater and more diverse than described in the following analysis.

Finally, our work leaves to future efforts detailed examinations of barriers, life-cycle, and cost benefit considerations, and existing protocols for storage, transportation, and use of industrial biotechnology materials. Each of these considerations are outside the scope of this report. Furthermore, that work would best be done by cooperative efforts between private, government, and NGO entities. This report may stimulate new interest in such cooperative research.

6. Case Studies and Projections: Industrial Biotechnology for Pollution Prevention

This chapter presents the analysis of potential benefits. Each of Sections 6.1 through 6.5 includes a description of biotechnology advances related to the sector, the traditional process commonly used, and the industrial biotechnology process used in the analysis; a table summarizing the data; and figures highlighting notable benefits.

6.1 Pulp and Paper Production and Bleaching

Converting wood into paper is an energy, water, and chemical intensive process. Cellulose fibers from wood and recycled papers are converted into pulp primarily by using a chemical process, although mechanical and semichemical processes are also used (Figure 1). Depending on the end-use paper, pulp is de-inked, bleached, and dewatered. Industrial biotechnology companies have discovered new ways to harness several enzymes to improve these processes. Enzymes used in bleaching allow the process temperature to be lowered and reduce the need for rinsing. These changes significantly reduce the amount of chlorine and energy used, thereby reducing the production costs, emissions of toxic chlorine residues (such as dioxin), and emissions of carbon dioxide from energy generation. Another biotechnology process could increase pulp production productivity by 30% from the same amount of wood,[13] further reducing energy demand and emissions. Approximately 155 million tons of wood pulp are produced worldwide, and approximately 260 million tons are projected to be produced in 2010.[14]

Biotechnology does more than reduce pollution associated with paper production. One biotechnology enzyme can speed paper making by 5%.[15] Other enzymes can be used to improve the de-inking process for recycled paper fibers. Because ink is fused onto paper fibers during printing and copying, de-inking recycled fibers is a difficult and resource-intensive process. In this application, biotechnology has proven more effective than the traditional process. Improved de-inking could allow greater quantities of recycled paper to become an economically viable feedstock for new paper production. Recycled fibers are easier to process than virgin fibers; therefore, increasing the use of this feedstock has the joint benefits of reducing the need to harvest trees and reducing paper-related wastes, emissions, and energy consumption.

Traditional Process

Pulp for paper making is typically produced from wood chips through either a chemical or mechanical process. The chemical process (Figure 2) requires boiling the wood chips in a high-temperature (160–170°C), high-pressure sulfide or sulfate solution. The pulp is then bleached using elemental chlorine or chlorine dioxide to remove the lignin. The EPA *Sector Notebook for the Pulp and Paper Industry* notes that “Overall,

---

[13] “Market Pulp: Pulp industry must run more efficiently,” *Pulp and Paper* available at *www.paperloop.com/db_area/archive/ p_p_mag/1997/9708/news.htm* (last visited Mar 22, 2004).

[14] Bajpai, Pratima, “Biotechnology for Environmental Protection in the Pulp and Paper Industry,” (1998): Executive Summary, available at *http://wwwenvironmental-center.com/publications/springer/3540656774.htm* (last visited Oct 28, 2003.)

[15] “Enzymatic Treatment of Paper Fines,” available at *http://www.swin.edu/au/ebc/bioremediation.html* (last visited Sept 22, 2003).

most of the pollutant releases associated with pulp and paper mills occur at the pulping and bleaching stages where the majority of chemical inputs occur."[16] Methanol (from pulping) and chlorinated compounds and sulfuric acid (from bleaching) are the main emissions.

After a link was made between the use of elemental chlorine and the formation of chlorinated dioxins,[17] the pulp industry was required to shift to a bleaching sequence that is free of elemental chlorine.[18] Chlorine dioxide is most commonly used as a replacement for elemental chlorine. Substantial concerns about pollution remain despite this change. Most end-of-pipe controls shift chlorinated wastes into the sludge waste because they cannot destroy many chlorinated compounds. The wastewater is sometimes discharged with a pH high enough to meet the Resource Conservation and Recovery Act definition of a corrosive hazardous waste.[19]

Industrial Biotechnology Process

The OECD report looked at two alternative processes using biotechnology products to improve bleaching while reducing the use of chlorine products (Table 4).

1) An enzyme called xylanase is applied before bleaching, replacing the chlorine-containing compounds in the first stage of the five-stage elemental-chlorine-free bleaching sequence. Biotechnology process changes in the production and bleaching of pulp for paper *reduce the amount of chlorine chemicals necessary for bleaching by 10–15%* (Figure 3). The subsequent stages include a number of washing steps and an alkaline extraction stage. One study estimated that the potential energy savings of industry-wide application of this process in the European paper industry would result in a carbon dioxide emissions savings of between 155,000 and 270,000 tons annually.[20]

2) White rot fungus is used in a preprocess step to break down the lignin in the wood cell wall structure. Wood chips are injected with the fungus and a growth medium, allowed to incubate for 2 weeks, and then treated using the traditional chemical or mechanical process. Because the wood cell walls get broken down during this preprocess treatment, it is less resource intensive to bleach the pulp. Biotechnology processes *cut bleaching-related energy uses by 40%*–a savings that has the potential to create additional pollution reductions (Figure 4).

> One study estimated that the potential energy savings of industry-wide application of this process in the European paper industry would result in a CO_2 emissions savings of between 155,000 and 270,000 tons annually.

---

[16] EPA, Office of Compliance, *Sector Notebook Project: Profile of the Pulp and Paper Industry,* Washington, DC (2002): 19.

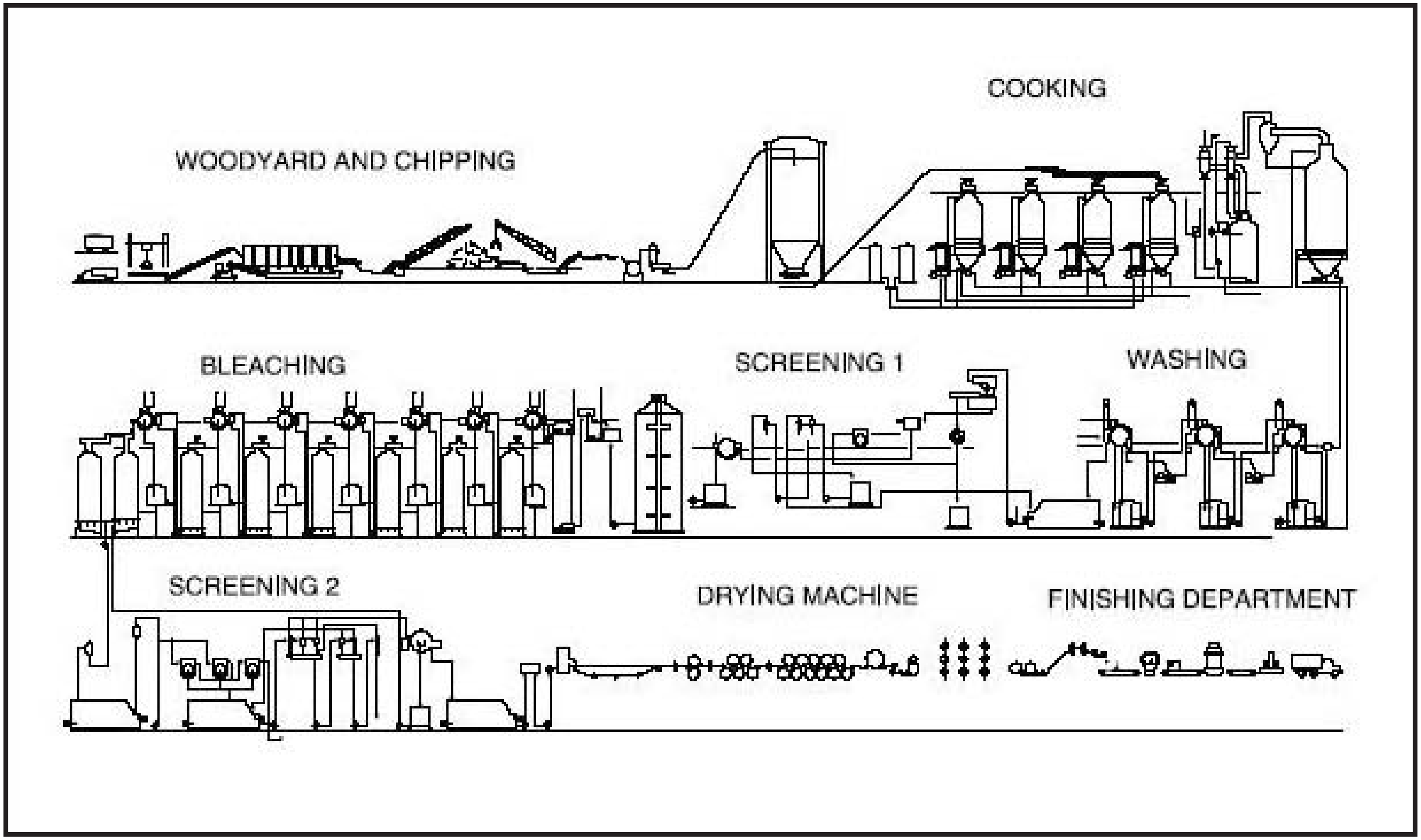
[17] About 90–95% of the atomic chlorine is converted into inorganic chloride (e.g., NaCl) and about 5–10% is converted into absorbable organic halides or total organic chlorine. OECD, "The Application of Biotechnology to Industrial Sustainability," (2001): 109.

[18] "Regulations worldwide require bleach chemical mills to have non-detectable concentrations of dioxins/furans and low levels of AOX [absorbable organic halides] in their effluent." *Ibid.*

[19] EPA, Office of Compliance, *Sector Notebook Project: Profile of the Pulp and Paper Industry,* Washington, DC (2002): 39.

[20] Vigsoe, Dorte, Espen Jürgensen, and Morten Kvistgaard, "The Assessment of Future Environmental and Economic Impacts of Process-Integrated Biocatalyst," European Commission Joint Research Center, (2002): 34.

Figure 1: Simplified Flow Diagram: Integrated Mill (Chemical Pulping, Bleaching, and Paper Production)[21]



---

[21] EPA, Office of Compliance, *Sector Notebook Project: Profile of the Pulp and Paper Industry,* Washington, DC (2002): 17.

"Enzyme Treatment of Pulp. Biotechnology research has resulted in the identification of a number of microorganisms that produce enzymes capable of breaking down lignin in pulp. Although the technology is new, it is believed that a number of mills are currently conducting enzyme treatment trials. The microorganisms capable of producing the necessary enzymes are called xylanases. Xylanases for pulp bleaching trials are available from several biotechnology and chemical companies. Since enzymes are used as a substitute for chemicals in bleaching pulp, their use will result in a decrease in chlorinated compounds released somewhat proportional to the reduction in bleaching chemicals used. Enzymes are also being used to assist in the de-inking of secondary fiber. Research at the Oak Ridge National Laboratories has identified cellulose enzymes that will bind ink to the smaller fiber particles facilitating recovery of the ink sludge. Use of enzymes may also reduce the energy costs and chemical use in retrieving ink sludge from de-inking effluent."

EPA, Office of Compliance, *Sector Notebook Project: Profile of the Pulp and Paper Industry*, Washington, DC (2002): 66

Barriers to Deployment

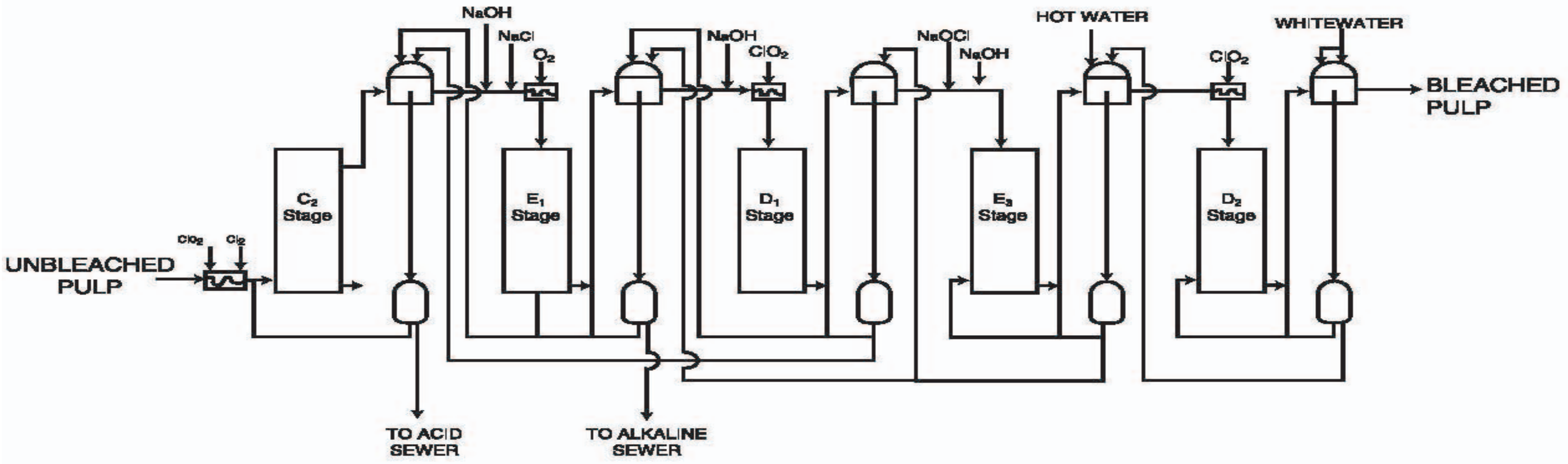
A recent report released by the European Commission Joint Research Center noted that although the "prospective for economic and environmental benefits in the sector of pulp and paper is good,"[22] there are still many factors that will impair industry-wide use of these techniques. The main barrier in the industry is what the report calls conservative thinking. "Conservative thinking" is a term used to describe the lack of knowledge of biocatalysts among managerial staff at companies, including a lack of familiarity with the existing chemicals and process, and the lack of suppliers and advertising of biocatalysts in the mills. Additional barriers to full use of the biotechnology process include international competition, which leaves little room for investments in new technology, and little demand.[23]

---

[22] Vigsoe, Dorte, Espen Jürgensen, and Morten Kvistgaard, "The Assessment of Future Environmental and Economic Impacts of Process-Integrated Biocatalyst," European Commission Joint Research Center, (2002): 8.

[23] *Ibid*, 37.

Figure 2: Typical Bleaching Plant Showing Chemical Bleaching Process[24]



---

[24] EPA, Office of Compliance, *Sector Notebook Project: Profile of the Pulp and Paper Industry,* Washington, DC (2002): 32.

Figure 3: Projection for Reduction of Chlorine in Wastewater from Pulp Production/Bleaching with a Biotechnology Process

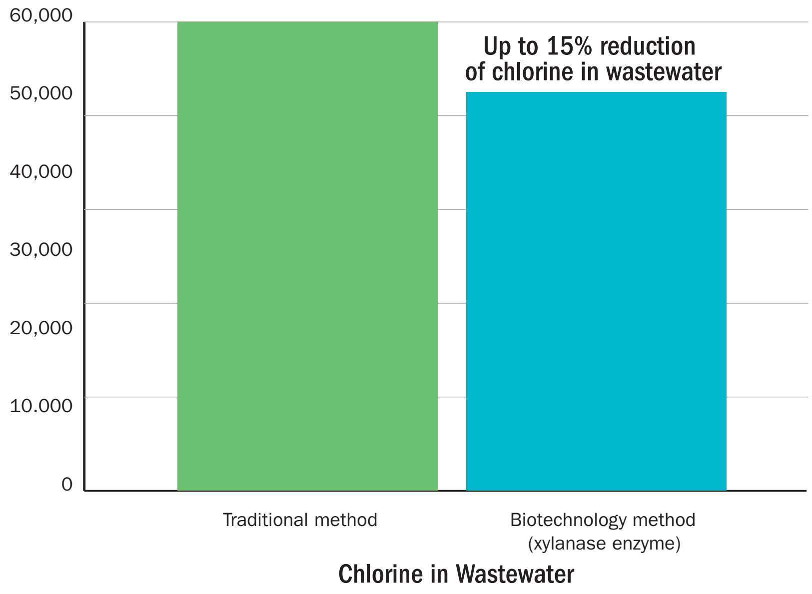


Figure 4: Projection for Reduction of Energy Consumption in Pulp Production/Bleaching with a Biotechnology Process

