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Research review paper

Biotechnology—a sustainable alternative for chemical industry

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Abstract

This review outlines the current and emerging applications of biotechnology, particularly in the production and processing of chemicals, for sustainable development. Biotechnology is "the application of scientific and engineering principles to the processing of materials by biological agents". Some of the defining technologies of modern biotechnology include genetic engineering; culture of recombinant microorganisms, cells of animals and plants; metabolic engineering; hybridoma technology; bioelectronics; nanobiotechnology; protein engineering; transgenic animals and plants; tissue and organ engineering; immunological assays; genomics and proteomics; bioseparations and bioreactor technologies. Environmental and economic benefits that biotechnology can offer in manufacturing, monitoring and waste management are highlighted. These benefits include the following: greatly reduced dependence on nonrenewable fuels and other resources; reduced potential for pollution of industrial processes and products; ability to safely destroy accumulated pollutants for remediation of the environment; improved economics of production; and sustainable production of existing and novel products.

Keywords: Industrial sustainability; Biotechnology; Chemicals; Biocatalysts; Environment

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Contents

1. Introduction

Among the major new technologies that have appeared since the 1970s, biotechnology has perhaps attracted the most attention. Biotechnology has proved capable of generating enormous wealth and influencing every significant sector of the economy. Biotechnology has already substantially affected healthcare; production and processing of food; agriculture and forestry; environmental protection; and production of materials and chemicals. This review focuses on achievements and future prospects for biotechnology in sustainable production of goods and services, specially those that are derived at present mostly from the traditional chemical industry.

2. Defining industrial sustainability

"Industrial sustainability" aims to achieve sustainable production and processing within the context of ecological and social sustainability. Sustainability and sustainable development have had different meanings in different epochs and not everyone is agreed on a common definition of these concepts. For the purpose of this review, sustainable development is understood to mean "... a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations... (It is) meeting the needs of the present without compromising the ability of future generations to meet their own needs", as defined by World Commission on Environment and Development (Brundtland, 1987). Sustainable development requires a framework for integrating environmental policies and development strategies in a global context (Hall and Roome, 1996). Increasingly, sustainability considerations will shape future technological, socio-econom-

ic, political and cultural change to define the boundaries of what is acceptable (Hall and Roome, 1996).

Politicians, scientists and various interest groups have periodically attempted to plan for sustainable development, to counter the earlier accepted wisdom that environmental degradation was the price for prosperity. For example, the 2002 United Nations World Summit on Sustainable Development discussed major issues such as depletion of freshwater reserves, population growth, the use of unsustainable energy sources, food security, habitat loss and global health, all in the context of social justice and environmental sustainability. Sustainable development is clearly the most difficult challenge that humanity has ever faced. Attaining sustainability requires addressing many fundamental issues at local, regional and global levels. At every level, science and technology have vital roles to play in attaining sustainability, but political decisions backed by societal support and coordinated policy approaches are just as essential. Industrial sustainability demands a global vision that holistically considers economic, social and environmental sustainability. Sustainability requires incorporating ''design for environment'', into production processes (Brezet et al., 2001; Wong, 2001; OECD, 2001a).

Compared to conventional production, sustainable processes and production systems should be more profitable because they would require less wasteful use of materials and energy, result in less emissions of greenhouse gases and other pollutants, and enable greater and more efficient use of renewable resources, to lessen dependence on nonrenewable resources (Zosel, 1994; Van Berkel, 2000; Gavrilescu, 2004a; Gavrilescu and Nicu, 2004). Sustainability demands products that not only perform well but, compared to their conventional counterparts, are more durable, less toxic, easily recyclable, and biodegradable at the end of their useful life. Such products would be derived as much as possible from renewable resources and contribute minimally to net generation of greenhouse gases.

Between 1960s and 1990s, industrial production attempted to minimize its adverse impact by treating effluent and removing pollutants from an already damaged environment. Designing industrial processes and technologies that prevented pollution in the first place did not become a priority until recently (Council Directive, 1996; Allen and Sinclair Rosselot, 1997; World Bank, 1999; EPA, 2003). Newer industries such as microelectronics, telecommunications and biotechnology are already less resource intensive in comparison with the traditional heavy industry (Kristensen, 1986; OECD, 1989; Rigaux, 1997), but this alone does not assure sustainability. Industry is truly sustainable only when it is economically viable, environmentally compatible, and socially responsible (OECD, 1998; UNEP, 1999; Wong, 2001). Models of sustainability have been discussed in various documents prepared by the Organization for Economic Cooperation and Development (www.oecd.org) (OECD, 1989, 1994, 1995, 1998).

3. Role of biotechnology in sustainability

Biotechnology refers to an array of enabling technologies that are applicable to broadly diverse industry sectors (Paugh and Lafrance, 1997; Liese et al., 2000). Biotechnology

comprises three distinct fields of activity, namely genetic engineering, protein engineering and metabolic engineering. A fourth discipline, known variously as biochemical, bioprocess and biotechnology engineering, is required for commercial production of biotechnology products and delivery of its services. Of the many diverse techniques that biotechnology embraces, none apply across all industrial sectors (Roberts et al., 1999; Liese et al., 2000). Recognizing its strategic value, many countries are now formulating and implementing integrated plans for using biotechnology for industrial regeneration, job creation and social progress (Rigaux, 1997).

Biotechnology is versatile and has been assessed a key technology for a sustainable chemical industry (Lievonen, 1999). Industries that previously never considered biological sciences as impacting their business are exploring ways of using biotechnology to their benefit. Biotechnology provides entirely novel opportunities for sustainable production of existing and new products and services. Environmental concerns help drive the use of biotechnology in industry, to not only remove pollutants from the environment but prevent pollution in the first place. Biocatalyst-based processes have major roles to play in this context. Biocatalysis operates at lower temperatures, produces less toxic waste, fewer emissions and by-products compared to conventional chemical processes. New biocatalysts with improved selectivity and enhanced performance for use in diverse manufacturing and waste degrading processes (Abramovicz, 1990; Poppe and Novak, 1992; Roberts et al., 1999) are becoming available. In view of their selectivity, these biocatalysts reduce the need for purifying the product from byproducts, thus reducing energy demand and environmental impact. Unlike non-biological catalysts, biocatalysts can be self-replicating.