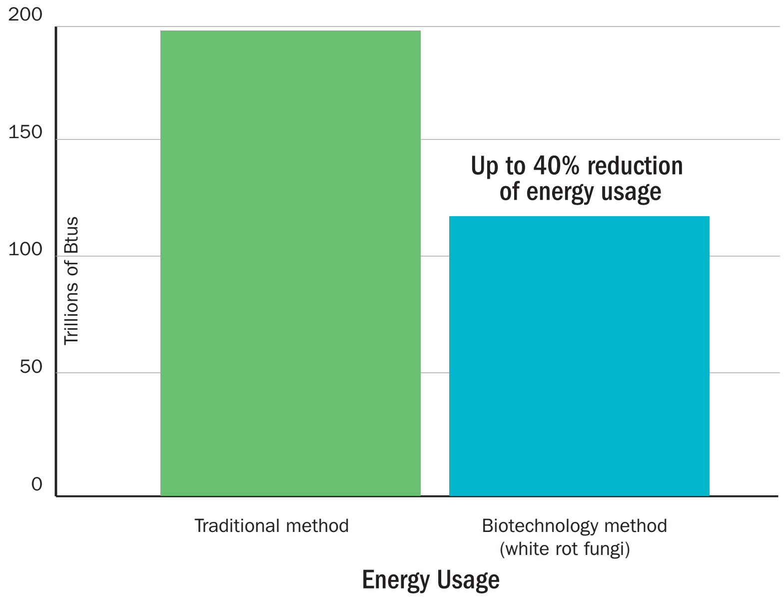


Table 4: Resources and Pollution Comparison for Pulp and Paper Production

Resource Consumption and Pollution Generation Using Traditional Processes	Resource Conservation and Pollution Prevented Using Biotechnology Processes	
The facilities in the U.S. pulp processing industry reported the following annual data:[25]	**INDIVIDUAL PROCESS SAVINGS** *Savings when one facility uses the xylanase enzyme in the bleaching process to reduce chlorine usage:*	**POTENTIAL INDUSTRY-WIDE SAVINGS** *Pollution savings if use of the xylanase enzyme were expanded industry-wide*[40] *in the United States:*
1) Fuel consumption: 198 trillion Btu[26]	1) Energy consumption: 3% less[32]	1) Energy (fuel consumption): reduced by 0.594 trillion Btu[41] (plus a related reduction of roughly 598,000 tons of CO_2)[42]
2) Chlorine in wastewater: 60,185 lbs/yr[27]	2) Bleaching chemicals (chlorine products): 10–15% less[33]	2) Chlorine in wastewater: 6,019–9,028 lbs/yr[43]
3) Chlorine in point air emissions: 512,871 lbs/yr[28]	3) See 2) above	3) Chlorine in air: 51,287–76,930 lbs/yr[44]
4) Chlorine dioxide in point air emissions: 716,647 lbs/yr[29]	4) See 2) above	4) Chlorine dioxide in air: 71,665–107,497 lbs/yr
5) Ozone emissions: 102,763 lbs/yr[30]	5) Ozone: 15% less[34]	5) Ozone: 15,414 lbs/yr
6) Air pollutants: 567,542 tons/yr of CO[31] 318,263 tons/yr of NO_2 85,403 tons/yr of PM_{10} 63,577 tons/yr of PM_{25} 488,029 tons/yr of SO_2 144,373 tons/yr of volatile organic compounds (VOCs)	6) Air pollutants: insufficient data[35]	6) Air pollutants: insufficient data
7) Carcinogens: insufficient data	7) Carcinogens: 16% less[36]	7) Carcinogens: insufficient data
8) Acidification: insufficient data	8) Acidification: 8% less[37]	8) Acidification: insufficient data
9) Heavy metals: insufficient data	9) Heavy metals: 12% less[38]	9) Heavy metals: insufficient data
10) Solid waste: insufficient data	10) Solid waste: 13% less[39]	10) Solid waste: insufficient data
	Savings when one facility uses white rot fungi:	*Pollution savings if the use of white rot fungi use were expanded industry-wide:*[51]
1) Fuel consumption: 198 trillion Btu[45]	1a) If using mechanical bleaching process, energy input reduced 30–40%[49] 1b) If using chemical bleaching process, 30% more lignin removed, or boiling time correspondingly reduced[50]	1) Fuel consumption: 5.94 – 7.92 trillion Btu
2) Chlorine in wastewater: 60,185 lbs/yr[46]	2) Chlorine in wastewater: data not available	2) Chlorine in wastewater: insufficient data
3) Chlorine in point air emissions: 512,871 lbs/yr[47]	3) Chlorine in point air emissions: data not available	3) Chlorine in point air emissions: insufficient data
4) Chlorine dioxide in point air emissions: 716,647 lbs/yr[48]	4) Chlorine dioxide in point air emissions: data not available	4) Chlorine dioxide in point air emissions: insufficient data

25 Data for fuel consumption and air pollutants are for the entire pulp process, not just for bleaching.

26 EIA, “Manufacturing Consumption of Energy,” (1998) *available at http://www.eia.doe.gov/emeu/mecs/mecs98/datatables/d98n1_2.pdf* (last visited Mar. 2, 2004), Table N1.2; Value given is a process-wide total; it is not specific to the bleaching process. We assume that 10% of fuel consumption (or 19.8 trillion Btu) is for the bleaching process.

27 EPA Office of Compliance, “Toxic Releases Inventory (TRI) Releases for Pulp and Paper,” (2000) *available at http://www.epa.gov/compliance/resources/publications/assistance/sectors/notebooks/data_refresh.html (*last visited July 1, 2003).

28 *Ibid.*

29 *Ibid.*

30 *Ibid.*

31 EPA, Office of Compliance, *Sector Notebook Project: Profile of the Pulp and Paper Industry,* Washington, DC (2002): 58.

32 OCED, “The Application of Biotechnology to Industrial Sustainability,” (2001): 117.

33 *Ibid,* 110.

34 *Ibid,* 117.

35 *Ibid.*

36 *Ibid.*

37 *Ibid.*

38 *Ibid.*

39 *Ibid.*

40 Numbers are generated by applying the savings experienced by one facility to the environmental indicators and pollutants reported by the entire industry. For example, one facility will see a 15% savings in ozone air emissions. If the entire industry reports 102,763 lbs/yr of ozone emissions, a 15% savings would result in 15,414 lbs/yr less ozone air emissions.

41 This study assumes that 10% of energy is consumed in the bleaching process. This number represents 3% of the19.8 trillion Btu consumed during bleaching.

42 The carbon dioxide emission factor is estimated to be 65,000 g per million Btu of fuel consumed, which is based on the combustion of half natural gas and half liquid petroleum gas (LPG is presumed to emit the same quantity of carbon dioxide per volume fuel consumed as refinery plant gas). M.Q. Wang, “GREET 1.4 – Transportation Fuel-Cycle Model,” Center for Transportation Research, Argonne National Laboratory (1999), Appendix C: Refinery Energy and Global Warming Impacts and Emissions located in United States Environmental Protection Agency, Office of Air and Radiation, Regulatory Impact Analysis – Control of Air Pollution from New Motor Vehicles: Tier 2 Motor Vehicle Emissions Standards and Gasoline Sulfur Control Requirements. This rate may not be precise for emissions related to fuel consumed by the pulp and paper industry but is being used as a proxy.

43 The industry-wide savings assumes a direct correlation between chlorine used in the bleaching process and chlorine pollution.

44 OECD, “The Application of Biotechnology to Industrial Sustainability,” (2001): 110.

45 EIA, Table N1.2. (see footnote 26)

46 EPA, Office of Compliance, “Toxic Releases Inventory (TRI) Releases for Pulp and Paper,” (2000) *available at http://www.epa.gov/compliance/resources/publications/assistance/sectors/notebooks/data_refresh.html* (last visited July 1, 2003).

47 *Ibid.*

48 *Ibid.*

49 OECD, “The Application of Biotechnology to Industrial Sustainability,” (2001): 106.

50 *Ibid.*

51 Numbers are generated by applying the savings experienced by one facility to the environmental indicators and pollutants reported by the entire industry. For example, one facility will see a 15% savings in ozone air emissions. If the entire industry reports 102,763 lbs/yr of ozone emissions, a 15% savings would result in 15,414 lbs/yr less ozone air emissions. (see footnote 40)

6.2 Textile Finishing

Biotechnology has numerous applications in the textile industry. Enzymes discovered and produced through biotechnology can be used in highly specialized textile finishing processes to brighten or tone down color, improve smoothness, reduce pilling, and improve the drape and hand of fabric. New fibers, developed through biotechnology, are proving to have more desirable characteristics than certain fibers derived from petroleum products. This may allow for the development of superior products such as more durable carpeting, lightweight bulletproof material, and stronger "silk."

An example explored in this analysis is the use of biotechnology processes to reduce the environmental impact of stonewashing denim. Traditionally this effect is achieved by washing denim fabric with pumice stone from open-pit mines. Enzymes can now do the same job with less effect on the environment. Using these enzymes often significantly reduces the amount of bleach and water used in each process.

Below we examine the replacement of one bleaching process, one stonewashing process, and one fiber process with biotechnology processes. These processes result in substantial energy and pollution savings (Table 5).

Traditional Processes

1) Textile bleaching is usually accomplished by using hydrogen peroxide followed by repeated rinsing (at least twice) in hot water (80–95°C [176–203°F])[52] to completely remove the bleaching residue. The rinsing is energy and water intensive.

Textile mills may cut water consumption by as much as 30–50% with this method.

2) The finishing of stonewashed jeans requires that the fabric be washed with crushed pumice stone, an acid, or both. This process is energy intensive, creates significant water wastes, and requires open-pit mining of pumice.

3) One of the most environmentally harmful textile production processes is the traditional method of preparing cotton fiber, yarn, and fabric. Before cotton yarn or fabric can be dyed, it goes through a number of processes in a textile mill (Figure 5). One important step is scouring, which is the complete or partial removal of the noncellulose components found in native cotton as well as the removal of impurities such as machinery and sizing lubricants. Traditionally, this purification is achieved through a series of chemical treatments (using hot sodium hydroxide to remove the impurities) and subsequent rinsing in water. This treatment generates large amounts of salts, acids, and alkali and requires huge amounts of water. The pollutants in wastewater streams include starch, surfactants, biocides, lubricants, chelants, alkaline compounds, metals, salts, unfixed dyes, organic additives, formaldehyde-based resins, metal catalysts, and softeners.

---

[52] OECD, "The Application of Biotechnology to Industrial Sustainability," (2001): 99-100.

Industrial Biotechnology Processes

1) To reduce the energy and water usage required in the rinse after bleaching, an enzymatic bleaching process[53] was developed that uses an enzyme to degrade residual peroxide into water and oxygen. The enzyme is applied to the second postbleach rinse for 15 minutes at 30–40ºC (86–104ºF); therefore, only one high-temperature rinse is required. The process reduces the amount of rinsing (i.e., water and energy) required after bleaching. Industry-wide use of this process would save about 3 trillion Btu per year, about the equivalent of one small natural gas combined-cycle power plant or the electricity consumed by 28,120 residential customers in one year.[54]

> Use of this process industry-wide would save about 3 trillion Btu per year, about the equivalent of one natural gas combined-cycle power plant or the electricity consumed by 28,120 residential customers in one year.

2) Instead of crushed pumice stone and/or acid being used to finish stonewashed jeans, the fabric is washed with a biotechnology enzyme (cellulase) to fade and soften jeans. This method can reduce the environmental costs of stonewashing by more than 50%. Biotechnology process changes in the textile finishing sector *reduce energy demand for bleaching by about 9–14%* (Figure 6) and *reduce water usage by about 17–18%* (Figure 7).

3) With BioPreparation™ using the enzyme BioPrep™ 3000 L, cotton fibers can be treated under very mild conditions. The environmental impact is reduced because less chemical waste is produced and lower volumes of water are needed. This process cuts both effluent load and water usage to the extent that the new technology becomes an economically viable alternative to chemical treatment processes. Hot sodium hydroxide, which damages parts of the fiber, is replaced by enzymes that leave the cotton fiber intact. Textile mills may cut water consumption by as much as 30–50% with this method.

Barriers to Deployment

When analyzing the benefits of the biotechnology process, it is important to keep in mind the drivers and barriers that will influence full industry-wide use of biotechnology processes in the textile industry. Although the biotechnology process improves the quality and functionality of the product and the use of enzymes can help in complying with new environmental legislation,[55] there remains a long list of barriers to overcome. In addition to the harsh economic restrictions in the sector, the enzyme process does not always reduce production costs. Moreover, the process requires the purchasing of new machinery and trials that can be very costly. With the difficulty associated with determining long-term benefits, many mill managers seek to avoid the risk and are remaining conservative.[56]

---

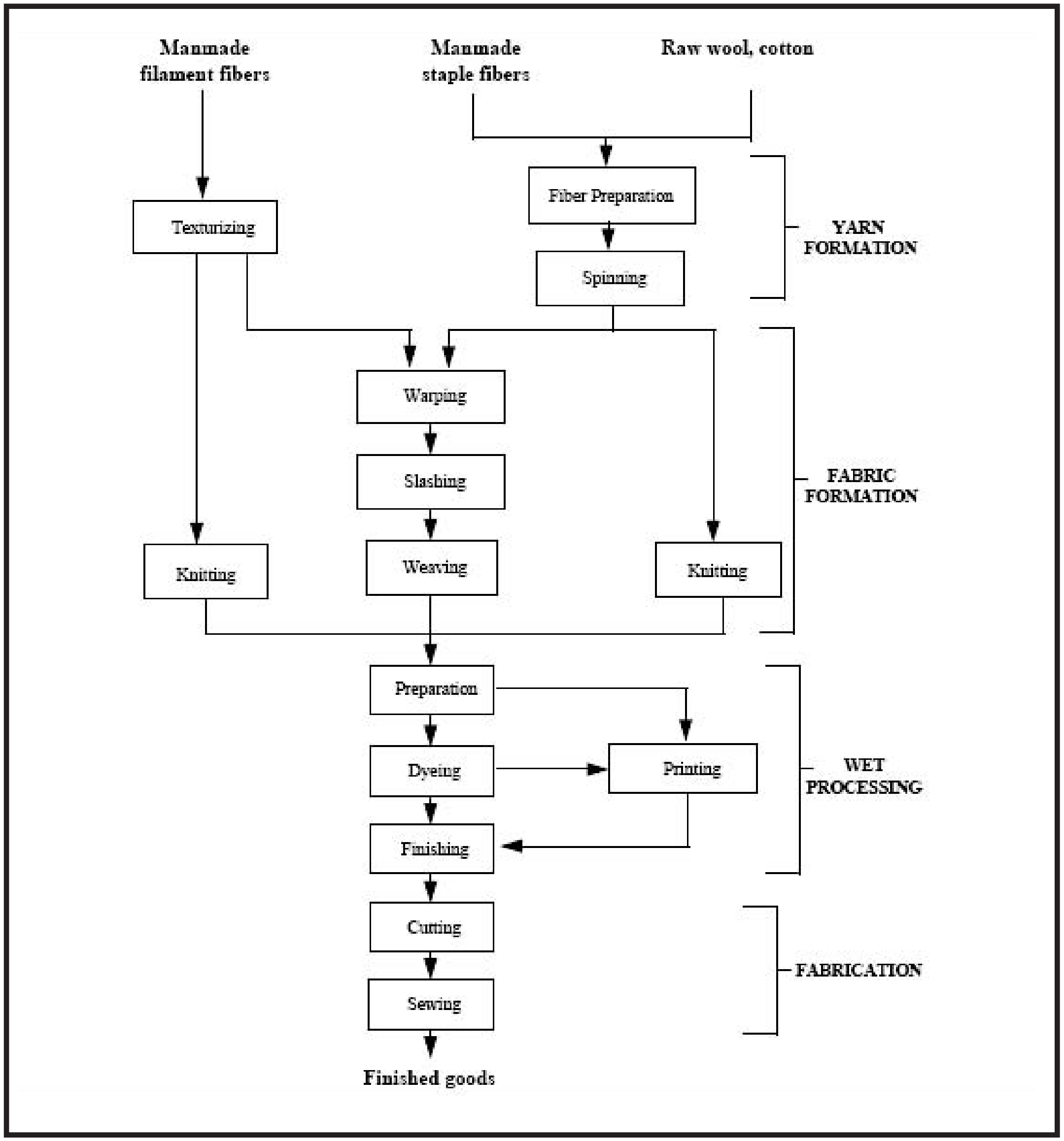
[53] *Ibid,* 98-103.

[54] If the average U.S. power plant consumes 10,000Btu/Kwh (about 34% efficiency), 3T Btu are the equivalent of 300,000 Mwh; assuming 80% capacity rating, this equates to about 42 MW or the size of small new natural gas combined cycle plants according to EIA Electric Power Monthly; according to EIA's Electric Sales and Revenue 2000, Table 1, the average residential customer consumes approximately 10,670 Kwh per year so 3T Btu equates to roughly the amount of electricity consumed in one year by 28,120 residential customers.

[55] Vigsoe, Dorte, Espen Jürgensen, and Morten Kvistgaard, "The Assessment of Future Environmental and Economic Impacts of Process-Integrated Biocatalyst," European Commission Joint Research Center, (2002): 9.

[56] *Ibid,* 50.