Biological production systems are inherently attractive because they use the basic renewable resources of sunlight, water and carbon dioxide to produce a wide range of molecules using low-energy processes. These processes have been fine tuned by evolution to provide efficient, high fidelity synthesis of low toxicity products. Biotechnology can provide renewable bioenergy and is yielding new methods for monitoring the environment. Biotechnology has already been put to extensive use specially in the manufacture of biopharmaceuticals. In addition to providing novel routes to well-established products, biotechnology is being used to produce entirely new products. Interfacing biotechnology with other emerging disciplines is creating new industrial sectors such as nanobiotechnology and bioelectronics. Biotechnology has greatly impacted healthcare, medical diagnostics (Xiang and Chen, 2000; D'Orazio, 2003), environmental protection, agriculture, criminal investigation, and food processing. All this is a mere shadow of the future expected impact of biotechnology in industrial production and sustainability. The following sections examine the use of biotechnology in processing and production of chemicals, for enhanced sustainability.

3.1. The chemical industry

The global chemical industry has contributed immensely to achieving the present quality of life, but is under increasing pressure to change current working practices in favor of greener alternatives (Ulrich et al., 2000; Matlack, 2001; Carpenter et al., 2002; Poliakoff et al., 2002; Sherman, 2004; Asano et al., 2004). Concerns associated with

chemical industry include its excessive reliance on nonrenewable energy and resources; environmentally damaging production processes that can be unsafe and produce toxic products and waste; products that are not readily recyclable and degradable after their useful life; and excessive regional concentration of production so that social benefits of production are less widely available.

Chemical industry is large. The world's chemicals production in 2002 was in excess of 1.3 trillion. This industry consists of four major subsectors: basic chemicals, specialty chemicals, consumer care products, and life science products. Biotechnology impacts all these sectors, but to different degrees. Demarcation between sectors is not clearcut. General characteristics of these sectors are outlined in the following sections (OECD, 2001b).

Basic chemicals or commodity chemicals represent a mature market. Most of the top 50 products by volume of production in this category in 1977 were still among the top 50 in 1993. During this period, the relative ranking by production volume of the products in this category remained largely unchanged (Wittcoff and Reuben, 1996). The basic chemical industry is characterized by large plants that operate using continuous processes, high energy input, and low profit margins. The industry is highly cyclical because of fluctuations in capacity utilization and feedstock prices. The products of the industry are generally used in processing applications (e.g. pulp and paper, oil refining, metals recovery) and as raw materials for producing other basic chemicals, specialty chemicals, and consumer products, including manufactured goods (textiles, automobiles, etc.) (Swift, 1999).

Specialty chemicals are derived from basic chemicals but are more technologically advanced and used in lesser volumes than the basic chemicals. Examples of specialty chemicals include adhesives and sealants, catalysts, coatings, and plastic additives. Specialty chemicals command higher profit margins and have less cyclic demand than basic chemicals. Specialty chemicals have a higher value-added component because they are not easily duplicated by other producers or are protected from competition by patents.

Consumer care products include soaps, detergents, bleaches, laundry aids, hair care products, skin care products, fragrances, etc., and are one of the oldest segments of the chemicals business. These formulated products are generally based on simple chemistry but feature a high degree of differentiation along brand lines. Increasingly, products in this category are high-tech in nature and developing them demands expensive research.

Life science products. These include pharmaceuticals, products for crop protection and products of modern biotechnology. Batch production methods are generally used in making these products. The sector is one of the most research intensive and relies on advanced technology.

3.2. The applications of biotechnology in the chemical industry

3.2.1. Commodity chemicals

At the basic level, life processes are chemical processes and understanding their chemistry provides a basis for devising manufacturing operations that approach nature's elegance and efficiency. Biotechnology uses the power of life to enable effective, rapid, safe and environmentally acceptable production of goods and services.

The chemical industry has used traditional biotechnological processes (e.g. microbial production of enzymes, antibiotics, amino acids, ethanol, vitamins; enzyme catalysis) for many years (Moo-Young, 1984; Poppe and Novak, 1992; Rehm et al., 1993; Chisti, 1999; Flickinger and Drew, 1999; Herfried, 2000; Demain, 2000; Spier, 2000; Schmid, 2003). In addition, traditional biotechnology is widely used in producing fermented foods and treating waste (Nout, 1992; Moo-Young and Chisti, 1994; Jördening and Winter, 2004).

Advances in genetic engineering and other biotechnologies have greatly expanded the application potential of biotechnology and overcome many of the limitations of biocatalysts of the preGMO era (Ranganathan, 1976; Liese et al., 2000; Schügerl and Bellqardt, 2000). Chemical companies such as Monsanto and DuPont that were once associated exclusively with traditional petrochemical based production methods have either moved exclusively to biotechnology-based production, or are deriving significant proportions of their income through biotechnology (Scheper, 1999; Bommarius, 2004). Important commodity chemicals such as ethanol and cellulose esters are already sourced from renewable agricultural feedstocks in the United States. New processes and renewable resources for other commodity chemicals that are currently derived almost exclusively from petrochemical feedstocks are in advanced stages of development. Examples of these chemicals include succinic acid and ethylene glycol.

By the early 1990s biotechnology used for cleaner production was already contributing about 60% of total biotechnology-related sales value for fine chemicals and between 5% and 11% for pharmaceuticals (OECD, 1989). Some fine chemicals being manufactured in multi-tonnage quantities using biotechnology are listed in Table 1 (Bruggink, 1996; Eriksson, 1997). Nearly all these products have been around for a long time, but many are now made using engineered biocatalysts.

Two major areas of biotechnology that are driving transformation of the conventional chemical industry are biocatalysis and metabolic engineering (Poppe and Novak, 1992; Kim et al., 2000). Genetic engineering and molecular biology techniques have been used to obtain many modified enzymes with enhanced properties compared to their natural counterparts. Metabolic engineering, or molecular level manipulation of metabolic pathways in whole or part, is providing microorganisms and transgenic crops and animals with new and enhanced capabilities for producing chemicals.

A future bioethanol based chemical industry, for example, will rely on biotechnology in all of the following ways: (1) generation of high yield transgenic corn varieties having starch that is readily accessible for enzymatic hydrolysis to glucose; (2) production of engineered enzymes for greatly improved bioconversion of starch to sugars; (3) genetically enhanced ethanol tolerant microorganisms that can rapidly ferment sugars to ethanol; (4) ability to recover ethanol using high-efficiency low-expense bioprocessing.