Figure 5: Typical Textile Processing Flow Chart[57]



---

57 EPA, Office of Compliance, *Sector Notebook Project: Profile of the Textile Industry,* (1997): 14.

Figure 6: Projection for Reduction of Energy Usage in Textile Finishing with a Biotechnology Process

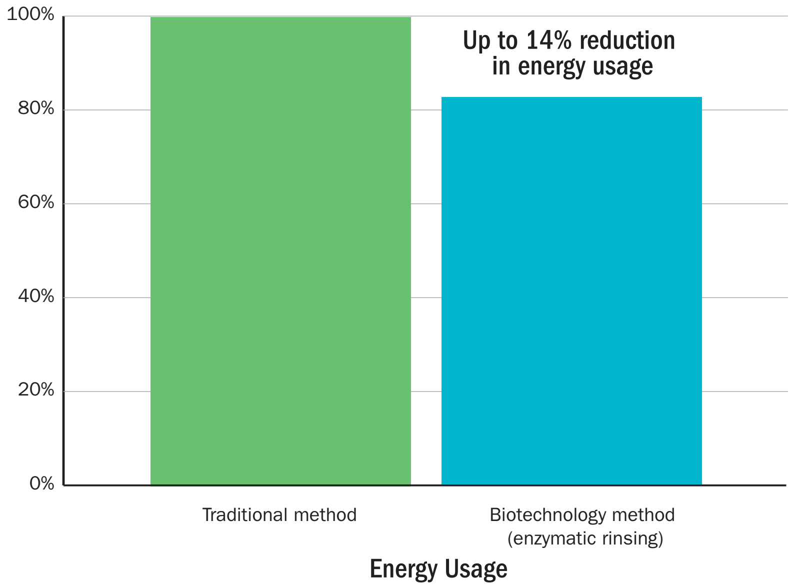


Figure 7: Projection for Reduction of Water Usage in Textile Finishing with a Biotechnology Process

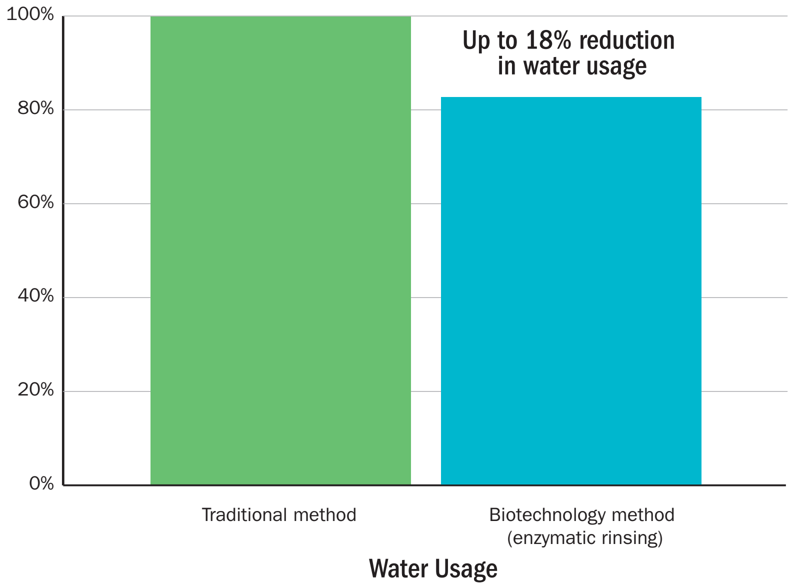


Table 5: Resources and Pollution Comparison for Textile Finishing

Resource Consumption and Pollution Generation Using Traditional Processes	Resource Conservation and Pollution Prevented Using Biotechnology Processes	
Facilities in the textile industry reported the following annual data:[58] 1) Fuel consumption: 254 trillion Btu[59] 2) Total water usage: data not available 3) Total wastewater discharge: 305,241 lbs/yr[60]	Individual Process Savings *Savings when one facility used the enzymatic bleaching process in the rinsing stage:* 1) Energy usage: 9–14% less[61] 2) Water usage: 17–18% less[62] 3) Reduced wastewater discharge: insufficient data	Potential Industry-wide Savings *Pollution savings if the use of enzymatic bleaching process were expanded industry-wide:*[63] 1) Energy (fuel consumption): 2.3– 3.6 trillion Btu/yr[64] 2) Water usage: insufficient data 3) Wastewater discharge: insufficient data
Stonewashed jeans: using crushed pumice. Environmental economic costs:[65] *Cost, $/100kg jeans* Air 8.31 Water 28.10 Waste 2.01 Total 38.42	Cost and savings [in brackets] when one facility uses biotechnology enzyme (cellulase) to finish stonewashed jeans:[66] *Cost [Savings]* Air 4.13 [49%] Water 16.37 [58%] Waste 0.62 [30%] Total 21.12 [55%]	*Pollutions savings if the use of a biotechnology enzyme to finish stonewashed jeans were expanded industry-wide:* Available data were not sufficient to analyze the potential total savings. This is partly because the multinational nature of the textile industry makes it difficult to estimate stonewashing activities in the United States.
162 knitting mills use 89 million cubic meters of water per year in processing goods from scouring to finishing.[67]	*Savings when the Novozymes BioPreparation™ process is applied to these 162 knitting mills:* Water usage: 30–50% less for scouring fibers (27–45 million cubic meters of water per year) Cost savings: 30% or more[68]	*Pollutions savings if the use of the Novozymes BioPreparation™ process were expanded industry-wide:* Water usage: insufficient data Cost savings: insufficient data

---

58 Data provided is for entire textile finishing process, not just the bleaching process.

59 EIA, “Manufacturing Consumption of Energy,” (1998) *available at http://www.eia.doe.gov/emeu /mecs/mecs98/datatables/d98n3_2.pdf* (last visited Mar. 2, 2004): Table N3.2; Value given is a process-wide total; it is not specific to the bleaching process. We assume 10% of fuel consumption (or 25.4 trillion Btu) is for the bleaching process.

60 EPA, Office of Compliance, “2000 Toxic Releases Inventory Releases for Textile Facilities,” (2000) *available at http://www.epa.gov/compliance/resources/publications/assistance/sectors/ notebooks/data_refresh.html* (last visited July 1, 2003).

61 OECD, “The Application of Biotechnology to Industrial Sustainability,” (2001): 102.

62 *Ibid.*

63 Numbers are generated by applying the savings experienced by one facility to the environmental indicators and pollutants reported by the entire industry. For example, one facility using the enzymatic bleaching process will see an energy savings of 9–14%. If the entire textile industry reports energy consumption at a rate of 254 trillion Btu/yr and we assume that 10% (or 25.4 trillion Btu/yr) of that is used during the bleaching process, then a 9–14% savings would result in a 2.3–3.6 trillion less Btu/yr.

64 This study assumes that 10% of energy is consumed in the bleaching process. This number represents 9–14% of the 25.4 trillion Btu consumed during bleaching.

65 OECD, “Biotechnology for Clean Industrial Products and Processes: Towards Industrial Sustainability,” (1998): 98.

66 *Ibid.*

67 EPA, “2001 Alternative Solvents/Reaction Conditions Award,” *available at www.epa.gov/ greenchemistry/ascra01.html* (last visited Mar 11, 2004).

68 *Ibid.*

6.3 Plastic and Chemical Production

The potential for dramatic transformation of an industry through the use of biotechnology is perhaps most readily apparent in discrete areas of the plastics manufacturing sector. In plastics, bioprocesses are allowing common agricultural crops–a renewable resource–to replace petroleum as the feedstock in the production of monomers and polymers for plastics such as polyester.

In an industrial breakthrough reminiscent of cracking the petroleum molecule to allow the development of thermoplastics in the 1930s, industrial biotechnology is finding ways to unlock the constituent elements of plants, carbon, and hydrogen and remake them into the constituent chemicals for plastics production. In some cases, the resulting plastics will be biodegradable. In all cases, the new industrial process will substitute agricultural products–even agricultural wastes–for petroleum as a key feedstock.

This means that biotechnology can reduce the use of chemicals and energy in the production of plastics, and it has the potential to significantly eliminate the waste from the use of the products themselves. More than 80 billion pounds of plastic products are produced annually in the United States. Of that, 1 billion pounds are biobased plastics.[69] The remaining potential for environmental benefits and reduced demand for foreign oil is substantial (Table 6). For example, if all plastics were made from biobased polylactic acid (PLA), oil consumption would decrease by 90–145 million barrels per year–or about as much oil as the United States consumes in one week.[70]

Conversion to biobased plastics is just getting under way on a moderate scale. In April 2002, Cargill-Dow opened the world's first commercial biorefinery to produce a biobased polymer (Figure 8).

> More than 80 billion pounds of plastic products are produced annually in the United States. Of that, 1 billion pounds are biobased plastics. The remaining potential for environmental benefits and reduced demand for foreign oil are substantial. For example, if all plastics were made from biobased polylactic acid, 90–145 million fewer barrels per year would be consumed–or about as much oil as the United States consumes in one week.

That same year, compostable PLA drink cups were used at the 2002 Winter Olympic Games in Salt Lake City, Utah. The use of compostable food-service items allows for the composting of food scraps without the cost of separating food from plates, containers, and utensils. Because composting costs are lower than landfill costs, one study estimated the potential reduction of food waste management costs at up to 35%.[71]

---

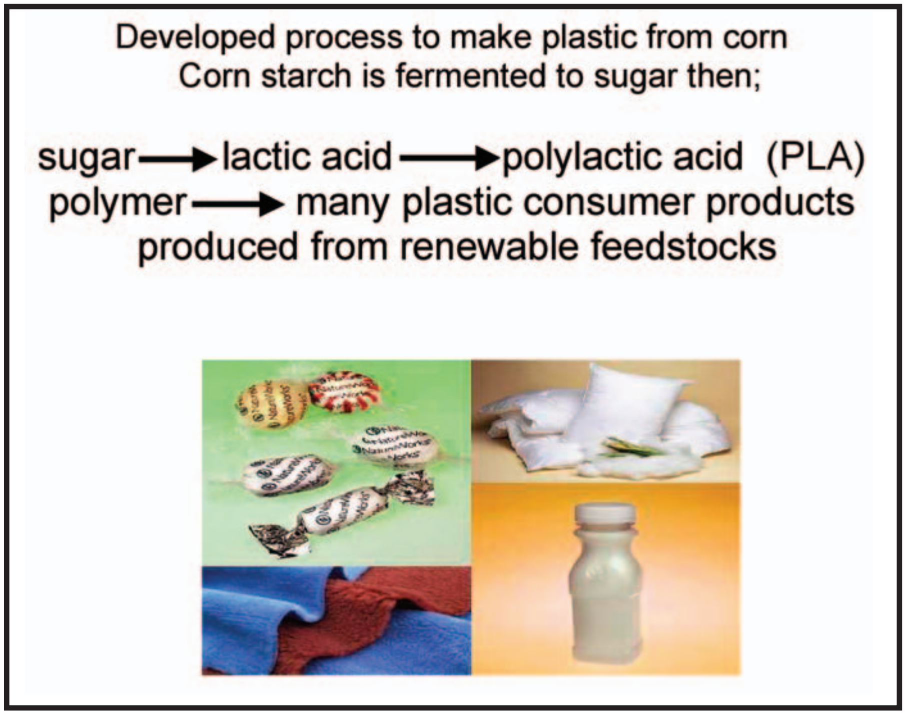
[69] Biomass Research and Development Board, "Fostering the Bioeconomic Revolution in Biobased Products and Bioenergy," (2001): 8.

[70] EIA, "Petroleum Products Supplied by Type," (2001) available at *http://www.eia.doe.gov/emeu/aer/pdf/pages/sec5-180.pdf* (last visited Mar 2, 2004): Table 5.11.

The organic chemical industry (which produces plastic or plastic precursors) is vast. More than 175 billion pounds of organic chemicals are produced each year in the United States. Predominantly derived from petroleum feedstock, these products comprise $188 billion of U.S. gross domestic product.[72] Enough agricultural crop residue is produced each year from agricultural crops such as common corn to entirely replace the 700 million barrels of petroleum used in organic chemical production[73] (Although industrial biotechnology process can use any agricultural feedstock, including genetically modified crops, the main focus of industrial biotechnology is to develop processes that might work on any agricultural feedstock.) Some technical and cultural challenges remain as barriers to overcome in this merger of the chemical and biological sciences.

PLA is not the only interesting development in the industrial intersection between biotechnology and plastics. DuPont, working with the biotechnology firm Genencor International, is developing additional ways to create polymers from renewable resources. Their scientists have developed a microorganism that converts the sugar in plants (glucose) into trimethylene glycol–the critical precursor to 1,3-propanediol, itself a key ingredient in the manufacture of polyester and other plastics. Another group of biotechnology plastics under development by Metabolix are polyhydroxyalkoanates. These unique plastics are generated by bacteria as plastic nodules inside the bacterium itself.

Figure 8: Recent Case Study Cargill-Dow


Developed process to make plastic from corn
Corn starch is fermented to sugar then;

sugar ⟶ lactic acid ⟶ polylactic acid (PLA)
polymer ⟶ many plastic consumer products
produced from renewable feedstocks

Scientists also have developed methods of using plants and industrial biotechnology to produce ethylene, one of the most important chemical feedstocks for production of plastic and many other products, including plywood, solvents, antifreeze, and paints (Figure 10). Ethylene is used in half of the plastic resins sold in the United States.

Traditional Processes

1) Common household products such as food containers and clothing are currently made from polymers that use petroleum as a feedstock. To create polymers, petroleum is broken (cracked) into several

---

[71] Energetics, Incorporated, Report for the Department of Energy “Industrial Bioproducts: Today and Tomorrow,” Columbia, MD (2003): 41.

[72] *Ibid,* 5.

[73] “In 2001, the fossil-based feedstock energy used in the production of chemicals was about 3.2 quads...which is equivalent to over 700 million barrels of oil.” *Ibid,* 13.

different monomers that are recombined into polymers that give different types of plastic their special characteristics. The polymerization process includes several steps and chemicals that vary depending on the properties required for each polymer. There are many different grades of polymers, each with its own unique physical characteristics. The polymers are processed further into plastic products or used to make synthetic fibers.

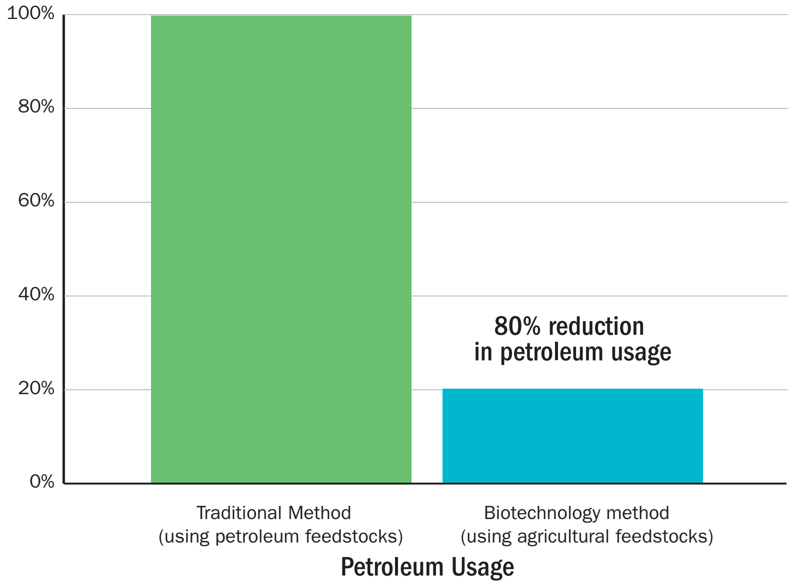
2) In classical chemistry, ethylene is produced from natural gas concentrates or petroleum fractions such as naphthas and atmospheric gas oils. These petroleum refinery byproducts are put through a hydrocarbon cracker and converted into several products, including ethylene. The process of cracking the hydrocarbon is referred to as pyrolysis and involves breaking the compound into smaller components by heating it and exposing it to a catalyst. Changes in the temperature and catalyst will change the chemical products and yields from this process.

Industrial Biotechnology Processes

1) PLA can replace petroleum in the creation of polymers. PLA is produced from plant sugars, predominantly from corn, which is a renewable feedstock. Methods are being developed to use lignocellulosic biomass, such as straw or corn residue left in the field, to make PLA. The process harnesses carbon stored in plants to create the PLA polymer, which can then be used to make common consumer items such as plastics cups and packing materials.[74] Products made with PLA perform as well as those made with conventional polymers. One major difference is that PLA products can be composted and are recyclable. Because PLA plastics are biodegradable, they offer the potential of eliminating plastic from our solid-waste landfills and incinerators. Replacing petrochemical feedstocks with feedstocks made from organic material such as corn *reduces demand for petrochemicals by 20–80%* (Figure 9).

2) Ethanol from either agricultural products or agricultural residues (see Section 6.4, Fuels Production) can be substituted for the conventional petroleum inputs and fed into a hydrocarbon cracker to produce ethylene. Because ethylene is used in so many consumer products, replacing it with the biobased ecothene would significantly reduce use, transport, and pollution related to ethylene. Ecothene would lower oil demand and reduce greenhouse gas emissions by substituting a renewable feedstock for petroleum. However, because we have found no data specific to ethylene-related pollution, this report does not estimate the total possible benefits.

Figure 9: Projection for Reduction in Petroleum Usage in Plastics Production with a Biotechnology Process



---

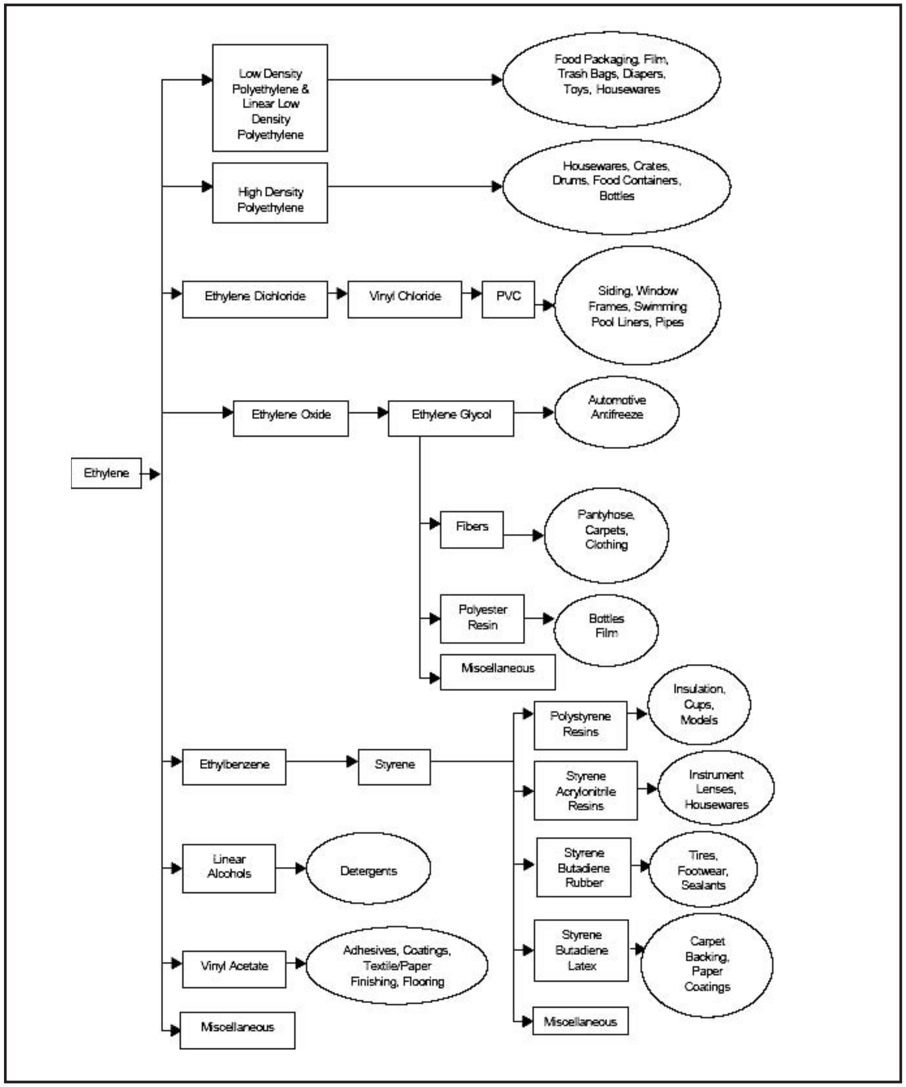
[74] OECD, "The Application of Biotechnology to Industrial Sustainability," (1998): 87-90.

Table 6: Resources and Pollution Comparison for Plastics and Chemical Production

Resource Consumption and Pollution Generation Using Traditional Processes	Resource Conservation and Pollution Prevented Using Biotechnology Processes	
	Individual Process Savings	Potential Industry-wide Savings
Facilities in the plastics industry have reported the following:	*Savings when one facility replaces petroleum feedstock with PLA:*	*Savings if PLA use were expanded industry-wide:*[81]
1) Energy use: 1,067 trillion Btu/yr[75]	1) Energy use: insufficient data If using lignocellulosic biomass (such as straw), petroleum use is reduced by 80%.[79]	1) Energy savings: if using lignocellulosic biomass (such as straw): 853 trillion Btu/yr
2) Air pollution releases:[76] 16,388 tons/yr of CO 41,771 tons/yr of NO_2 2,218 tons/yr of PM_{10} 7,546 tons/yr of PT (total particulates) 67,546 tons/yr of SO_2 74,138 tons/yr of VOC	2) Air pollution releases: insufficient data	2) Air pollution releases: Insufficient data
3) Petroleum use as feedstock: insufficient data	3) Petroleum use as feedstock: reduced 20–50%[80];	3) Petroleum use as feedstock: insufficient data
4) Total surface water discharges: 71,092 lbs/yr[77]	4) Reduced wastewater emissions: insufficient data	4) Wastewater emissions: Insufficient data
5) Total thermoplastic consumption in 2000 (solid waste): 26.8 million tons[78] (Thermoplastic resins are resins that can be heated and molded into shapes repeatedly.)	5) Total thermoplastic consumption: data not available; if removed from waste stream and biodegraded, up to 80%	5) Thermoplastic consumption: insufficient data
Releases specific to ethylene production and use are not available.		*Savings if ecothene replaces ethylene:* 75–80% of feedstock carbon is sequestered [82]

> Enough agricultural crop residue is produced each year to entirely replace the 700 million barrels of petroleum used in organic chemical production.

Figure 10: Ethylene Products [83]



---

75 EIA, "First Use of Energy for All Purposes (Fuel and Nonfuel)," (1998) available at *http://www.eia.doe.gov/emeu/mecs/mecs98/datatables/d98s1_1.pdf* (last visited Mar 3, 2004): Table S1.1.

76 EPA, Office of Compliance, *Sector Notebook Project: Plastic Resin and Manmade Fiber Industries*, Washington, DC (1997): 99.

77 EPA, "Industry Report: TRI On-site and Off-site Reported Releases (in pounds)", U.S., 2001 available at *http://www.epa.gov/tri/* (last visited July 1, 2003)

78 Society of the Plastics Industry. "Executive Summary: World ThermoPlastic Consumption and Forecast," (2003) available at *http://www.plasticsdatasource.org/global.htm*. (last visited Mar 15, 2004). The global consumption in 2000 was 117.3 million tons.

79 OECD, "The Application of Biotechnology to Industrial Sustainability," (2001): 88.

80 *Ibid.*

81 Numbers are generated by applying the savings experienced by one facility to the environmental indicators and pollutants reported by the entire industry. For example, one facility will see an 80% reduction in energy usage. If the entire industry reports 1,067 trillion Btu per year, an 80% reduction in energy usage would result in a savings of 853 trillion Btu per year.

82 Energetics, Incorporated, Report for the Department of Energy "Industrial Bioproducts: Today and Tomorrow," Columbia, MD (2003): 20.

83 EPA, Office of Compliance, *Sector Notebook Project: Profile of Organic Chemical Industry*, Washington, DC (2002): 18.

6.4 Fuels Production

The production and use of petroleum-based fuels are a significant source of environmental pollution, and are also substantial factors in the vitality of the nation's economy. For example, small fluctuations in the price of fuels, such as gasoline, can greatly affect economic productivity.

One way to mitigate these impacts is to add ethanol to gasoline. Ethanol is a type of alcohol that is made by fermenting organic material. It acts as an oxygenate when added to gasoline, helping it to burn more completely and efficiently. As a result, the fuel economy of vehicles is increased and pollution emissions decreased. However, traditional ethanol production can be resource and energy intensive – it takes almost as much energy input to make traditional ethanol as ethanol delivers. Biotechnology provides a new way to produce ethanol by using crop residues containing cellulose as the feedstock instead of grain. Ethanol made by using industrial biotechnology enzymes to convert cellulose to ethanol is called bioethanol. The net benefits from bioethanol are significantly positive. According to Professor Bruce Dale of Michigan State University, bioethanol from cellulose generates 8 to 10 times as much net energy as is required for its production. It is estimated that one gallon of cellulosic ethanol can replace 30 gallons of imported oil equivalents (Professor Bruce Dale, personal communication, May 25, 2004).

Biocatalysts have been developed to unlock the hydrogen and carbon stored in carbohydrate molecules of plants and transform them into bioethanol. Although the production of traditional ethanol is not new, there are now biotech based ethanol processes that are becoming commercially viable. Today we produce over 3 billion gallons of traditional ethanol in the United States. With biotechnology, it could be possible in the future to produce 20 to 40 billion gallons of bioethanol from cellulosic biomass. This will provide economic benefits to farmers, environmental benefits to the public and will help the nation to reduce its dependence on foreign sources of petroleum.

Corn-based, or conventional, ethanol requires significant petroleum inputs from farm machinery operations and fertilizers used to grow the crop. Bioethanol from agricultural residues uses plant components left unused from crops grown for other purposes and therefore does not require significant additional energy to produce the feedstock. Currently, a farmer must make two passes over a field to collect the grain crop and the cellulosic crop residue, and farm equipment is being designed that may eliminate that extra step. Removal of these biomass residues for conversion to bioethanol (or plastic) gives farmers a second cash crop and promotes reduced-tillage farming practices that prevent soil erosion. According to a recent study, the trend toward reduced-tillage farming techniques means that 156 million tons of agricultural crop residues could be made available each year for bioethanol production.[84]

Reliance on reduced tillage farming practices (e.g., low till, no till) prevents other forms of pollution as well. Roughly half of the nitrogen applied in traditional fertilization operations is lost to water runoff or evaporation. Much of that nitrogen is deposited into waterways and contributes to eutrophication (enrichment of water that often sparks excess growth of algae and bacteria) and dead zones. With reduced tillage practices, the soil retains more carbon dioxide and fertilized topsoil. A comparison of energy inputs to the production E10 fuels using biomass and fossil fuels is shown in Table 7.

Industrial paper mill wastes are another untapped bioethanol source. The sludge residues from paper production often include wood and

---

[84] Arthur D. Little, Inc., "Aggressive Growth in the Use of Bio-derived Energy and Products in the United States by 2010, Final Report," (2001): 81.

paper fiber containing a high concentration of cellulose–a chemical raw material for bioethanol. A biotechnology process is being developed to turn that waste into bioethanol. When that process becomes available, paper producers will be able to sell the sludge to bioethanol producers instead of paying hundreds of dollars to dispose of it.

Bioethanol delivers significant climate change benefits. Because it is derived from renewable resources, bioethanol can be used to recycle carbon dioxide emissions in a closed loop from atmosphere to plant to ethanol back again. As mentioned earlier, bioethanol reduces the need to use fossil fuels in processing: one study estimates that to drive one mile on E85 bioethanol derived from corn stover will require only 14% of the energy inputs compared to the same distance driven using traditional gasoline derived from petroleum.[85] A similar greenhouse gas benefit results when waste materials that would otherwise be incinerated or allowed to decompose are substituted for virgin fossil fuels in the production of energy.

A study of the potential economic impact of increased bioethanol production from corn stover indicated that, at a selling price of $1.25 per gallon, bioethanol would support 15 economically feasible plants producing 1 billion gallons per year. That level of bioethanol production would create more than 22,000 jobs in the industrial, transportation, and agriculture sectors, adding nearly $11.6 billion a year to the economy in Iowa alone.[86]

Industrial biotechnology's reach into fuel production is not limited to bioethanol. Products developed through biotechnology can be used to remove sulfur from gasoline and diesel fuel in ways that are more environmentally friendly than traditional methods. Because sulfur lowers the efficiency of automotive catalytic converters, EPA is developing strict limits for sulfur content in gasoline and diesel fuels.

> In a "Wyatt Andrew's Eye on America" report in February of 2002, CBS Correspondent Wyatt Andrew described the use of agricultural products in producing plastics and other petroleum-based products. He noted that "these advances are part of a coming era of what's called industrial biotechnology—a revolution in which very high tech materials, fabrics and plastics come from raw materials here on the farm. The impact of this revolution is energizing the nation's farmers. Gerald Tumbleson can now sell his corn crop for industrial products like the shirt he wears–part cotton, part cornstarch. More important, spider fibers and corn-plastic can replace goods now made from petrochemicals. The bonus of this industrial revolution is there is no shortage of fuel. Cargill Dow will draw on the immense surplus of corn sitting in the nation's silos."
>
> —Wyatt Andrew, Correspondent for CBS News, "Wyatt Andrew's Eye on America Report takes you inside the biotech revolution," February 7, 2002, *available at http://www.cbsnews.com/stories/2002/02/07/eveningnews/main328681.shtml*

---

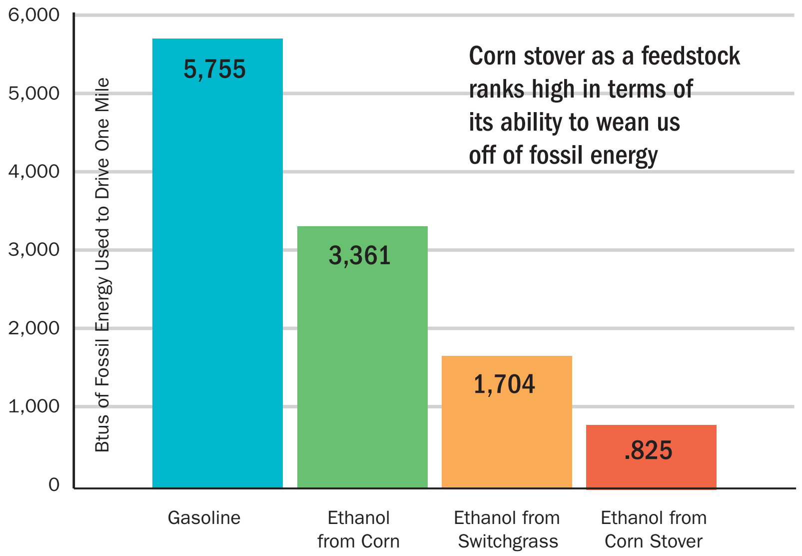
[85] National Renewable Energy Laboratory, "What is a life cycle assessment?" (2002) *available at http://www.nrel.gov/docs/gen/fy02/31792.pdf* (last visited Mar 22, 2004).

[86] Anderl, Georg, BIOWA Powerpoint presentation by of Genencor International, Inc., May 2003, available at *www.eesi.org/briefings/2003/EnergyandClimate/ 5.20.03%20Biomass/anderl.ppt* (last visited Mar 22, 2004).

Traditional Ethanol Process

Ethanol has been produced from the fermentation of food and feed grains for centuries. It is been blended with gasoline (the most common mix is 10% ethanol although increasingly a mix of 85% ethanol is available) and can improve the environmental performance of an engine in certain circumstances. One barrier to greater use has been that the traditional method for producing ethanol is somewhat energy and resource intensive and, therefore, does not yield a very large benefit when compared, on a lifecycle basis, to gasoline.

Comparison of Energy Consumed in a Vehicle Fueled by Ethanol vs. Gasoline



Corn stover as a feedstock ranks high in terms of its ability to wean us off of fossil energy

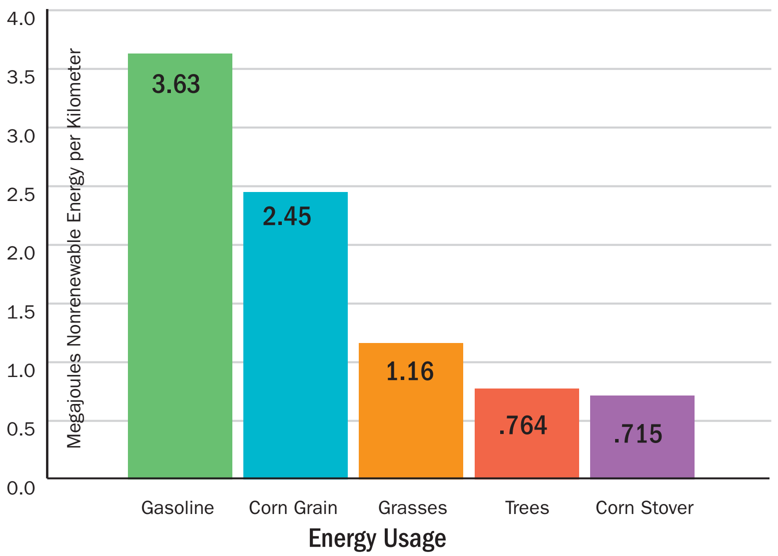
This bar graph shows the total fossil energy used in driving one mile in a car fueled by gasoline compared to E85 (85% Ethanol, 15 % gasoline) with the ethanol component coming from conventional ethanol (corn grain), and cellulosic ethanol (switch grass or corn stover). Energy used includes fossil energy inputs in making the fuel.

Source: see footnote 85 on page 43.

Industrial Biotechnology Process

Advances in industrial biotechnology allow bioethanol to be produced from cellulosic crop residues. Cellulase enzyme technology can convert cellulose to its constituent sugars, which are then fermented and distilled to make bioethanol (and other chemicals and products if desired). The use of crop residue rather than the grain crop itself allows for significant reductions in energy inputs and pollution related to bioethanol production. Bioethanol from cellulose generates 8 to 10 times as much net energy as is required for its production. It is estimated that one gallon of cellulosic ethanol can replace 30 gallons of imported oil equivalents. When biomass is used in making E10 fuels, it further reduces the energy inputs by 3%. A life cycle analysis shows net negative greenhouse gas emissions when ethanol in a fuel mix is higher than the standard 10%.

Nonrenewable energy used in production of various fuels*



*Source: John Sheehan, Andy Aden, Keith Paustian, Kendrick Killian, John Brenner, Marie Walsh and Richard Nelson, “Energy and Environmental Aspects of Using Corn Stover for Fuel Ethanol”, *Journal of Industrial Ecology*, Cambridge, MA (2003): 138.

Table 7: Resources and Pollution Comparison for Fuel Production

Resource Consumption and Pollution Generation Using Traditional Processes	Resource Conservation and Pollution Prevented Using Biotechnology Processes	
	Individual Process Savings *Savings when using biomass fuels to power steam-generation plants to produce E10 fuels:*	Potential Industry-wide Savings *Pollutions savings if bioethanol fuels were used industry-wide:*
1) Energy demand for production:[87] ■ Gasoline: ~5.29 MJ ■ E10-a (standard 10% ethanol fuel mix, feedstock cultivation is included, produced with traditional steam generation): ~5.1MJ ■ E10-b (standard 10% ethanol fuel mix, feedstock cultivation is excluded, produced with traditional steam generation): ~5.09 MJ ■ E10-c (feedstock cultivation is included, produced with steam generated with biofuels): ~ 4.96MJ ■ E10-d: ~4.95 MJ (feedstock cultivation excluded produced with steam generated with biofuels)	1) Biomass energy reduces life cycle analysis energy demand for producing E10 by about 2.7%,[89] ,or roughly 0.14 MJ.[90]	1) Energy demand: insufficient data.
2) Greenhouse gas emissions from whole life cycle of specific fuel[88]: ■ Gasoline: ~ 253 g/mi (CO_2 equiv.) ■ E10-a: ~256 g/mi (CO_2 equiv.) ■ E10-b: ~255 g/mi (CO_2 equiv.) ■ E10-c: ~245 g/mi (CO_2 equiv.) ■ E10-d: ~244 g/mi (CO_2 equiv.)	2) Biomass energy reduces life cycle analysis CO_2 equivalent emissions by roughly 4.3%,[91] or roughly g/mi.[92]	2) Greenhouse gas emissions: insufficient data.

---

[87] OECD, "The Application of Biotechnology to Industrial Sustainability," (2001): 139.

[88] *Ibid.*

[89] This number was generated by taking the average energy demand in the production of E10a and E10b (5.095 MJ) and subtracting the average energy demand in the production of E10c and E10d (4.955). E10a and E10b are fossil fuel derived whereas E10c and E10d are biofuel derived. The difference is 0.14 MJ, which is 2.7% of the energy demand in the production of fossil fuel–derived E10.

[90] This number was generated by taking the average energy demand in the production of E10a and E10b (5.095 MJ) and subtracting the average energy demand in the production of E10c and E10d (4.955). E10a and E10b are fossil fuel derived whereas E10c and E10d are biofuel derived. The difference is 0.14 MJ.