3.2.2. Specialty and life science products

Biotechnology's role in production of commodity chemicals is significant, but not as visible as its role in production of agrochemicals and fine chemicals (Hsu, 2004). Many renewable bioresources remain to be used effectively because they have been barely studied. Flora and fauna of many of the world's ecosystems have been barely investigated for existence of novel compounds of potential value. For example, microalgae contribute substantially to primary photosynthetic productivity on Earth, but are barely used

Table 1
Some well-established biotechnology products (by production volume)

Product	Annual production (tons)
Bioethanol	26,000,000
L-Glutamic acid (MSG)	1,000,000
Citric acid	1,000,000
L-Lysine	350,000
Lactic acid	250,000
Food-processing enzymes	100,000
Vitamin C	80,000
Gluconic acid	50,000
Antibiotics	35,000
Feed enzymes	20,000
Xanthan	30,000
L-Threonine	10,000
L-Hydroxyphenylalanine	10,000
6-Aminopoenicillanic acid	7000
Nicotinamide	3000
D-*p*-hydroxyphenylglycine	3000
Vitamin F	1000
7-Aminocephalosporinic acid	1000
Aspartame	600
L-Methionine	200
Dextran	200
Vitamin B12	12
Provitamin D2	5

commercially. Microalgae are a source or potential source of high-value products such as polyunsaturated fatty acids, natural colorants, biopolymers, and therapeutics (Borowitzka, 1999; Cohen, 1999; Belarbi et al., 2000; Lorenz and Cysewski, 2000; Banerjee et al., 2002; Mirón et al., 2002; Lebeau and Robert, 2003a, b; Lopez et al., 2004; León-Bañares et al., 2004). Microalgae are used to some extent in biotreatment of wastewaters, as aquaculture feeds, biofertilizers and soil inoculants. Potentially, they can be used for removing excess carbon dioxide from the environment (Gòdia et al., 2002). Other microalgae are regarded as potential sources of renewable fuels because of their ability to produce large amounts of hydrocarbons and generate hydrogen from water (Nandi and Sengupta, 1998; Banerjee et al., 2002). Depending on the strain and growth conditions, up to 75% of algal dry mass can be hydrocarbons. The chemical nature of hydrocarbons varies with the producer strain and these compounds can be used as chemical precursors (Dennis and Kolattukudy, 1991; Banerjee et al., 2002). Some microalgae can be grown heterotrophically on organic substrates without light to produce various products (Wen and Chen, 2003).

As with microalgae, sponges (Belarbi et al., 2003; Thakur and Müller, 2004) and other marine organisms are known to produce potentially useful chemicals, but have not been used effectively for various reasons. Natural sponge populations are insufficient or inaccessible for producing commercial quantities of metabolites of interest. Production techniques include aquaculture in the sea, the controlled environments of aquariums, and culture of sponge cells and primmorphs. Cultivation in the sea and aquariums are currently

the only practicable and relatively inexpensive methods of producing significant quantities of sponge biomass (Belarbi et al., 2003).

Extremophiles, or organisms that have adapted to extreme conditions such as high pressure, heat, and total darkness, are attracting much interest as possible sources of unusual specialty compounds (Eichler, 2001). Some extremophiles have already provided commercial biotechnology products (Henkel, 1998).

3.2.2.1. Fermentation processes. Microbial fermentation is the only method for commercial production of certain products that are made in substantial quantities (Weiss and Edwards, 1980; Strohl, 1997; Leeper, 2000; Liese et al., 2000; Schreiber, 2000). Table 1 compiles the production figures for a number of established fermentation products. The antibiotics market alone exceeds US$30 billion and includes about 160 antibiotics and derivatives. Other important pharmaceutical products produced by microorganisms are cholesterol lowering agents or statins, enzyme inhibitors, immunosuppressants and antitumor compounds (Demain, 2000). The world market for statins is about US$15 billion. The total pharmaceutical market is well in excess of US$400 billion and continues to grow faster than the average economy. Biotechnology processes are involved in making many of these drugs.

Novel fermentation production methods for established drugs and drug precursors are being developed continually (Moody, 1987; Chisti, 1989, 1998; Gavrilescu and Roman, 1993, 1995, 1996, 1998; Roman and Gavrilescu, 1994; Sanchez and Demain, 2002). One example is the production of cholesterol lowering drug lovastatin that is also used for producing other semisynthetic statins (Chang et al., 2002; Casas López et al., 2003, 2004a,b, 2005; Vilches Ferrón et al., 2005). Various novel bioprocess intensification strategies are being put to use to substantially enhance productivities and efficiencies of numerous bioprocesses (Chisti and Moo-Young, 1996).

Vitamins are still mainly produced using organic chemistry, but biotechnology is making increasing contribution to vitamin production. For example, DSM Nutritional Products replaced the company's traditional; six-step process for producing vitamin B2 (riboflavin) with a one-step fermentation process that has a lower environmental impact compared with conventional production. The bacterium *Bacillus subtilis* is the producer microorganism. Production by fermentation was made feasible by gene engineering the bacterium to increase vitamin yield by 300,000-fold compared to what could be achieved with the wildtype strain. The one-step fermentation process reduced cost of production by 50% relative to the conventional process.

Biopharmaceuticals, mostly recombinant proteins, vaccines and monoclonals, represent an entirely different class of drugs compared to small molecule compounds such as antibiotics. Examples of this class of products include tissue plasminogen activator (tPA), insulin and recombinant hepatitis B vaccine. The global market for biopharmaceuticals already exceeds US$40 billion, having grown by more than 3-fold compared to only 4 years ago (Melmer, 2005). Market size of selected biopharmaceuticals is shown in Table 2. The total market for recombinant proteins is of course much larger when nonbiopharmaceutical products are included. A generics industry is expected to emerge around some of the older biopharmaceuticals that are now coming off patent (Melmer, 2005).

Table 2
Market size (2001) of selected biopharmaceuticals (Melmer, 2005)

Product	Indication	Market (US$ million)
Erythropoietin	Anemia	6803
Insulin	Diabetes	4017
Blood clotting factors	Hemophilia	2585
Colony stimulating factor	Neutropenia	2181
Interferon beta	Multiple sclerosis, hepatitis	2087
Interferon alpha	Cancer, hepatitis	1832
Monoclonal antibody	Cancer	1751
Growth hormone	Growth disorders	1706
Monoclonal antibody	Various	1152
Plasminogen activator	Thrombotic disorders	642
Interleukin	Cancer, immunology	184
Growth factor	Wound healing	115
Therapeutic vaccines	Various	50
Other proteins	Various	2006

Better processes for producing biopharmaceuticals such as alpha-1-antitrypsin are being developed continually (Tamer and Chisti, 2001). As with numerous enzymes, many naturally occurring first-generation protein therapeutics such as insulin and tissue plasminogen activator that are being produced by modern biotechnology processes are being protein engineered to products that are potentially superior to their natural counterparts (Rouf et al., 1996). For example, various modifications of streptokinase have been used for extending its half-life in circulation, improving plasminogen activation, and reducing or eliminating immunogenicity (Galler, 2000; Banerjee et al., 2004). Protein engineering has been broadly successful in altering bioactivity, stability, ease of recovery and other attributes of proteins (Nosoh and Sekiguchi, 1990; Sassenfeld, 1990; El Hawrani et al., 1994; Nygren et al., 1994).

3.2.2.2. Enzymatic processes. Enzymes are increasingly penetrating the chemical industry as catalysts for numerous reactions. The global market of enzymes is estimated at around US$1.5 billion and is expected to grow by 5–10% annually (Lievonen, 1999). Table 3 lists major types of industrial enzymes, their substrates and reactions they catalyze. Millions of years of evolution has provided enzymes with unparalleled capabilities of facilitating life reactions in ways that are sustainable. Compared with conventional chemical catalysts, enzyme catalysis is highly specific (Scheper, 1999; Bommarius, 2004) and it functions under temperatures, pressures and pHs that are compatible with life (Abramovicz, 1990; Roberts et al., 1999). Unlike many processes of conventional synthetic chemistry, enzymes require nontoxic and noncorrosive conditions.

About 75% of the enzyme use by value is accounted for by the detergent, food and starch processing industries. These are mostly hydrolytic enzymes such as proteases, amylases, lipases and cellulases. Specialty enzymes account for around 10% of the enzyme market and are finding increasing uses in the development of new drugs, medical diagnostics and numerous other analytical uses. Of the enzymes used commercially, about 60% are products of modern biotechnology. In addition to their ever increasing diagnostics

Table 3
Some industrial enzymes and their applications

Enzyme	Substrate	Reaction catalyzed	Application industry
Proteases	Proteins	Proteolysis	Detergents, food, pharmaceutical, chemical synthesis
Carbohydrases	Carbohydrates	Hydrolysis of carbohydrates to sugars	Food, feed, pulp and paper, sugar, textiles, detergents
Lipases	Fats and oils	Hydrolysis of fats to fatty acids and glycerol	Food, effluent treatment, detergents, fine chemicals
Pectinases	Pectins	Clarification of fruit juices	Food, beverage
Cellulases	Cellulose	Hydrolysis of cellulose	Pulp, textile, feed, detergents
Amylases	Polysaccharides	Hydrolysis of starch into sugars	Food

and analytical applications, new uses are being developed for enzymes in production, degradation and biotransformation of chemicals, foods and feeds, agricultural produce and textiles. A few examples for bulk enzymes are the following:

- A new class of sugars known as isomalto-oligosaccharides is being produced using glucosyl transferases. Isomalto-oligosaccharides have potential commercial applications in food industry as non-digestible carbohydrate bulking agent. They are also known to suppress tooth decay associated with consumption of conventional carbohydrates and prevent baked goods going stale.
- Cellulases are complexes of enzymes that synergistically break down cellulose. Cellulases are a subject of intense research because of their potential for providing fuels, food and other chemicals from widely available cellulose. Cellulases produced by *Trichoderma* fungi are used for 'stonewashing' jeans. Changing the relative proportions of the enzymes in the cellulase complex creates different effects on the textile fibers.
- Enzymes such as amylases and proteases are being added to animal feed to improve digestibility by supplementing the animals' own enzymes. A lot of the plant-derived animal feed contains antinutritional factors that interfere with digestion or absorption of nutrients. Adding enzymes such as beta-glucanases and arabinoxylanase to feed cereals breaks down non-starch polysaccharide antinutritional factors, aiding digestion and absorption of nutrients. Phytic acid found in plant matter is another antinutritional compound that reduces dietary absorption of essential minerals such as iron and zinc. Phytic acid eventually appears in animal manure as highly polluting phosphorous. Digestion of phytic acid is facilitated by adding phytases to feed. Phytase for feed supplementation became available in sufficient amounts only after it was produced in recombinant microorganisms.

Extremophilic enzymes, or extremozymes, are finding increasing industrial use because of their ability to withstand extremes of temperatures and other conditions (Eichler, 2001). Enzyme catalysis in nonaqueous media has created new possibilities for producing useful

chemicals such as modified fats and oils, structured lipids and flavor esters (Sharma et al., 2001; Krishna, 2002).

Enzyme and other biocatalysis allow pharmaceutical manufacturers to significantly reduce the number of synthetic steps that would be required for conventional synthesis. This enhances efficiency of manufacturing operations (Simon et al., 2003; Blaser, 2003). Furthermore, biocatalysts enable production and biotransformation of single enantiomers of chiral compounds. Different enantiomers of bioactive chiral molecules generally have different biological activities. Often, only one enantiomer has the desired activity and the other may be harmful. This was the case with thalidomide, for example. One enantiomer of this compound had the desired pharmacological effect of preventing morning sickness during pregnancy, while the other caused deformities in the developing fetus (Augusti et al., 2002; Rajkumar, 2004). Because of these differences, the pharmaceutical industry is under increasing regulatory pressure to ensure that the final products contain only the pharmacologically active enantiomer of a drug and not racemic mixture. Ability to selectively produce a single desired enantiomer saves on expensive precursor materials, although this factor is not of great significance in the specialty chemicals industry (Simon et al., 2003). More important are the reduced cost of downstream purification and the absence of product contamination with the unwanted enantiomer. Stereoselective biocatalysis is now used for a diverse array of reactions (Patel, 2000). A well-established example is the hydantoinase process that is used to produce different enantiomerically-pure D and L amino acids.