[91] This number was generated by taking the average CO_2 equivalent emissions from the whole life cycle of E10a and E10b (255.5 g/mi) and subtracting the average CO_2 equivalent emissions from the whole life cycle of E10c and E10d (244.5 g/mi). The difference is 11g/mi, which is 4.3% of the CO_2 equivalent emissions from the whole life cycle of fossil fuel–derived E10.

[92] This number was generated by taking the average CO_2 equivalent emissions from the whole life cycle of E10a and E10b (255.5 g/mi) and subtracting the average CO_2 equivalent emissions from the whole life cycle of E10c and E10d (244.5 g/mi). The difference is 11g/mi.

6.5 Pharmaceutical and Vitamin Production

Biotechnology has been a boon in healthcare biologics development and manufacturing. The technology also has great potential for improving the manufacture of heretofore chemically synthesized pharmaceuticals and supplements.

Quantifying the benefits to pharmaceutical manufacturing is a challenge because of the speed of innovation in the sector, its tremendous range of products, and the fragmented nature of data collection in the industry. The pharmaceutical industry is made up of four subcategories within the standard industrial classification (SIC) codes established by the U.S. Office of Management and Budget: Medicinals and Botanicals (SIC 2833); Pharmaceutical Preparations (SIC 2834); In Vivo and In Vitro Diagnostic Substances (SIC 2835); and Biological Products, Except Diagnostics (SIC 2836).

As a result, the available data do not allow for the nationwide extrapolation of the previous examples. The information below is included, however, because the speed of change in production lines means that infrastructure costs associated with making process modifications are likely to be less of a barrier in this sector than in others. Furthermore, the pharmaceutical industry's reliance on innovation is likely to make manufacturing executives receptive to exploring the many ways that industrial biotechnology can improve overall productivity and profitability.

Two examples are described here. In the first example, a biotechnology process is used to improve the process for manufacturing riboflavin and in the second, a biotechnology process is used to create a semisynthetic antibiotic. These cases are particularly noteworthy because they demonstrate that significant adoption of a technology is possible within a sector. The pharmaceutical industry differs from many manufacturing sectors in that it goes through rapid change as new products are introduced. In more traditional manufacturing, equipment may be turned over infrequently and thus it can be more expensive to adopt new processes. A comparison of resources and pollution for pharmaceutical and vitamin production from traditional and biotechnology processes is shown in Table 8.

Traditional Processes

1) Production of vitamin B_2, an important food and feed supplement, starts with glucose followed by six chemical steps using hazardous chemicals and generating hazardous waste.

2) Cephalosporin C is one of a class of antibiotics active against certain gram-negative bacteria. The biotechnology process known as the cephalexin process results in a semisynthetic antibiotic that overcomes some of the disadvantages of cephalosporin C, such as low antibacterial activity and a requirement for injection rather than oral dosing.

Industrial Biotechnology Processes

1) The chemically intensive process for production of vitamin B_2 is replaced with a biological process (Figure 11). In the biological process, crude riboflavin is produced directly from glucose with a genetically modified strain of Bacillus subtilis (a gram-positive bacterium). The biotechnology process is less chemically intensive and is based of the use on a renewable raw material (glucose).[93] Use of this process reduced land disposal of hazardous waste, waste-to-water discharge by 66%, air emissions by 50%, and costs by 50%.[94] The market share of the biotechnology method of vitamin B_2 production increased from 5% in 1990 to 75% in 2002 (Figure 12).

---

[93] OECD, "The Application of Biotechnology to Industrial Sustainability," (2001): 60.

[94] *Ibid*, 51-53

Table 8: Resources and Pollution Comparison for Pharmaceutical and Vitamin Production

Resource Consumption and Pollution Generation Using Traditional Processes	Resource Conservation and Pollution Prevented Using Biotechnology Processes	
	Individual Process Savings	Potential Industry-wide Savings
In 1997 and 2000 the pharmaceutical industry reported the following releases:	*Case I: Savings when one facility uses the biotechnology process in producing riboflavin:*[101]	*Data insufficient to determine total benefits due solely to changes in riboflavin and cephalexin production.*
1) Air pollutant releases:[95] 6,586 tons/yr of CO 19,088 tons/yr of NO$_2$ 1,576 tons/yr of PM$_{10}$ 4,425 tons/yr of PT 21,311 tons/yr of SO$_2$ 37,214 tons/yr of VOCs	50% less VOCs 67% less water emissions 75% less nonrenewable materials *Case II: Savings (and actual performance) when one facility uses the biotechnology process in producing cephalexin:*[102]	
2) Total water discharges: 1,429,065 lbs/yr[96]		
3) Wastes (1995): 15 kg/kg cephalexin[97]	3) Waste: ■ In biocatalyst process: 33-66% (10 [1995] to 5 [2000] kg/kg cephalexin) ■ In direct fermentation process: 66-86% (2–5 kg/kg cephalexin)	
4) Organics: 1 kg/kg cephalexin[98]	4) Organics: 80% (0.2 kg/kg cephalexin)	
5) Nonhalogenated solvents: 1.7 kg/kg cephalexin[99]	5) Non-halogenated solvents: 82% (0.3 kg/kg cephalexin)	
6) Halogenated solvents: 0.9 kg/kg cephalexin[100]	6) Halogenated solvents: 100% (0.0 kg/kg cephalexin)	
	Note: Electricity use increases by 50% and water usage increases by 200% with this process.	

---

[95] EPA, Office of Compliance, *Sector Notebook Project: Profile of the Pharmaceutical Manufacturing Industry,* Washington, DC (1997): 75.

[96] EPA Office of Compliance, "2000 Toxic Releases Inventory (TRI) Releases for Pharmaceutical Facilities," (2000) available at *http://www.epa.gov/compliance/resources/publications/assistance/sectors/notebooks/data_refresh.html* (last visited July 1, 2003).

[97] OECD, "The Application of Biotechnology to Industrial Sustainability," (2001): 60.

[98] *Ibid.*

[99] *Ibid.*

[100] *Ibid.*

[101] *Ibid,* 51.

[102] *Ibid,* 60.

2) Biotechnology process improvements involving the use of biocatalysts and direct fermentation significantly reduced waste production and toxicity while improving quality.[103] A 10-step chemical process was replaced by a single fermentation process, eliminating the use of numerous toxic chemicals and reducing the acidity of the wastewater produced. *Carbon dioxide emissions were reduced by 50%, energy demand was reduced by 20%, and water usage was reduced by 75%* (Figure 13).

Figure 11: Biotechnology Example[104]

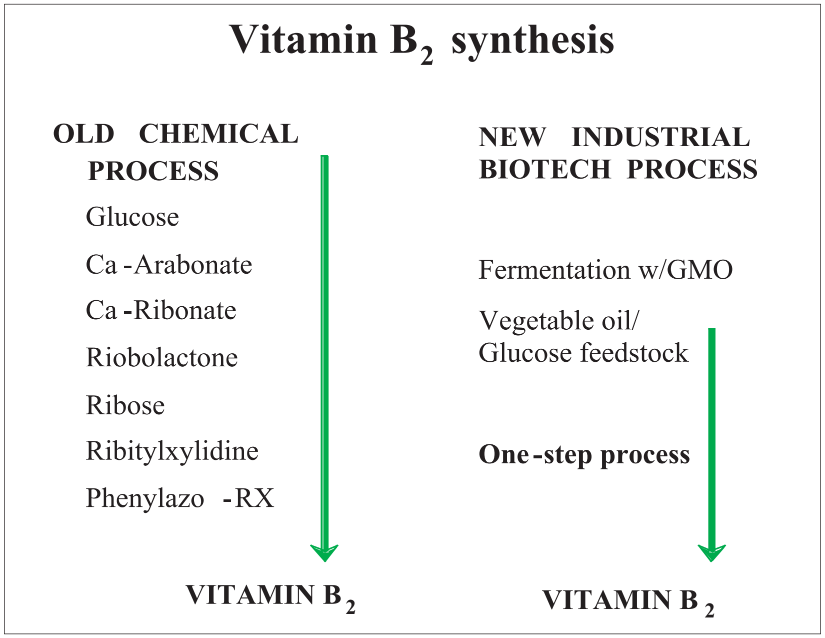


Figure 12: Market Share of Vitamin B2 Production, by Method of Production[105]

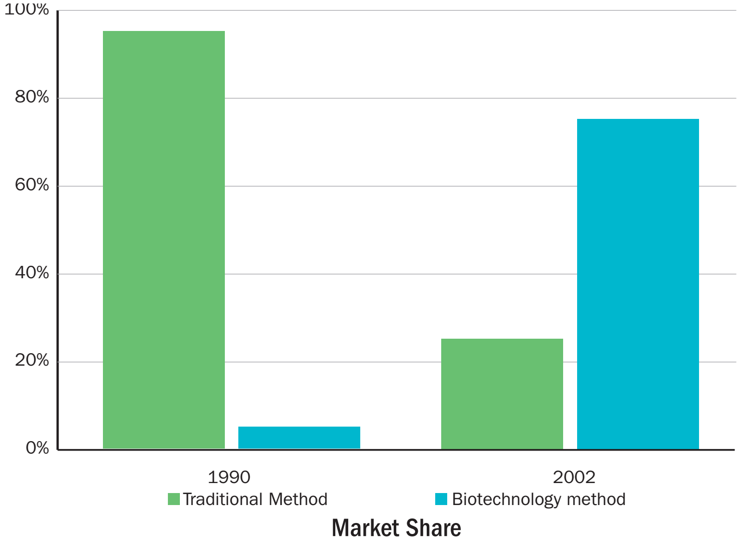
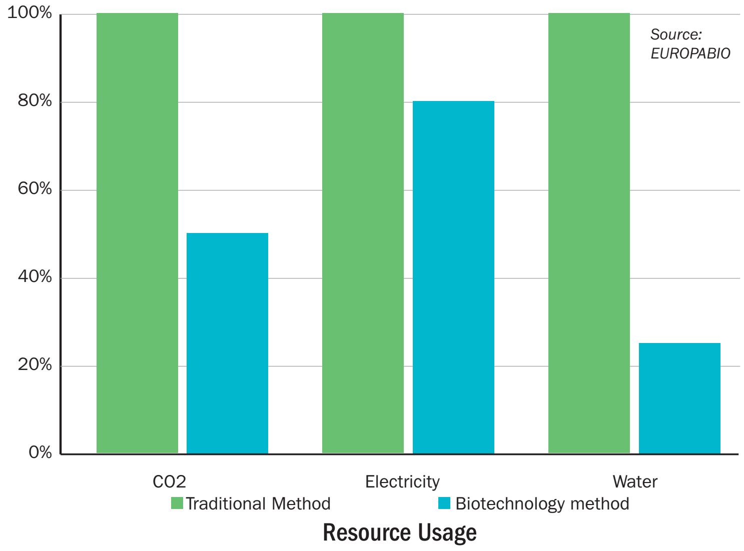


Figure 13: Biological versus Traditional Processing: Analysis of Resource Usage of Antibiotic Intermediate Processing[106]



Source: EUROPABIO

---

[103] OECD, "The Application of Biotechnology to Industrial Sustainability," (2001): 51-53.

[104] *Ibid*.

[105] SOURCE: BASF Powerpoint, presentation by GV Specialty Chemicals Research.

[106] Europabio, "White Biotech," *available at http://www.europabio.org/pages/white_biotech.asp#what* (last visited Mar 16, 2004).

6.6 Additional Examples of Industrial Biotechnology in Action

Energy

There is more to the story of biotechnology and energy than ethanol. Biotechnology is improving extraction efficiency for traditional activities such as drilling for petroleum and is unlocking energy from surprising sources, including sewage sludge.

An enzyme developed by British Petroleum Exploration assists in breaking the cake of mud in the drill stem during horizontal drilling for oil. This enzyme substitutes for hazardous chemicals previously used in this process.[107]

Bacteria are used for treating sewage sludge under anaerobic conditions, producing methane gas as a byproduct. The gas can be collected and used either as an energy source or a feedstock chemical. This process lowers greenhouse gas emissions from sewage treatment and provides an essentially renewable form of methane.

Mining

By studying bacteria found in the high-temperature conditions of hot springs and around oceanic vents, researchers are developing techniques that will allow microbial extraction of various metals. Currently, more than 10% of the copper produced in the United States is leached from ores by microorganisms.[108] The process–known as bacterium-catalyzed leaching–can be applied to crushed copper ores or piles of mine waste. If widely applied, this process could eliminate most of the environmental hazards of copper mining. Additional work is under way to adapt the process to the extraction of other metals, including mercury, cadmium, and arsenic.

Textile Manufacturing

The global textile industry uses more than 40 billion pounds of cotton each year. Cotton wax, a natural component of the outer layer of a cotton fiber, must be removed to prepare cotton for dyeing or finishing. The conventional chemical preparation uses various chemicals at high temperatures. Novozymes North America has developed an alternative that uses an enzyme to scour the wax from the fiber. By using this method, textile mills can cut water, chemical, and energy demand for the process by 30–50%. An industry-wide shift to this process could cut water consumption alone by 45 million cubic meters each year.

Food Processing

Food processing is a water-intensive process that produces a significant amount of organic waste; however, with the use of a biotechnology process there is the potential for significant reductions in both water and waste. A vegetable processing plant run by Pasfrost, a company located in the Netherlands, uses a biological water treatment system that has reduced water usage by 50% and led to significant cost savings.[109] Similarly, the German-based Cereol Deutschland implemented an enzyme-based system for the degumming of vegetable oil. A conventional degumming process uses sulfuric acid, phosphoric acid, caustic soda, and large quantities of water. When the two processes were compared, it was determined that the enzyme system eliminated the need for treatment with strong acid and base, reduced water usage by 92% and waste sludge by 88%, and reduced overall cost by 43%.[110] Moreover, this process has unrealized ancillary benefits in the form of potential energy cost saving and related pollution reductions.

---

[107] OECD, "The Application of Biotechnology to Industrial Sustainability," (2001): 15.

[108] Noorzad, Hazrat, "Biotechnology: Its Evolution, Application and Environmental Implications," Massachusetts Office of Technical Assistance (2000): 15.

[109] *Ibid*, 13-14.

[110] *Ibid*.

6.7 Future Research Needs

This report provides rough estimates and projections that illuminate the significant environmental and energy benefits of replacing traditional industrial processes with industrial biotechnology processes. However, these encouraging results are only a next step and this subject deserves further quantitative and qualitative study and articulation. This report is a solid starting point for further investigation.

Data mismatch and unavailability were obstacles to our providing greater quantitative detail, refined extrapolations, and more sector studies. We required that two main data needs be satisfied for a case to be included in this report. First, it was necessary to have specific estimates of the potential for an industrial biotechnology process to prevent pollution or reduce resource demand. Second, it was necessary to have an estimate of the aggregate pollution output or energy consumption related to the traditional industry process that might be supplanted by the biotechnology process. When sufficient data were available for both, we extrapolated the potential benefit on a sector-wide basis. This important preliminary work should be expanded through additional government and private research efforts.

Most of the data sources used for this report were created for other regulatory reporting purposes (such as the EPA Sector Notebook Project profiles) and more often than not were of only partial use in this analysis. Many existing industrial biotechnology processes could not be included because of a lack of specific data in one of the prerequisite data sets. In some cases, information on savings for an individual process was available but no sector-wide data were available from publicly available sources. In other cases, such data were available but were not subcategorized for the discrete portion of the manufacturing process that biotechnology could address. In still other cases, the available data on processes were simply not specific enough to allow comparisons with publicly available data.

Despite these obstacles, the data collected and the results of our analysis presented here make a potent and compelling case for a more extensive effort to quantify the potential benefits of industrial biotechnology. Such information will prove useful to policymakers, regulators, the regulated community, NGOs, and the general public. Future studies on this subject should go well beyond a review of emissions and resource consumption data and include an economic analysis to more fully quantify cost savings from adopting these new technologies as well as the potential costs for transitioning to them. Such studies may be helpful in assessing what policy changes or incentives are necessary to shift the demand for innovative biotechnology processes. Sections 6.1 and 6.2 reference potential barriers to further deployment of industrial biotechnology related to the industrial sectors discussed. These examples are indicative of the larger question of barriers that warrants further study.

Areas for Further Study

The BIO Industrial and Environmental Section is committed to working with interested parties, including industrial customers, government entities, and NGOs, to further delineate the scope of benefits of industrial biotechnology. To improve the research contained in this report and further clarify the areas in which industrial biotechnology could provide environmental benefits, we recommend the following steps:

- Existing and emerging biotechnology applications should be further studied to assess potential cost savings and to determine the value of speeding voluntary adoption in additional manufacturing sectors. This effort should quantify economic benefits of biotechnology in specific industries.
- Greater investigation of available emissions data from public and

private sources should be undertaken. Much of the necessary data exists but is not published or is not in easily accessible formats.

- More work should be done to quantify the pollution prevention, natural resource conservation, energy, and societal benefits of emerging industrial biotechnologies.
- New studies should be initiated to quantify the public health benefits achievable through greater use of industrial biotechnology. Reducing toxic raw materials, intermediates, and emissions should confer health benefits to both employees of industrial facilities and the general public.
- Because the use of industrial biotechnology is rapidly spreading worldwide, organizations such as OECD and the European Commission should assess the potential for pollution prevention in Europe and Asia.
- Studies should include an economic and social analysis to quantify cost savings, job creation benefits, and costs that can develop as biobased industries arise and traditional industries are disrupted or restructured.

This report does not focus on the mitigation of greenhouse gas emissions although industrial biotechnology offers several pathways for such reductions including energy savings and the use of biomass instead of petroleum as feedstock. Research is under way to produce biohydrogen from algae or bacteria. These and other processes are likely to have a significant impact on greenhouse gas emissions and will be the subject of a separate report.