Semisynthetic penicillin and cephalosporin antibiotics derived from 6-aminopenicillanic acid (6-APA) and 7-aminocephalosporanic acid (7-ACA), respectively, are produced using enzymatic processes (Nam and Ryu, 1984; Parmar et al., 2000; Torres-Bacete et al., 2000; Alkema et al., 2003; Scheper, 2004). Production of numerous other pharmaceuticals relies on enzymatic biotransformations (Liese et al., 2000; Patel, 2000). Cephalexin is a semisynthetic antibiotic derived from cephalosporin C. DSM Company (www.dsm.com), the Netherlands, is a major producer of cephalexin. The conventional chemical production of this compound required up to 10 steps. The conventional process generated up to 50 kg of waste per kg of antibiotic (Table 4) but this was reduced to about 15 kg with extensive developmental effort. Subsequently, a four-step enzymatic process was developed that further reduced waste and consumption of most resources. A direct fermentation rout is now available and this is even better than the enzymatic route. The various processes for production of cephalexin are compared in Table 4 (OECD, 2001b; Vandamme and Bienfait, 2004).

Use of enzymatic processes is not limited to specialty chemicals. Large-scale enzymatic processes are used for converting corn starch to high-fructose corn syrup, a major sweetener in commercial processed foods and beverages. Approximately US$1 billion worth of high-fructose corn syrup is produced annually. Enzymatic processes for producing commodity chemicals such as acrylamide have been developed. Conventionally, acrylamide has been produced from acrylonitrile by two chemical synthetic processes: a sulfuric acid hydrolysis process and a copper-catalyzed hydrolysis process. Using technology developed in 1985, Mitsubishi Rayon Co., Ltd. (www.mrc.co.jp) commenced production of acrylonitrile from acrylamide using immobilized bacterial enzyme nitrile hydratase (Vandamme and Bienfait, 2004). This process is now accepted as being low-

Table 4
Comparison of chemical and biotechnology processes for producing cephalexin (Demain, 2000)

Production category	Process type		
	Conventional chemical	Enzyme biocatalysis	Direct fermentation
Waste (kg/kg cephalexin)	50 (1970) to 15 (1995)	10 (1995) to 5 (2000)	2–5
Inorganics (kg/kg)	0.5	0.5	
Organics (non-halogenated) (kg/kg)	1.0	0.2	
Solvents (non-halogenated) (kg/kg)	1.7	0.3	
Solvents (halogenated) (kg/kg)	0.9	0	
Electricity (%)	100	150	
Steam (%)	100	40	
Water (%)	100	300	
Liquid nitrogen (%)	100	0	

cost, high-quality and environmentally friendly. New production facilities based on this process are being built worldwide (OECD, 2001b). About 100,000 tons of acrylamide is produced annually by this process (Vandamme and Bienfait, 2004). Table 5 compares the conventional chemical and biotechnology-based production of acrylamide. The bioprocess requires milder conditions, achieves greater single-pass conversion and a higher final concentration of the product in the bioreactor. The bioprocess uses about 20% as much energy as the conventional process and produces much less carbon dioxide than the traditional process (Table 5).

While enzymatic process can have definite advantages compared to their chemical alternatives, much research is needed to make them cost-competitive for use in the broader chemical industry. A report entitled *New Biocatalysts: Essential Tools for a Sustainable 21st Century Chemical Industry* (www.eere.energy.gov/biomass/pdfs/biocatalysis_roadmap.pdf) identified the following major objectives for biocatalysts for a sustainable chemical industry:

1. developing biocatalysts that are better, faster, less expensive and more versatile than comparable chemical catalysts;
2. development of biocatalysts that can catalyze an increased range of reactions, have higher temperature stability and improved solvent compatibility;

Table 5
Chemical versus biotechnological production of acrylamide (Vandamme and Bienfait, 2004)

Parameter	Chemical process	Bioprocess process
Reaction temperature	70 °C	0–15 °C
Single-pass reaction yield	70–80%	100%
Acrylamide concentration	30%	48–50%
Product concentration	Necessary	Not required
Energy demand (steam and electricity demand in MJ/kg acrylamide)	1.9	0.4
CO_2 production (kg CO_2/kg acrylamide)	1.5	0.3

3. developing molecular modeling and other tools to permit rapid design of new enzyme catalysts.

Progress is underway in all of the above areas to provide the chemical industry with diverse new useful biocatalysts. Newer ways of using enzymes and cells in bioreactors are being established (Drioli and Giorno, 1999; Park and Chang, 2000).

3.2.2.3. Plastics and other polymers. Occurrence of biodegradable plastics such as polyhydroxyalkanoic acids (PHA) in bacteria has been known since the 1920s. Expense of producing bioplastics and the availability of versatile low-cost petrochemicals-derived plastics led to bioplastics being ignored for a long time. Concern over persistence of petrochemical plastics in the environment is a renewing interest in biologically derived polymers (Kim et al., 2000; Babel and Steinbüchel, 2001; Stevens, 2002). The Japan Institute of Physics and Chemical Research engineered a microorganism to produce up to 96% of its dry weight as biodegradable plastic (Lenz, 1995). Many diverse plastic and nonplastic biopolymers are now available. Even though they remain relatively expensive, their production and use are environmentally sustainable.

Substantial effort is underway in developing improved production of polyhydroxyalkanoates (PHAs) and other biodegradable, renewable, biopolymers (Tamer et al., 1998a, b; Grothe et al., 1999; Grothe and Chisti, 2000; Babel and Steinbüchel, 2001; Stevens, 2002; Salehizadeh and Van Loosdrecht, 2004). Biopolymers with enhanced properties and microbial strains for producing them are being developed. More efficient fermentation and product recovery processes are being investigated (Tamer et al., 1998a, b; Grothe et al., 1999; Grothe and Chisti, 2000; Salehizadeh and Van Loosdrecht, 2004). The use of mixed cultures and inexpensive substrates can substantially reduce the production cost of PHAs (Salehizadeh and Van Loosdrecht, 2004).

The conversion of acrylonitrile to acrylic acid for the production of anionic polyacrylamides is an example of a large-scale biotransformation with significant commercial and environmental benefits. Ciba Specialty Chemicals (www.cibasc.com) manufactures a range of polymers based on acrylamide and acrylic acid using biological technologies. The conventional method for producing acrylic acid was a hazardous, multi-step, energy-intensive process that required high concentrations of toxic acrylonitrile, operated at an elevated temperature and produced hazardous emissions. Ciba's biotransformation route is claimed to have the following benefits: a simple, one-step process that is cost-effective and provides a product of good quality; production at ambient temperature and atmospheric pressure; low concentration of hazardous acrylonitrile throughout manufacture; few by-products; and near quantitative conversion. As another example, the Mitsubishi Rayon's bioprocess for producing acrylamide has already been mentioned. Acrylamide is then polymerized to the conventional plastic polyacrylamide. In the UK, Baxenden Company (www.baxchem.co.uk) manufactures polyesters, acrylic polymers and emulsions and other specialty chemicals using biocatalytic processes that have reduced the reaction temperature to 60 °C compared to 200 °C for equivalent chemical processing.