Specific Examples of Research Needs

- **Textile Industry:** To thoroughly analyze the impact on enzymatic replacement of stonewashing, data are needed on the amount of pollution or resource damage created by pumice mining and on the energy requirements for mining, preparing, and transporting pumice versus the energy required to make and transport enzymes for stonewashing.
- **Plastics Industry:** Greater definition is needed of the quantities of petroleum used for each part of the manufacturing process. In some cases, petroleum savings related to the production of PLA were not separated by feedstock and energy uses. New bioplastics (from 1,3-propanediol and polyhydroxyalkoanates) are emerging and should be included in future investigations.

  More detail is needed regarding the air emissions and water discharges avoided in manufacturing PLA versus traditional plastic manufacturing. Again, the specific chemical reactions that lead to various waste compounds from plastic manufacturing must be well understood by the process experts, but such information was not available for this report.
- **Ethanol Industry:** Life cycle estimates for emissions and energy consumption related to the production of ethanol and bioethanol vary and sometimes conflict. More reliable estimates are needed so that researchers can accurately compare these products with each other and with petroleum-based fuels. Measures or estimates of impact on carbon dioxide emissions should be a central part of this research.
- **Nutriceutical and Pharmaceutical Industry:** Little information was readily available about the wastes produced or energy consumed by the production of any individual pharmaceutical product. Future research should attempt to define the per-unit pollution and energy demands for traditional pharmaceutical manufacturing versus processes that incorporate industrial biotechnology steps.

7. Policy Considerations

There are different types of environmental regulations. Some prescribe the specific actions or technologies that must be used for compliance. Others set standards of performance that may be met in a variety of ways. Both of these regulatory approaches could play an important role in encouraging the development, testing and ultimately the deployment of technology innovations such as new industrial biotechnology processes. However, current regulations often seem to discourage the development and adoption of many technology innovations, including industrial biotechnology, for compliance.

Industrial biotechnology has matured to the point that its potential to deliver public benefits now warrants consideration of how it might appropriately be treated in public policy. In this section, we review several existing environmental statutes and regulations to identify options for encouraging technological innovation from industrial biotechnology. Our review results in a list of potential options for modifying existing programs. Development of this list also points to the option of developing an entirely new framework to address both the hopes and concerns related to greater diffusion of these technologies.

The list presents an intriguing set of potential opportunities to provide incentives for biotechnology. It is important to note, however, that this list in only meant to inspire further discussion. It is understood that policymakers, industry, NGO's and the public will be cautious about modifying existing policies to promote industrial biotechnology until they have been convinced of both the merits and the safety of industrial biotechnology products and processes.

Existing environmental regulations tend to be geared toward end-of-pipe, command-and-control clean-up technologies and often do not encourage—or even recognize—the benefits of adopting innovations such as biotechnology-based process changes.

Clean Air Act (CAA)

Greater substitution of industrial biotechnology manufacturing processes for traditional processes could reduce air pollution from a variety of sources. Some of the CAA's programs result in specific emission limitations that are included in an operating permit and would not necessarily discourage the use of industrial biotechnology. Much of the CAA is driven by the requirement that states meet overall air quality standards while individual facilities use prescribed emission control equipment. In many cases, conversion of an existing conventional process or part of a process to an industrial biotechnology process would make both economic sense (for the facility) and environmental sense (reducing local or regional air pollution). However, if the conversion does not meet the CAA technology requirements, it may be dismissed as a viable option. Specific areas for policymakers to consider for increasing the flexibility of the CAA might include

- *allowing states to get credit in their state implementation plans for emission reductions that are related to industrial facilities voluntarily converting to biotechnology processes that are less polluting;*
- exploring ways to quantify emission reductions related to biotechnology conversions and allow those who create such reductions to *participate in emission trading market activities;*
- exploring the possibility of i*ncluding certain industrial biotechnology processes in the definitions of technology-specific programs, including the RACT, BACT, LAER, and MACT definitions;* and
- allowing industrial biotechnology to *become eligible for pollution control technology research grants under the CAA.*

Clean Water Act

State and federal water programs are increasingly beginning to incorporate flexible permit programs that are less burdensome for the regulated community but ensure steady progress toward the water quality goals. Policymakers should consider the potential for greater use of industrial biotechnology to complement these ongoing efforts. Many of the permit programs should be examined by policymakers to ensure that, where appropriate, *permits issued under the Clean Water Act include incentives for permit holders to use industrial biotechnology* when it will result in less-polluted effluent being released into the nation's waterways.

Energy Policy Act

Industrial biotechnology processes could have sweeping consequences for the future of energy production and consumption in the United States. Industrial biotechnology can be used to produce energy products such as ethanol. It can also reduce the energy used in various manufacturing activities such as paper production. Future efforts to consider national energy policy should encourage greater deployment of industrial biotechnology where it is consistent with other national energy objectives such as reduced dependence on foreign oil. *Funding should be made available under the existing law, or required by any revision to existing law, to assist in the development of the nation's first biorefining industry.* This would enable a robust exploration of all of the technical, legal, and market implications of using biotechnology to replace oil consumption with the use of renewable resources.

EPA Pollution Prevention Innovation Strategy

EPA should explicitly include industrial biotechnology in its pollution prevention innovation strategy and should aggressively promote this technology where its effectiveness has already been demonstrated. An initiative similar to *EPA's source reduction review project could be undertaken to assess how new regulatory programs could achieve the dual goals of protecting the environmental while encouraging a shift to more sustainable industrial practices.*

National Environmental Policy Act

The President's Council on Environmental Quality (CEQ) created by the National Environmental Policy Act is charged with looking at environmental issues that cut across the jurisdiction of multiple government agencies and departments. Greater deployment of industrial biotechnology can result in benefits ranging from improved environmental protection to greater national security; industrial biotechnology can be used in nearly every sector of the economy including transportation, energy, and manufacturing. The broad scope of opportunity presented by industrial biotechnology fits well with the mandate given CEQ for addressing multifaceted environmental issues. *CEQ should* *actively undertake specific activities to explore the myriad national benefits of industrial biotechnology and recommend ways to realize those benefits.*

Pollution Prevention Act

State grants authorized by the Pollution Prevention Act should add a focus on exploring the practical opportunities and limits of greater deployment of industrial biotechnology for pollution prevention. *These grants should also be made in a manner that will provide feedback about government policies that encourage or discourage the use of industrial biotechnology in cases where it would lead to environmental benefits.* Also, data related to industrial biotechnology should be collected and made available as part of the source reduction clearinghouse authorized in the act.

Toxic Substances Control Act

Policymakers should encourage the numerous benefits of reduced toxic substance usage, disposal, and release into the environment that could be driven by an increase in industrial biotechnology. Government authorities should ensure that industries regulated under the Toxic Substances and Control Act are aware of these benefits. *Equally important, policymakers should ensure that any new reporting requirements triggered by the use of industrial biotechnology processes are defined quickly so that market decisions are not disrupted and the realization of environmental benefits produced by biotechnology is not inadvertently or unnecessarily hindered.*

We believe that lawmakers, policymakers, regulators, the regulated community, nongovernmental organizations, the press, and the general public could all benefit from the information in this report and in the OECD report on which it is based. Because industrial biotechnology has the potential to achieve environmental benefits and cost savings at the same time, it is a powerful tool for solving many difficult environmental challenges without causing financial hardship to business or consumers. Existing environmental regulations tend to be geared toward end-of-pipe, command-and-control cleanup technologies and often do not encourage–or even recognize–the benefits of adopting innovations such as biotechnology-based process changes. We also believe that efforts should be undertaken to study the development of policy mechanisms that provide incentives for such change rather than disincentives.

We recognize our enthusiasm for industrial biotechnology will be met with cautious reactions by some. Industrial biotechnology encompasses a multitude of products and processes. Some industrial biotechnology applications will necessarily encounter greater levels of public policy scrutiny. This is both appropriate and welcome. We view industrial biotechnology as a very promising technology, but not a panacea. Rather, it represents a vast new set of powerful and beneficial tools. Helping fit the appropriate tools to the appropriate jobs is a key goal. As stated elsewhere in this document, BIO believes that greater scrutiny of industrial biotechnology will lead to greater enthusiasm for its use. But we do not presume to skip over the need for full discussion of policy implications and the public interest in order to realize the maximum public benefits of this new technology.

8. Conclusions

This report attempts to take the next step in answering the question: **What if industrial biotechnology were more widely used?** *The answer is that industrial biotechnology can revolutionize pollution prevention, control, and innovation strategies and overall environmental protection strategy. Furthermore, industrial biotechnology can revolutionize how goods are manufactured.* Industrial biotechnology is revolutionary because it provides new tools for the manufacturing sector that not only reduce pollution but reduce costs and improve profitability all at the same time.

During the past half century, advances in biotechnology have launched a new wave of biotechnology–industrial biotechnology–which offers new tools to safely reduce manufacturing costs and consumption of energy and raw materials; it also promises the creation of new markets for innovative products that are superior to existing ones.

The analysis articulated in this report can–and should–be expanded in numerous directions. For example, greater use of industrial biotechnology will have multiple upstream and downstream consequences. We believe that further study will show these to be overwhelmingly beneficial. Nevertheless, quantifying the benefits and addressing trouble spots before they become problems necessitates additional work.

Given the wide scope of industrial biotechnology in terms of business sectors it would be futile for this report to attempt to address every question. This document should encourage enough interest so that corporate, government, and NGO entities will join our future efforts to frame questions and find answers.

What could this mean for our future? As previously stated, the sectors examined in this report may account for up to 40% of energy use, 50% of industrial pollution, and are also a significant contributor to greenhouse gas emissions. With accelerated diffusion of industrial biotechnology into these sectors, rapid and dramatic environmental improvements are possible. Because industrial biotechnology reduces–and in some cases eliminates–industrial waste, businesses will spend less on cleanup, disposal, and control of pollution. Bioprocessing primarily uses renewable agricultural products, such as corn, corn stover, wheat straw, rice straw, and other materials, as raw feedstocks and it could provide new markets for these agriculture crop residues. *Industrial biotechnology is on the leading edge of a green industrial revolution.*

Admittedly, the analysis provides an overview at best; however, even this rough overview reveals that the potential magnitude of benefits is startling. As described in this report:

- Biotechnology process changes in the **production and bleaching of pulp for paper** *reduce the amount of chlorine chemicals necessary for bleaching by 10–15%.* If applied across the industry, these process changes could *reduce chlorine in water and air as well as chlorine dioxide by a combined 75 tons per year.* Biotechnology processes cut bleaching-related energy uses by 40%–a savings that has the potential to create additional pollution reductions–and *lower wastewater toxicity.*
- Biotechnology process changes in the **textile finishing sector** *reduce water usage by about 17–18%, cost associated with water usage and air emissions by 50–60%, and energy demand for bleaching by about 9–14%.*
- Biotechnology process changes in **plastics production** replace petrochemical feedstocks with feedstocks made from organic material such as corn or even corn stovers, thereby *reducing demand for petro-*

chemicals by 20–80%. Because these bioplastics are biodegradable, their use could also *reduce plastics in the waste stream by up to 80%*. Waste burdens are reduced partly because disposable food service items such as plates, cups, and containers can be composted along with the food waste, eliminating the need for separation. These bioplastics can be used to make products ranging from clothing to car parts, all of which can be composted instead of disposed in landfills or incinerators.

- Biotechnology process changes allow for **bioethanol production** not only from corn but from cellulosic biomass such as crop residues; *bioethanol from cellulose generates 8 to 10 times as much net energy as is required for its production. It is estimated that one gallon of cellulosic ethanol can replace 30 gallons of imported oil equivalents*. The closed-loop nature of *using cellulosic biomass to produce bioethanol can contribute substantially to the mitigation of greenhouse gas emissions* and can help provide a partial solution to global warming.
- Biotechnology process changes in the **nutriceutical and pharmaceutical sector** in the production of riboflavin (vitamin B_2) *reduce associated carbon dioxide emissions by 80% and water emissions by 67%*. Changes in the production of the antibiotic cephalexin *reduce carbon dioxide emissions by 50%, energy demand by 20%, and water usage by 75%*. The market share of the biotechnology method of vitamin B_2 production increased from 5% in 1990 to 75% in 2002.

Many biocatalytic tools are becoming available for industrial applications because of the recent and dramatic advances in biotechnology techniques. In many cases, the biocatalysts or whole-cell processes are so new that many companies are not yet aware that they are available for deployment. This is a good example of a technology gap where there is a lag between availability and widespread use of a new technology. This gap must be overcome to accelerate progress in developing more economic and sustainable manufacturing processes through the integration of biotechnology. In addition, public officials in the environmental policy apparatus in the United States seem only vaguely aware of the existence of these new biotechnology tools and their ability to "green" the industrial landscape.

This report is an attempt to stimulate action by key stakeholder groups, including corporations, policymakers, NGOs, the agricultural community, and the general public. Specific findings, recommendations, and suggestions for further research follow. For industrial biotechnology to deliver on its potential to revolutionize pollution prevention, control, and innovation strategies and current environmental protection strategies, it needs to be tested, adopted, and deployed. In fact, industrial biotechnology is creating a new industrial revolution where man and DNA are working hand in glove to green the industrial landscape. The future is now.

Snapshots

Key Findings

- Industrial biotechnology offers the private sector remarkable new tools for pollution prevention that have not been widely available before now.

- These new tools not only prevent pollution but can also significantly cut energy demand, natural resource consumption, and production costs while creating high-quality intermediates or consumer products.

- Accelerated uptake of new industrial biotechnology processes could lead to further pollution prevention, waste reduction, and energy cost savings in related services such as waste disposal or energy production.

- Public policies and regulations do not provide adequate incentives for technological innovations, such as biotechnology-based pollution prevention and energy savings.

- The industrial biotechnology processes used in this analysis involve cutting-edge technologies. More research and development must be undertaken to increase the utility and efficiency of these biotechnology processes across a broad range of industrial applications.

Recommendations

- Corporate leaders should review the benefits of industrial biotechnology processes by placing them on the agendas of their boards and business units.

- Corporate, governmental, and nongovernmental organization stakeholders should work together to further define issues for analysis and identify next steps that could accelerate the uptake of specific industrial biotechnology processes.

- Policymakers should make a concerted effort to learn more about the wide range of industrial biotechnology applications and environmental benefits that can be derived from greater deployment of these biotechnologies.

- Federal and state policymakers should fund research that will quantify the pollution prevention benefits of this technology in greater detail to assist policy decision making.

- Policymakers should explore incentives for greater use of industrial biotechnology to accelerate pollution prevention and cleanup of the environment; approaches may include the incorporation of industrial biotechnology into regulatory and nonregulatory programs.

- International organizations such as the United Nations Conference on Trade and Development and the United Nations Industrial Development Organisation should help developing countries understand that these processes can contribute to economic development with less pollution. They should help identify appropriate technologies that can be readily adopted by the developing world and strategies for technology transfer.

- National representatives of countries participating in the Johannesburg Summit on Sustainable Development should seek to include specific references to industrial and environmental biotechnology in the implementation program resulting from the summit.

Areas for Further Study

Because data were not always available for specific processes being reviewed, estimates in this report often indicate trends or estimates rather than precise measurements. Furthermore, some factors of pollution reduction are not covered in U.S. government databases so that the total benefits are not fully described. Additional studies are needed to improve and expand on the information contained in this report and to clarify areas in which industrial biotechnology could provide environmental benefits. The research priorities are as follows:

- Existing and emerging biotechnology applications need further study to assess potential cost savings and to determine the value of speeding voluntary adoption in additional manufacturing sectors. This effort should quantify the economic benefits of biotechnology in specific industries.
- Greater investigation of available emissions data from public and private sources is needed. We believe that the much of the necessary data exist but are not published or are not in easily accessible formats.
- Further study is necessary to more accurately quantify the pollution prevention, natural resource conservation, and energy and societal benefits of emerging industrial biotechnologies.
- Studies are needed to quantify the public health benefits that could be achieved through greater use of industrial biotechnology by the private sector because reducing use of toxic chemicals can confer health benefits to both employees of industrial facilities and the general public.
- Because use of industrial biotechnology is rapidly spreading worldwide, organizations such as the Organisation for Economic Co-operation and Development, the European Commission, and others should also undertake assessments of pollution prevention potential in Europe and Asia.
- Another key component for study should be an economic and social analysis to quantify cost savings, job creation benefits, and transition costs that can develop as biobased industries arise and traditional industries are disrupted or restructured.

Policy Considerations

Increased Flexibility

- Opportunities may exist within the *Clean Air Act* to increase the flexibility of states and companies to use industrial biotechnology to help meet environmental goals. These opportunities may include options to allow states to get credit in their state implementation plans for emission reductions related to use of industrial biotechnology; emission reductions related to industrial biotechnology in existing emission trading markets; and certain industrial biotechnology processes in the definitions of allowed or preferred technologies in technology-specific programs, such as RACT, BACT, LAER, and MACT.
- Opportunities may arise under the *Clean Water Act* to include incentives for permit holders to use industrial biotechnology when it will result in less pollution.
- The Environmental Protection Agency may be able to explicitly include industrial biotechnology in its *pollution prevention innovation strategy*. Its *source reduction review project* could be undertaken to assess how new regulatory programs could achieve the dual goals of protecting the environmental while encouraging a shift to more sustainable industrial practices.

Funding

- Additional funding for the use of industrial biotechnology may be possible under the *Energy Policy Act* to assist in the development of the nation's first biorefining industry.
- Industrial biotechnology projects may be eligible for the grants under the *Clean Air Act's* research program on pollution control technology.
- There may be opportunities to add a focus on exploring the practical opportunities and limits of greater deployment of industrial biotechnology for pollution prevention to the state grants authorized by the *Pollution Prevention Act*.

National Policy Initiatives

- The *Council on Environmental Quality* may be able to proactively assess the myriad national benefits of industrial biotechnology and recommend ways to realize those benefits.

Outreach

- Opportunities may arise to inform industries regulated under the *Toxic Substance Control Act* of the numerous benefits of reduced toxic substance usage, disposal, and release into the environment that could be driven by an increase in industrial biotechnology. Government may be able to work with industry and environmental stakeholders to ensure that new reporting requirements triggered by the use of industrial biotechnology processes are defined quickly so as to facilitate rather than discourage use of these processes.

Appendix I: History of Industrial Biotechnology

Note: The following is an edited excerpt of the Joseph Priestly Society Lecture delivered by BIO President Carl B. Feldbaum September 11, 2003.

When scientists Stanley Cohen and Herbert Boyer met at a conference in Hawaii almost 20 years after the double-helix discovery, they quickly realized that Cohen's plasmid and Boyer's DNA-cutting enzyme would make a patentable recombinant DNA machine. Two years later, Boyer and venture capitalist Robert Swanson teamed up to create Genentech. Soon, with the added push of the 1980 Bayh-Dole Act streamlining technology transfer, dozens of professors in Cambridge, Massachusetts, and San Francisco were patenting their discoveries and seeking to partner with the business community. The biotechnology industry was off and running.

The fledgling companies that resulted had thick portfolios of ideas but little experience developing complex products and bringing them to market. In the industry's early days, biotechnology companies partnered not only with pharmaceutical firms but with oil, agricultural and chemical companies, and even distilleries. It was clear to biologists from the outset that biotechnology could provide novel enzymes and whole-cell systems capable of making industrial processes cleaner and/or more efficient and could perhaps even create new products, such as biobased materials or organisms that convert environmental toxins to harmless substances.

Industrial biotechnology drifted to the backburner by the mid-1980s. It had become apparent that even though health care posed the most formidable regulatory obstacles, it was usually the only avenue of development that offered sufficient marketplace rewards to justify the enormous cost of overcoming technical and production hurdles to commercializing recombinant DNA products.

Health care, thus, was the first wave of biotechnology, followed about a decade later by agriculture. Industrial biotechnology is now finally poised to come of age as the third wave of biotechnology. What changed in 20 years? The technical and cost hurdles that shuffled industrial applications to the backburner in the 1980s have largely been overcome. Bioprocesses are stable, high-yielding, and cost-competitive–or even offer cost advantages–in many chemical applications, plus they offer a public acceptance edge over chemical processes.

The Organisation for Economic Co-operation and Development says that biotechnology should be on every industrial agenda. According to McKinsey & Co., "Biotech is technologically ready for take-off and will be one of the key innovation drivers over the next 10 years in chemicals." And the National Academy of Sciences' National Research Council has predicted the industrial impact of the biological sciences in the 21st century will be as great as that of the physical and chemical sciences in the 20th.

The media seems to be getting the message. *The Economist* opined in the spring of 2003, "What is needed is an industry that delivers the benefits without the costs. And the glimmerings of just such an industry can now be discerned. At the moment, biotech's main uses are in medicine and agriculture. But its biggest long-term impact may be industrial."

The Technologies

Industrial and environmental biotechnology applies the technologies that have transformed health care and agriculture to manufacturing processes and environmental remediation. These technologies include recombinant DNA, genomics, proteomics, gene shuffling, high-throughput screening, metabolic engineering, and advanced fermentation. Their applications are broad and include the discovery and manufacture of industrial enzymes, the development of enzymes and whole-cell technologies for chemical manufacture and synthesis, and biological solutions for energy production.

As an indicator of just how quickly the transition to a biobased process can occur, in 1990 biotechnology was used for 5% of the production of vitamin B2. By 2002, production of vitamin B2 had expanded 250%, with biotechnology accounting for 75% of the total. Most consumers are not even aware of the role biotechnology plays in this and other common products, but the technology is really already everywhere we look. Indeed, biotechnology processes translate into cleaner, more efficient, and often cheaper ways of making everyday products such as faded blue jeans, detergents, plastic cups, contact lens cleaner, antibiotics, cheese, and fructose for soft drinks.

In the future, further value will be created by using biotechnology to transform production of additional products, including fine chemicals, fuel and polymers, and by creating enzyme- and whole-cell-based processes that aid the manufacture of many other products.

Some of the largest opportunities, at least in terms of volume, lie in the conversion of plant material–biomass–into polymers and fuel. In 2002 the world's first modern biorefinery, a Cargill-Dow project, came online in Blair, Nebraska. The plant converts the sugar in corn to polylactic acid (PLA) and from there into biodegradable polymers that can be used to make a wide array of products, including plastic cups and containers, wrappers, carpeting, and polyester textiles. In addition to these products being biodegradable, biomass-produced PLA can reduce fossil use in plastic manufacture up to 80%; if all plastics were made from PLA, this would translate into annual savings of 90–145 million barrels of oil per year–or about one week's worth of U.S. oil consumption.

The goal now is to find and develop new enzymes that break up cellulose–the tough cell wall substance that gives plants their rigidity–so that agricultural waste such as leaves, stalks, hulls, and husks as well as wood-processing waste such as chips and sawdust can also be used as feedstock. Dissolving the cellulose would enable production of sugars that could be used not only to make polymers but also that other high-volume petroleum product, fuel.

The environmental, political, and economic benefits of this technology are impressive: cleaner-burning fuel and biodegradable materials, replacement of a limited resource (petroleum) with renewable biomass resources, less reliance on foreign suppliers of petroleum, and a new outlet for agricultural production. This concept is so compelling that biomass conversion measures consistently win bipartisan support in the United States and are popular in Europe, where governments are committed to implementing the Kyoto climate change accords.

The momentum we are seeing really started with the release of the National Academies report on industrial biotechnology in 1999. That same year, President Clinton set up infrastructure within federal agencies to support development of a bioeconomy, and in 2000 Congress passed the Biomass Research and Development Act. In 2001 the Organisation for Economic Co-operation and Development issued a report, *The Application of Biotechnology to Industrial Sustainability.* 2002 brought passage of comprehensive farm legislation that, for the first time in history, contained a bioenergy title. In 2003 a House-Senate conference produced comprehensive energy legislation that includes $830 million in bioenergy incentives. The House passed the conference report and the Senate is slated to take it up in 2004.

Public Perception

Biotechnology has been front and center in the public eye from the outset: from the controversy over the ethics and safety of recombinant DNA in the 1970s to ongoing debates about agricultural biotechnology. The good news is that industrial biotechnology wins ready acceptance among the public. In focus groups, people describe it as working in concert with nature. They associate enzymes with laundry detergent cleaning power. They like the idea of using biomass instead of petroleum and biological processes instead of chemical synthesis. They like the fact that industrial enzymes are produced in contained fermentation systems.

A minor hurdle remains for this technology's broader incorporation into chemical processes: the expertise gap. Whereas medical and agricultural scientists have always been immersed in biology–and hence biotechnology techniques were a natural step on the continuum of progress–chemists and chemical engineers typically have little experience working with biological systems and technologies or with thinking in terms of biological solutions to chemical problems. Obviously, this is not an insurmountable barrier.

Industrial biotechnology started off slowly but is rapidly gaining speed. It promises to revolutionize the way we use agricultural feedstocks and the way we make chemicals and consumer products. Industrial biotechnology will do all of these things and, in most cases, at lower cost. It will offer social and environmental benefits in the form of prevention pollution–a revolutionary advance over command-and-control systems. More work needs to be done to develop industrial biotechnology processes and to measure their benefits but it is clear that when the third wave in biotechnology washes over the industrial landscape, it leaves our planet a cleaner place to live.

Appendix II: Opportunities for Biobased Plastics

This talk was presented by Barbara Miller, technical director of the Dow Chemical Company at the Agricultural Outlook Forum on February 23, 2001. It illustrates not only the benefits of and barriers to industrial biotech but also discusses its potentially disruptive nature.

Good afternoon, and thank you. It is a pleasure to be here and share with you my thoughts on opportunities for biobased plastic products in the chemical industry. Looking at the effect of biotechnology on our industry, five major thoughts come to mind:

1) If history repeats itself, biotechnology, like other new sciences in the past, will not evolve exclusively in a life sciences mode. Instead, it will converge seamlessly with other sciences to create new applications and even new industries.

2) This technology is potentially disruptive. It will compete with existing chemical technologies at a low level for some time and then roll forward in a groundswell.

3) Evidence for this evolution exists already. There are many examples of biotechnology's ability to create innovative new products and processes.

4) This technology is not mature; it has many missing links that need to be worked on.

5) And finally, as an industry or industries, we need to take collectively all the public policy actions that allow the power of the technology to unfold.

Convergence

So, let's first go to the notion of seamless convergence of biotechnology with other sciences. The 20th century is known as the century of physics and chemistry. These were the dominant sciences that fed on each other to create an endless stream of new materials, products, processes, and equipment at ever-higher performance and at ever-lower cost. Without chemistry, no pharmaceutical industry. Without silicon, no information technology. The 21st century is already earmarked as the century of biotechnology. The addition of biotechnology to an already impressive arsenal of sciences will over time impact every facet of our lives. This co-evolution and convergence has begun: bioethanol as energy, genetically enhanced seeds for improved food, biomaterials, biopharmaceuticals are all for real already; biosensors and biocomputers are on the lab bench. The power of this technology is much broader than just Ag, nutrition and pharma.

Convergence takes time. All of the major chemical discoveries that make up today's large uses were discovered in the 30's, 40's and early 50's. It took the chemical industry 30-40 years to convert the initial scientific discoveries into reliable and large-scale use. By large-scale use, I mean low cost and high performance materials, made with safe production technologies and used with Responsible Care®. As examples, nylon and polyethylene were discovered in the late 30's. These initial products had nothing in common with the packaging materials or clothing fibers we use today. Only a massive amount of new science and new knowledge enabled this performance improvement over time.

Disruption

For the chemical industry, biotechnology is likely to be disruptive. This is what a study by the National Research Council of the U.S. predicts. The prediction of 10% liquid fuels and 25% organic chemicals production from biofeedstocks by 2020 is viewed by many as very reachable, if not conservative. Today, 1-2% of liquid fuels are made up by essentially bioethanol. For organic chemicals and polymers, 10% of today's world production is biofeedstock based. These are mostly fermentation based organic and amino acids, enzymes, bulk antibiotics, vitamins and the like. The current worldwide production of fermentation based products including bioethanol is already 10 billion pounds, worth about 4.5 billion dollars and growing at 7-8% yearly.

The oil based chemical industry we know today was rapidly built to an enormous scale, turning out low-cost products with good quality and applications profiles. The key competencies developed over the years were catalysis, chemical engineering and material science. It is easy to visualize a possible future duality in feedstock's and processes. The existing commodity grain and oil processing infrastructure produces the carbohydrates needed for bioprocessing in the form of sugars. Technology and specialty processing is put in place in order to also use plants as factories and express specific oils, biopharmaceuticals or polymers in identity preserved crops. However, bioprocessing is significantly different from conventional chemical processing, with operations conducted on mostly solid feedstocks without pressure or heat and mostly in an aqueous medium. In order to participate in this future duality in feedstock's and processes, Dow's Industrial Biotechnology Business Vision is to transform renewable resources into existing or new value added products. Our core strengths in process engineering and low cost production provide us a competitive advantage in new product development from biotechnology.

Let's take a closer look at large scale bioprocessing. In order to be useful economically, biocatalysis, either fermentation or enzymatic conversion needs to be matched with efficient bioreactor, separation and recovery designs. As mentioned already, the dilute aqueous media operation adds a lot of cost. So the challenge is not to lose the benefits of low-cost biobased feedstock's through excessive downstream processing costs. And plant expression has similar engineering challenges in separation and recovery. The advent of genetically enhanced host systems in the late 90's that brings about new exciting prospects for the chemical industry. New enabling technologies create an enormous diversity potential for biocatalyst discovery and development. In addition, metabolic engineering enables pathway shunts and elimination of side products, thereby improving yields and reducing separation costs. These capabilities will result in a dramatic upgrade of the bioprocessing tools available So, looking ahead, we can identify three major driving forces that will create disruptive change in the chemical industry: First, biotechnology is a powerful source of innovation for new products. New products are the lifeblood of companies, critical to business renewal and growth. And they respond to profound societal aspiration, by now even expectation. Second, biotechnology can demonstrate improved economics. Not only lower feedstock costs, but also lower investment and operating costs. Significant potential business value can be captured here. Finally, there is the promise of products with reduced environmental footprint.

Innovation/New Product Development

Let me now give a few examples, from Dow that illustrate the progress being made. New plastic product opportunities are envisioned from bio-derived oleochemicals. Convergence of Dow's low cost processing expertise with bioderived materials offer the opportunity to develop products with new attributes or lower cost plastics for existing markets. Discovery R&D is occurring now through an Oilseed Engineering Alliance to discover options for enhancing plant oils so they can be used to replace traditional petrochemical based raw materials in chemical manufacturing.

The next example is one of a large volume, lower price product. Last January, Cargill-Dow announced the construction of a 300MM pounds polylactic acid plant and 400MM pounds lactic acid unit. Polylactic acid is the first polymer produced from renewable resources that competes with high volume products such as Nylon, PET and polyethylene and this in a multitude of large applications. The production process involves dextrose fermentation to lactic acid, followed by a dehydration to lactide. Polymer production takes place in a conventional polymerization process using a chemical catalyst. The dextrose to lactic acid route has 100% theoretical yield and conserves all the carbon, thereby making it an economically favorable configuration. This slide shows some of the key performance attributes of PLA in a variety of packaging applications.

- in candy wraps, PLA replaces cellophane
- in bottles, PET
- in paper coating, polyethylene
- in rigid containers, again PET

This demonstrates quite a broad performance spectrum and a good price/performance value proposition for PLA! We see the same versatility in fiber applications. PLA competes advantageously with nylon and polyester and can be blended with other natural fibers such as cotton. Woven cloth made from PLA fibers has a silk like feel to it. It also unique wicking and moisture management characteristics, in addition to other valuable attributes. Life cycle inventory data such as gross energy requirements shown on this slide gives a good measure of comparative sustainability of products. About a third of PLA's energy requirement comes from sunlight. So PLA's consumption of fossil fuel energy compares favorably with all competitive products. And this data includes all energy needs from cradle to grave, from farming input for corn to the disposal of the material.

We see a lot of evidence that biotechnology and bioprocessing are becoming useful tools in the hands of chemical engineers. I showed you a few examples just now; and there is a lot more exploration and product development effort underway in oil, chemical and biotechnology platform companies. There are, however, some missing links on the way to a broader use base. This chart from the U.S. Council for Chemical Research describes the overall knowledge and experience base for the two sets of feedstock's and processes. The chemical processes using fossil fuels are mature, with decades of experience. Bioprocessing of renewable resource feedstock's is emerging, but still has a narrow working base.

To be truly successful, we will have to bulk up the lower right hand quadrant with substantially more knowledge. Just a few biotechnology challenges to be solved, by way of example:

- technology to access potentially fermentable sugars in lignocellulosic biomass
- single microbial systems to efficiently convert 5 and 6 carbon sugars
- biocatalysts which can operate in solvent media.

Public Policy

Our experience in the Chemical Industry has taught us that communication and outreach are the basis for transition and change management. It is vital to discuss our viewpoints and knowledge with all stakeholders. Trust and credibility is only built if safety is foremost on our mind and scientific uncertainty questions receive credible answers. Ours must be the highest standards of ethics at all times, documented by clear guiding principles and transparent industry behavior. And solidarity and performance by all industry peers or value chain members is what makes or breaks this effort. So, in analogy to the Chemical Industry, a set of Responsible Care principles will be an absolute must for future success of this technology.

In summary, I have talked this afternoon about convergence, disruption, innovation, missing links and public policy. These dimensions are relevant not only to the chemical industry, but in the end to all industries impacted by biotechnology. We need to manage the related change with vigor and creativity; only then will we speed up the process of acceptance of this new technology and deliver a truly revolutionary impact on society. Thank you.