DuPont (www.dupont.com), in association with Genencor International (www.genencor.com), has developed a process that uses a genetically modified *Escherichia coli* to convert

sugar from cornstarch into 1,3-propanediol in a high yield fermentation. According to DuPont, this technology represents the world's lowest cost route to a key chemical intermediate. DuPont has backed this conviction with the construction of new processing factories based on this technology. Propanediol is the principal starting material for polypropylene terephthalate, a new kind of polyester fiber. This novel polyester is unlike others in properties such as stretch recovery, resiliency, toughness and ability to dye easily without requiring chemical modifiers.

In addition to bioplastics, a wide range of nonplastic biopolymers is available for use a thickeners, gelling agents, lubricants and other purposes (Paul et al., 1986; Sutherland, 1994; García-Ochoa et al., 2000; Laws et al., 2001). For example, about 30,000 tons of the polysaccharide biopolymer xanthan valued at US$408 million was being produced by 1999 (Demain, 2000).

3.2.2.4. Cosmetics, toiletries, soaps and detergents. The cosmetics and toiletries industry has traditionally been a major user of biologically sourced materials and fine chemicals. Enzymes are finding use in cosmetics. For example, laccase is used in hair dyeing products. The soaps and detergents industry uses biomass-derived feedstock and enzymes. Most soaps are produced from oils and fats derived from plants and animals. Although biotechnology per se does not appear to be used in processing of soaps and detergents, most washing detergents contain enzymes. Lipases and proteases are added to help in removing oil and protein stains, respectively. In addition, cellulases are added to help prevent pilling of cotton (Kirk et al., 2002). These enzymes are increasingly produced by using genetically modified microorganisms.

Detergent formulations typically contain less than 1% enzyme by volume, but the enzymes contribute about 8% to the cost of the detergent. Biotechnological production of enzymes of course consumes resources, but reduced severity of washing regimens as a result of their use can produce overall benefits. Clothes laundered with enzyme-containing detergents tend to be much cleaner compared to clothes washed with traditional phosphate-containing detergents. Compared with traditional detergents, enzyme-containing detergents may be formulated with less phosphate, to greatly reduce the release of this eutrophication agent to the environment. Enzyme-containing washing detergents are more environment-friendly overall.

Companies such as Henkel (www.henkel.com) have successfully incorporated natural enzymes in detergent formulations since the 1970s. Genetically engineered enzymes have been added to detergents since the late 1980s (Maurer and Kottwitz, 1999). For example, the development of the *Bacillus lentus* alkaline protease (BLAP) is estimated to have reduced environmental pollution associated with detergents, by more than 65%. BLAP-S protease is an example of a genetically modified enzyme that is used in washing detergents. This enzyme has been produced since 1995 and is based on the genetically modified BLAP protease. Microbial proteases have numerous other applications (Kumar and Takagi, 1999).

3.2.3. Agricultural chemicals

Agricultural chemicals, mainly fertilizers and pesticides, are used in massive amounts worldwide to sustain the productivity of land. Because of their widespread use,

agrochemicals are an important source of pollution, health risk, and consume large amounts of resources in their production. Biotechnology can supply useful products that can replace conventional agrochemicals, or enhance their effectiveness so that their overall consumption is reduced. In addition, biotechnology can provide animal feeds with enhanced nutritional and keeping quality, to improve the sustainability of animal production.

3.2.3.1. Biopesticides. Pesticides are used in crop protection, management of weeds, control of insects, treatment of seeds, control of algae in swimming pools and preservation of wood and textiles (Waxman, 1998). A biopesticide is any microscopic biological agent or product derived from microorganisms, for use in controlling insects, weeds and rodent pests. Packaging, handling, storage and methods of application of biopesticides are similar to those for traditional pesticides. Biopesticides have had some spectacular successes, but there have been concerns related to their effectiveness (Auld and Morin, 1995). Approximately US$160 million worth of biopesticides were sold in 2000. Of this, over 90% represented sales relating to Bt products (Vega, 1999). At present, biopesticides capture less than 2% of the global pesticides market but this is expected to increase significantly in the future.

Biopesticides generally tend to be highly target specific, do not leave toxic residues, reduce the risk of resistance development in the target species (Pimentel, 2002) and produce a lesser overall impact on the environment than conventional chemical pesticides. Biofungicides have been used in both the phylloplane and rhizosphere to suppress fungal infection in plants. Species of *Bacillus* and *Pseudomonas* have been successfully used as seed dressings to control certain soilborne plant diseases (Johnsson et al., 1998). Table 6 shows some of the commercial biopesticide products being marketed for use against soilborne plant pathogens.

The variety of biopesticides is already large and increasing (Hall and Menn, 1999; Koul and Dhaliwal, 2002). In addition to biologically produced chemicals, pest pathogenic bacteria, fungi, viruses and parasitic nematodes are being developed or used for managing various pests. Both spore-forming and nonsporulating bacterial entomopathogens are being used or assessed for biopesticidal use. Nonspore-forming species in the Pseudomonaceae and the Enterobacteriaceae families are potential biocontrol agents. The sporeformers *Bacillus popilliae* and *Bacillus thuringiensis* (Bt) are already well-established insecticides.