Appendix III: Some Examples of Industrial Enzymes and Their Uses

ENZYMES	SOURCE OR TYPE	APPLICATIONS
CARBOHYDRASES		Laundry detergents, dishwashing detergents, industrial pipe/tank cleaners, textiles, pulp and paper, fermentation ethanol
α-Amylase	**Bacterial** α-amylase (e.g., *Bacillus subtilis*), **Fungal** α-amylase (e.g., *Aspergillus niger*), **Alkaline** α-*amylase*	Textiles, starch syrups, laundry and dishwashing detergents, paper desizing, fermentation ethanol, animal feed
ß-Amylase	from a strain of *Bacillus*	Brewing, maltose syrup
Cellulase		Dishwashing, animal feed, textiles, bioenergy production
ß-Glucanase	Exo-ß-1,4-glucanase, endo-ß-1,4-glucanase	Brewing industry
ß-Glucosidase		Transformation of isoflavone phytoestrogens in soymilk
Dextranase	Made by various microorganisms (e.g., *Leuconostoc mesenteroides*)	Hydrolysis of the polysaccharide dextran
Dextrinase (almost identical to α-glucosidase)		Cleaving of dextrin into two molecules of glucose
α-Galactosidase (melibiase)		Sucrose yield, Beet sugar industry
Glucoamylase	*Aspergillus niger, Rhizopus, Endomyces*	Manufacture of dextrose syrup and high-fructose syrup
Hemmicellulase and xylanase	*Thermomyces lanuginosus, Penicillium simplicissimum*	Baking, fruit juice manufacture, wood pulp processing
Invertase		Manufacture of invert syrup from cane or beet sugar
Lactase	*Kluyveromyces lactis, Asperigillus oryzae, Bacillus sp.*	Lactose elimination from dairy foods
Naringinase		Citrus peel debittering
Pectinase		Fruit processing
Pullulanase	*Klebsiella aerogenes, Bacillus acidipullulyticus, Bacillus subtilis*	Antistaling agent in baked goods
PROTEASES		Brewing, baking goods, protein processing, distilled spirits, laundry detergents, dishwashing detergents, lens cleaners, leather and fur, chemicals

ENZYMES	SOURCE OR TYPE	APPLICATIONS
Acid proteinase	*Endothia parasitica, Rhizopus, Aspergillus niger, A. oryzae*	Improvement of dough handling in baking
Alkaline protease	*Bacillus subtilis, Bacillus licheniformis*	Detergents, leather, fur
Bromelain	Pineapple stem	Food industry
Pepsin	Porcine or bovine stomach	Cheese production
Aminopeptidase	*Lactococcus lactis*	Food and animal feed
Endo-peptidase		
Subtilisin	*Bacillus subtilis* var. Carlsberg, *Bacillus licheniformis*	Chiral resolution of chemical compounds or pharmaceuticals
LIPASES AND ESTERASES	Phospholipases, pregastric esterases, phosphatases	Cleaners, leather and fur, dairy, chemicals
Aminoacylase	Porcine kidney and Aspergillus melleus	Optical resolution of amino acids
Glutaminase	*Bacillus, Aspergillus*	Conversion of glutamine to glutamate
Lysozyme	Chicken egg white, *Saccaromyces cerevisiae, Pichia pastoris*	Antibacterial/germicidal in dairy industry
Penicillin acylase	Bacillus megaterium, Escherichia coli	Chemical synthesis
Isomerase		Conversion of glucose syrup to high fructose syrup in food industry
OXIREDUCTASES		Chemicals, detergent bleaches, pulp bleaching
Alcohol dehydrogenase	*Saccharomyces cerevisiae, Thermoanarobium brachii*	Chiral synthesis of chemicals
Amino acid oxidase	Porcine kidney, snake venom	Chiral resolution of racemic amino acid mixtures
Catalase	*Aspergillus niger*	Desugaring of eggs
Chloroperoxidase	Algae, bacteria, fungi, mammalian tissues	Steroid synthesis
Peroxidase	Horseradish	Laundry and wood pulp bleaches
LYASES		
Acetolactate decarboxylase		Brewing industry
Aspartic _-decarboxylase		Manufacture of L-alanine from L-aspartic acid
Histidase	Achromobacter liquidum	Cosmetics
TRANSFERASES		
Cyclodextrin glycosyltransferase		Manufacture of cyclodextrins from starch

SOURCE: DIVERSA AND NOVO NORDISK

Appendix IV: Some Tools in the Genomic, Proteomic, and Bioinformatics Toolbox

Industrial and environmental biotechnology uses many of the same genomic, proteomic, and bioinformatics tools used by medical biotechnology. These tools are used to discover new products, and enzymes (biocatalysts) and other useful proteins. Some of these tools are listed below.

Gene Shuffling – This process generates genetic diversity and then selects genes for a specific function. This technology can increase the performance of a gene or the protein product it produces. It is accomplished by fragmenting a group of similar DNA sequences into a group of random DNA fragments that are then reassembled to create a library of recombinant DNA molecules with varying genetic outputs.

High Throughput Screening – This technique tests the output of recombined genes to determine whether a new sequence improves a specific product or enzyme. If it does, then the recombinant process is performed over and over again to produce even greater improvements.

Directed Evolution – A process where natural selection is used at the cellular and molecular levels to cause and then identify evolutionary adaptations to new environmental changes. This process can also include the combination of deliberate genetic modification with environmental challenges. New industrial enzymes and new microorganisms useful in bioremediation of toxic waste have been found with this process.

Molecular Breeding – A less random process that produces libraries of gene variants with a predominance of active genes with desired traits or functions.

Protein Engineering – With this technique, proteins are modified to give them novel properties. Modifications can be accomplished by conventional biochemical methods or with genomic technologies mentioned here.

Extremeophiles – Industrial biotechnology companies have discovered novel microorganisms in diverse locations, including the deep ocean trenches, the hot springs of Yellowstone National Park, and Antarctica. Scientists are exploring the genomes of these extremeophiles to develop novel enzymes. The enzymes produced by these organisms are very promising for industrial biotechnology because they are able to operate in severe temperature and pressure conditions.

Bioinformatics – This advanced computing technique involves use of computer software and genomic information to create accurate gene maps of living organisms. This tool allows scientists to better understand gene functions and to develop methods for manipulating genes for desired outcomes. Bioinformatics was used in the human genome project and is becoming very useful in the industrial biotechnology arena as well as a powerful tool for gene mapping.

Appendix V: Additional Information About the Performance of Select Industrial Biotechnology Processes

The purpose of this report is to educate readers about the potential benefits of industrial biotechnology. For this report, we drew on several of the real-world examples included in the OECD report *The Application of Industrial Biotechnology*. The OECD report reviewed several additional case studies. We encourage readers to visit the OECD website to obtain the full report: *http://www1.oecd.org/publications/e-book/9301061e.pdf*.

Two other examples were developed by OECD but not included in their report: BASF and COGNIS GmbH.

BASF

Production of vitamin B2 from vegetable oil. Data reported at the Antwerp conference).[111]

An ecoefficiency analysis of current processes and a possible future process.

Environmental Factors (relative)	Chemical Process	Biotechnology Process	Future Biotechnology Process
Energy consumption	100	85	58
Emissions	60	100	15
Toxicity potential	100	18	10
Risk potential	100	75	68
Raw materials use	100	70	33

COGNIS GmbH

Production of detergent proteases by fermentation using recombinant and unmodified microorganisms. From Henkel.[112]

The assessment covers not the whole life cycle of detergent proteases but only enzyme production, including all processes from the production of raw materials to the finished granulate. Consideration was also given to the transport of the raw materials used during enzyme production from the individual manufacturers to the enzyme producers.

Environmental Factors (per kg enzyme washing power)	Conventional Organism	Recombinant Organism
Raw material (kg)	3.54	2.34
Process energy (MJ)	131	52
Emissions to air		
Total carbon dioxide(g)	8 507	3 422
■ from renewable raw materials (g)	1 548	849
■ from fossil raw materials (g)	6 959	2 572
Hydrocarbons (g)	67	36
Sulfurous oxides (g)	60	25
Nitrous oxides (g)	49	15
Dusts (g)	24	7
Carbon monoxide (g)	14	2
Waste water		
Chemical oxygen demand (g)	158	77
Biological oxygen demand (g)	7	4
Waste		
Organic waste (g)	1 033	313
Slag/ashes (g)	98	26

---

[111] OECD (unpublished).

[112] OECD (unpublished).

Appendix VI: References

Anderl, Georg, BIOWA Powerpoint presentation (2003), available at *www.eesi.org/briefings/2003/EnergyandClimate/ 5.20.03%20Biomass/ anderl.ppt* (last visited Mar 22, 2004).

Andrew, Wyatt , Correspondent for CBS News, "Wyatt Andrew's Eye on America Report takes you inside the biotech revolution" (February 7, 2002) available at *http://www.cbsnews.com/stories/2002/02/07/eveningnews/main328681.shtml* (last visited Mar 26, 2004).

Arthur D. Little, Inc., "Aggressive Growth in the Use of Bio-derived Energy and Products in the United States by 2010, Final Report," Cambridge, MA, (Oct 31, 2001).

Bajpai, Pratima, "Biotechnology for Environmental Protection in the Pulp and Paper Industry," Executive Summary (1998) available at *http://wwwenvironmental-center.com/publications/springer/3540656774.htm* (last visited Oct 28, 2003.)

Biomass Research and Development Board, "Fostering the Bioeconomic Revolution in Biobased Products and Bioenergy" (2001).

Cambridge Healthtech Institute, "Biotechnology & pharmaceutical applications overview" (2004) available at *http://www.genomicglossaries.com/content/genomic_overview.asp* (last visited Mar. 2, 2004).

Energetics, Incorporated, Report for the Department of Energy, "Industrial Bioproducts: Today and Tomorrow," Columbia, MD (2003).

[EIA] Energy Information Administration, "First Use of Energy for All Purposes (Fuel and Nonfuel)" (1998) available at *http://www.eia.doe.gov/emeu/mecs/mecs98/datatables/d98s1_1.pdf* (Last visited March 3, 2004), Table S1.1.

[EIA] Energy Information Administration, "Manufacturing Consumption of Energy" (1998) available at *http://www.eia.doe.gov/emeu/mecs/mecs98/datatables/* (last visited Mar. 2, 2004).

[EIA] Energy Information Administration, "Petroleum Products Supplied by Type" (2001) available at *http://www.eia.doe.gov/emeu/aer/pdf/pages/sec5-180.pdf* (last visited Mar 2, 2004), Table 5.11.

[EPA] Environmental Protection Agency, "Pollution Prevention Act: 42 U.S.C. 13101 and 13102, s/s et seq." (1990) available at *http://www.epa.gov/region5/defs/html/ppa.htm* (last visited Mar 2, 2004).

[EPA] Environmental Protection Agency, Office of Compliance, *Sector Notebook Project: Profile of the Pharmaceutical Manufacturing Industry,* Washington, DC (1997).

[EPA] Environmental Protection Agency, Office of Compliance, *Sector Notebook Project: Plastic Resin and Manmade Fiber Industries,* Washington, DC (1997).

[EPA] Environmental Protection Agency, Office of Compliance, *Sector Notebook Project: Profile of the Textile Industry,* Washington, DC (1997).

[EPA] Environmental Protection Agency, Office of Compliance, "2000 Toxic Releases Inventory (TRI) Releases for Pharmaceutical Facilities" (2000) available at *http://www.epa.gov/compliance/resources/publications/assistance/sectors/notebooks/data_refresh.html* (last visited July 1, 2003).

[EPA] Environmental Protection Agency, Office of Compliance, "Toxic Releases Inventory (TRI) Releases for Pulp and Paper Facilities"(2000) available at *http://www.epa.gov/compliance/resources/publications/assistance/sectors/notebooks/data_refresh.html* (last visited July 1, 2003).

[EPA] Environmental Protection Agency, Office of Compliance, "2000 Toxic Releases Inventory (TRI) Releases for Textile Facilities" (2000) available at*http://www.epa.gov/compliance/resources/publications/assistance/sectors/notebooks/data_refresh.html* (last visited July 1, 2003).

[EPA] Environmental Protection Agency, "2001 Alternative Solvents/Reaction Conditions Award" (2001) available at *www.epa.gov/greenchemistry/ascra01.html* (last visited Mar 11, 2004).

[EPA] Environmental Protection Agency, Office of Compliance, ""Industry Report: TRI On-site and Off-site Reported Releases (in pounds)", U.S., (2001) available at *http://www.epa.gov/tri/* (last visited July 1, 2003).

[EPA] Environmental Protection Agency, Office of Compliance, *Sector Notebook Project: Profile of Organic Chemical Industry,* Washington, DC (2002).

[EPA] Environmental Protection Agency, Office of Compliance, *Sector Notebook Project: Profile of the Pulp and Paper Industry,* Washington, DC (2002).

"Enzymatic Treatment of Paper Fines" (2002) available at *http://www.swin.edu/au/ebc/bioremediation.html* (last visited Mar 30, 2004).

Europabio, "White Biotech," (2004) available at *http://www.europabio.org/pages/white_biotech.asp#what* (last visited Mar 16, 2004).

Hambleton, P., J. Milling and T.T. Salisbury (eds), Biosafety in *Industrial Biotechnology*, London, England (1994).

Hitzmann, Bernd, "Identification of Substitutional Potentials of Chemical Production Procedures By the Use of Biotechnical/Genetic Methods for Risk Prevention," (English Version). The Federal Environmental Agency, Berlin, Germany (August 2001).

"Market Pulp: Pulp Industry must run more efficiently," *Pulp and Paper* (1997) available at *www.paperloop.com/db_area/archive/p_p_mag/1997/9708/news.htm* (last visited Mar 22, 2004).

National Pollution Prevention Roundtable, *What are the Economic Incentives for Pollution Prevention?* (2002) available at *http://www.p2.org/about/nppr_p2.cfm* (last visited Mar. 2, 2004).

National Renewable Energy Laboratory, "What is a life cycle assessment?" (2002) available at *http://www.nrel.gov/docs/gen/fy02/31792.pdf* (last visited Mar 22, 2004).

Nilges, Michael and Jens P. Linge, "Bioinformatics," Unité de Bio–Informatique Structurale, Institut Pasteur (2002) available at *http://www.pasteur.fr/recherche/unites/Binfs/definition/bioinformatics_definition.html* (last visited Mar 21, 2004).

Noorzad, Hazrat, "Biotechnology: Its Evolution, Application, and Environmental Implications" Massachusetts Office of Technical Assistance (2001) available at *http://www.state.ma.us/ota/pubs/Biotech.pdf.*

Novoymes, "Using surplus materials as fertilizer" (Nov 2000) available at *http://www.novozymes.com* (last visited Mar 16, 2004).

[OECD] Organisation for Economic Co-operation and Development, "Biotechnology for Clean Industrial Products and Processes: Towards Industrial Sustainability," Paris, France (1998).

[OECD] Organisation for Economic Co-operation and Development, "The Application of Biotechnology to Industrial Sustainability," *Sustainable Development,* Paris, France (2001).

Powell, Colin, "Making Sustainable Development Work: Governance, Finance, and Public-Private Cooperation," Remarks at State Department Conference, Meridian International Center, Washington, DC (July 12, 2002) available at *http://www.state.gov/secretary/rm/2002/11822.htm*

"Saving the World in Comfort," editorial, *The Economist* (Mar 27, 2003).

Sheehan, John, Andy Aden, Keith Paustian, Kendrick Killian, John Brenner, Marie Walsh and Richard Nelson, "Energy and Environmental Aspects of Using Corn Stover for Fuel Ethanol", *Journal of Industrial Ecology*, Cambridge, MA (2003).

Society of the Plastics Industry. "Executive Summary: World ThermoPlastic Consumption and Forecast" (2003) available at *http://www.plasticsdatasource.org/global.htm.* (last visited Mar 15, 2004).

Vigsoe, Dorte, Espen Jürgensen, and Morten Kvistgaard, "The Assessment of Future Environmental and Economic Impacts of Process-Integrated Biocatalyst," European Commission Joint Research Center (2002).

Wang, M.Q. ,"GREET 1.4 – Transportation Fuel-Cycle Model," Center for Transportation Research, Argonne National Laboratory. Argonne, IL (1999).

"Well Defined: Brush Up on Your 'Omics'," *Chemical and Engineering News* (Dec 8, 2003):

"The Yuk Factor," editorial, *Nature Biotechnology* 19 (June 2001):

> “Biobased products have the potential to improve the sustainability of natural resources, environmental quality, and national security while competing economically.”
>
> —*Biobased Industrial Products: Research and Commercialization Priorities,* National Research Council, 2000.

> “The move to industrial bioprocessing clearly goes hand in hand with the public desire for a cleaner environment. It is in tune with increasing public enthusiasm for more sustainable lifestyles and the demand for cleaner products... As many of the founders of biotechnology were fond of saying in their youth, ‘Seize the time.’”
>
> —*Nature Biotechnology,* editorial, June 2001.

About the Preparation of this Report

This report was published by the **Biotechnology Industry Organization's (BIO's) Industrial and Environmental Section.** As a whole, BIO represents more than 1,000 biotechnology companies, academic institutions, state biotechnology centers and related organizations in all 50 U.S. states and 33 other nations. BIO members are involved in the research and development of health-care, agricultural, industrial and environmental biotechnology products. For more information on BIO, visit the website at *www.bio.org*. The Industrial and Environmental Section is a discrete part of BIO, and the views expressed in this report do not necessarily reflect those of all BIO members. The mention of specific company, trade and product names does not constitute an endorsement.

AJW, Inc. was commissioned to develop the analysis in Chapter 6 and to assist in the development of the other chapters. AJW, Inc provides consulting and lobbying services related to energy and environmental issues. Its principals have more than 30 years combined experience working on these issues in the private sector, federal and state government, and the environmental community.

Principal Authors

Brent Erickson is Vice President in charge of the Industrial and Environmental Section at BIO in Washington, D.C. In May of 2001, he was elected vice-chair of The OECD's Task Force on Biotechnology for Sustainable Industrial Development. In addition to his work at BIO, he currently heads up the Bioenergy/Agriculture Working Group of the Energy Future Coalition that is funded by the United Nations Foundation. He also serves as a member of the board of the Western Research Institute, a non-profit research entity of the University of Wyoming Research Corporation. Previously, he worked for 15 years in the United States Senate as a legislative aide to Senator Alan K. Simpson and later Senator John H. Chafee. During that time, he was involved in the reauthorization of all the major environmental statutes.

Christopher J. Hessler, a partner at AJW, Inc. has more than 15 years of state government and congressional experience during which time he managed environmental and energy policy issues for elected officials and corporate and non-profit clients. Mr. Hessler represents a diverse group of clients ranging from Fortune 500 companies to non-profit policy organizations. Previously, Mr. Hessler served as the Deputy Staff Director for the United States Senate Committee on Environment and Public Works. There he was the principle staff member for issues related to the Clean Air Act, global climate change, and energy. He also participated in a broad range of activities related to many other environmental statutes as well as highway, water, and other infrastructure funding issues.

Project Team

Patricia Doerr, AJW, Inc ■ Meghan Higgins, AJW, Inc ■ Lauren Pannenbacker, BIO ■ Jason Rupp, BIO ■ Sarah Wade, AJW, Inc

Editors

Judy Dickson, Science Editing, Inc ■ Debbie Strickland, BIO

Graphic Design

Bussolati Associates, www.bussolati.com

Biobased Products for a Cleaner Environment