3.2.3.2. Biofertilizers and soil inoculants. Biofertilizers and inoculants are attracting attention as inexpensive and safe alternative to chemical fertilizers that are used to deliver nitrogen, phosphorus, potassium, sulfur and certain other inorganic nutrients required for crop growth (Subba Rao, 1982). The first generation of biological fertilizers was based on nitrogen fixing rhizobial bacteria found naturally in the root nodules of legumes. These bacteria fix nitrogen from the air, to provide the plant with assimilable nitrogen. Microbial inoculants may be used to complement conventional fertilizers, by enhancing their absorption by plants. Enhanced use of biofertilizers is expected to contribute significantly to reducing pollution, energy and resource consumption associated with the use of conventional fertilizers. The US sales of biofertilizers were US$690 million in 2001 and

Table 6
Some commercial biocontrol products for use against soilborne crop diseases (Pimentel, 2002)

Biocontrol fungus	Trade name	Target pathogen/disease	Crop	Manufacturer
Ampelomyces quisqualis M-10	AQ 10 biofungicide	Powdery mildew	Cucurbits, grapes, ornamentals, strawberries, tomatoes	Ecogen Inc., USA
Candida oleophila I-182	Aspire	*Botrytis, Penicillium*	Citrus, pome fruit	Ecogen Inc., USA
Fusarium oxysporum (nonpathogenic)	Biofox C	*Fusarium oxysporum*	Basil, carnation, cyclamen, tomato	SIAPA, Italy
Trichoderma harzianum and *T. polysorum*	Binab T	Wilt and root rot pathogens, wood decay pathogens	Fruit, vegetables, flowers, ornamentals, turf	Bio-innovation, Sweden
Conothyrium minitans	Contans	*Sclerotinia sclerotiorum* and *S. minor*	Canola, sunflower, peanut, soybean, lettuce, bean, tomato	Prophyta, Biologiscare, Planzenschutz, Malchow/ Poel, Germany
Fusarium oxysporum (nonpathogenic)	Fusaclean	*Fusarium oxysporum*	Basil, carnation, tomato, cyclamen, gerbera,	Natural Plant Protection, Nogueres, France
Pythium oliggandrum	Polygandron	*Pythium ultimum*	Sugar beet	Plant Protection Institute, Slovak Republic
T. harzianum and *T. viride*	Promote	*Pythium, Rhizoctonia, Fusarium*	Greenhouse nursery transplant seedlings; trees and shrubs transplants	JH Biotech, USA

T. harzianum	RootShield, Bio-Trek T-22G, Planter Box	*Pythium, Rhizoctonia, Fusarium, Sclerotinia homeocarpa*	Corn, cotton, cucumber, bean, ornamentals, potato, soybean, cabbage, tomato, turf	Bioworks, USA
Phlabia gigantean	Rotstop	*Heterobasidium annosum*	Trees	Kemira Agro Oy, Finland
Gliocladium virens GL-21	SoilGard (formerly GlioGard)	Damping-off and root pathogens, *Pythium, Rhizoctonia*	Ornamentals and food crops grown in greenhouses, nurseries, homes, interiorscapes	Thermo Triology, USA
T. harzianum	Trichodex	*Botrytis cinerea, Colletotrichum, Monilinia laxa, Plasmopara viticola, Rhizopus stolonifer, Sclerotinia scelrotiorum*	Cucumber, grape, nectarine, soybean, strawberry, sunflower, tomato	Makhteshim Chemical Works, Israel
T. harzianum and *T. viride*	Trichopel, Trichoject	*Armillaria, Botryosphaeria, Fusarium, Nectria, Phytophthora, Pythium, Rhizoctonia*		Agrimm Technologies, New Zealand

are expected to grow to US$1.6 billion by 2006 (Tengerdy and Szakács, 1998). Some biofertilizers and soil conditioners used currently in agriculture are shown in Table 7.

Efforts are under way to engineer non-leguminous plants with symbiotic rhizobial root nodules so that like the legumes they can be grown without the need for added nitrogen fertilizers. In addition, the biofertilizer research is focusing on enhancing the consistency and reliability of performance of products; developing stable formulations and effective delivery systems; demonstration of effectiveness under a range of field conditions; and elucidation of mechanisms of action. Work is underway on producing mycorhizal soil inoculants for enhancing the effectiveness of plant root systems.

3.2.4. Fiber, pulp and paper processing

Through biotechnology and improved silviculture, trees and other bioresources used in papermaking can be specifically tailored to match the properties required in cellulose fibers for different product applications (Buschle-Diller and Ren, 2002). This can greatly increase useful paper yield from trees, enhance product quality and decrease requirements for energy and chemicals used in papermaking. Producing optimal fibers for papermaking through genetic engineering is an important long-term objective that requires a better understanding of fiber biosynthesis in plants. Furthermore, use of engineered micro-organisms and enzymes can displace many of the environmentally adverse practices used in pulp processing. Some of these developments are discussed next.

3.2.4.1. Biopulping. Biopulping is the treatment of wood chips with lignin-degrading fungi prior to pulping. Biopulping is an experimental technology that has been researched extensively mostly as a pretreatment prior to mechanical pulping of wood. Prior biopulping greatly eases subsequent mechanical and chemical pulping by improving penetration and effectiveness of chemicals during the 'cooking' of wood chips for separating the cellulose fibers from the lignin. Consequently, biopulping reduces the demand for energy and chemicals, improves paper quality, and decreases the environmental impact of pulp production (Pullman et al., 1998).

3.2.4.2. Enzyme-aided pulp, paper and textile processing. Enzymes are already well established in processing of pulp and paper. For example, enzymes are used in biobleaching of pulp to reduce chlorine consumption; pulp dewatering and deinking; removal of pitch; degradation of dissolved and suspended organics in concentrated

Table 7
Biofertilizers and soil conditioners used in agriculture (Pimentel, 2002)

Type	Mode of action	Crop	Geographic region
Rhizobium spp.	N_2 fixation	Legumes	Russia, several countries
Cyanobacteria	N_2 fixation	Rice	Japan, several countries
Azospirllum spp.	N_2 fixation	Cereals	Several countries
Mycorrhizae	Nutrient acquisition	Conifers	Several countries
Penicillinum bilaii	P solubilization	Cereals, legumes	Canada
Directed compost	Soil fertility	All plants	Several countries
Earthworm	Humus formation	Vegetables, flowers	Cottage industry

effluents of mills; and enhanced fibrillation to give stronger paper (Ericksson, 1997). Uptake of enzymatic processing has been driven by savings they generate by reducing the use of chemicals and energy and the improved quality of the product that can be attained with there use. Energy savings are produced, for example, by elimination of processing steps, their simplification and reduction of the severity of treatment that would be required in the absence of enzymes.

In kraft pulping, bleaching of the pulp remains one of the most expensive operations and a prime target for cost reduction. Because of the polluting potential of chlorine bleach, pulp mills in the United States and Canada are mostly moving to using bleaching methods that do not require elemental chlorine. This has added to costs. In Canada, about 10% of bleached kraft pulp is now manufactured with xylanase treatment to reduce the consumption of chlorine dioxide and associated costs. Thermostable microbial xylanases that are free of cellulases and active under alkaline conditions of pulping are generally preferred for biobleaching (Raghukumar et al., 2004). Oxidative enzymes such as laccase provide other promising options for reducing costs in pulp mills. Other processing improvements have been obtained by using lipases to control deposits of pitch; cellulases to improve rates of dewatering of pulp; and pectinases for digesting pectins. Ongoing developments will provide engineered enzymes that are better suited to the needs of pulp processing and cost less than enzymes used at present. In the future, it may be possible to manufacture unique paper products by developing enzymes that can be used to control properties of the pulp fiber and, therefore, the end product. For example, the hydrophobicity of fiber surfaces can be altered by the enzyme laccase (Wright, 1998).

In processing of textiles, cellulose pulp is usually bleached with hydrogen peroxide which must be removed before the fibers are colored. The traditional removal of hydrogen peroxide relied on extensive washing in hot water and inorganic salts. Use of catalase to convert residual hydrogen peroxide to water and oxygen has meant that the bleached fibers need be rinsed only once (http://www.bio-pro.de/en/region/ulm/magazin/00698/). The enzymatic process saves water and energy and the effluent is ecologically harmless.

3.2.4.3. Attaining total water recycling in paper mills. Production of paper consumes huge amounts of water. Extensive research is underway in treating the wastewater from paper mills, for total recycling. Pulp and paper mills in Canada are aiming for total effluent reuse after secondary and tertiary biotreatment. Wastewater recycling potentially saves on the expense of treating any freshwater entering the mill and greatly reduces the environmental impact of effluent disposal.

3.2.4.4. Biotechnology for paper recycling. Market for recycled paper is substantial, global and profitable. Recycled newspaper reduces input of new resources in the pulp and paper industry. Recycled newspaper needs to be deinked before it can be used to make new newsprint and white paper. A deinking process involving sodium hydroxide, flocculants, dispersants and surfactants is used widely currently. The alkali can yellow the treated pulp and, consequently, hydrogen peroxide is used subsequently to bleach the alkali deinked pulp. In addition, alkaline deinking diminishes the strength of the pulp fiber and the chemicals used contribute to environmental pollution. An enzyme-based biotechnology alternative to chemical deinking is being developed. Enzymes can facilitate

dewatering of pulp and removal of contaminants without reducing the strength of the recycled pulp fibers. Speedier dewatering improves sheet formation and allows faster processing in paper machine (Jackson et al., 1993; Rutledge-Cropsey et al., 1998; Pala et al., 2001).

In the enzymatic process, cellulase and hemicellulase enzymes are mixed with the paper pulp. The enzymes hydrolyze some of the surface sugars on the pulp fiber and this releases the ink particles bound to the fiber. Washing and draining of the pulp remove most of the ink. Any remaining ink is removed during a conventional flotation step. Treatment with alkali is not used and this eliminates the need for subsequent bleaching with hydrogen peroxide. Any residual enzymes are deactivated during drying of the paper. Enzymatic deinking works with old newsprint and office waste paper. Unlike conventional deinking, the enzyme treatment effectively removes laser printer and photocopier inks that are mostly found in office wastepaper (Prasad, 1993).

3.2.5. Bioenergy and fuels

Biotechnology-based production of fuels continues to attract much attention. Bioethanol (Wyman, 1996; Roehr, 2001), firewood, biogas, biodiesel (Graboski and McCormick, 1998) and biohydrogen (Nandi and Sengupta, 1998) are examples of biofuels. Except for biohydrogen, commercial or pilot experimental use of the other biofuels is already established or emerging.

Although bioconversion of lignocellulosic biomass to sugars for fermentation to ethanol has been extensively studied (Aden et al., 2002), it remains intractable. More successful and widely used is the bioconversion of starch to sugars for producing bioethanol. Similarly, fuel ethanol produced from residues of cane and beet sugar processing has been in use for several decades. Anaerobic digestion of organic waste to methane is another widely used technology. Modern biotechnology has already greatly impacted the traditional production of bioethanol. For example, the higher yielding genetically modified corn reduces cost of the main feedstock; the starch in gene engineered corn is more amenable to enzymatic bioconversion to sugars, than natural corn starch; microbial enzymes have been engineered for enhanced stability and ability to rapidly convert starch to fermentable sugars; microorganisms have been engineered to withstand higher levels of toxic ethanol and achieve rapid fermentation. These and other future improvements will make bioethanol more economic than it is today. Similar advances are being targeted for enhancing anaerobic digestion technologies.

Blending of gasoline with bioethanol directly reduces consumption of fossil fuels and environmental pollution (e.g. volatile organic compounds, nitrous oxides, benzene and particulates) associated with combustion of unblended gasoline. Similarly, biodiesel is significantly less polluting than petrodiesel. Conversion of biomass to energy is highly attractive. Although in energy terms annual land production of biomass is about five times the global energy consumption, only 1% of commercial energy originates from biomass at present (OECD, 1998). Organic waste from landfill sites and farms can be converted to combustible biogas (approximately 55% methane and 45% carbon dioxide) through anaerobic digestion (OECD, 1998). Liquid hydrocarbon fuels can be produced from plant, animal and microbial oils.

3.2.6. Bioprocessing of biomass to produce industrial chemicals

Nearly US$24 billion worth of hydrocarbon feedstocks are used annually in the chemical industry. Hydrocarbon purchases represent the major share of the industry's raw materials costs. As reserves of high-quality fossil fuels are depleted, other renewable sources will need to be found for any hydrocarbon feedstocks that cannot be substituted. These resources include renewable vegetable, animal and microbial matter. A change of feedstocks from fossil hydrocarbons to plant-derived matter will dramatically restructure chemical manufacture to enable sustainable production. Local agricultural production would provide the feedstocks. Local availability of feedstock, reduced energy demand for processing, less need for waste disposal and efficient production would mean that small production facilities located close to markets would become economically viable, particularly for high-value products. Net decreases in emissions of greenhouse gases would be achieved without compromising the current quality of life. In fact, until the 1930s, most bulk chemicals were produced from biomass such as corn, potatoes, wood and plant oils by chemical and fermentation processes. Modern biotechnology is greatly expanding the scope of what is possible and the capability of traditional biomanufacturing. Primary resources are already providing a remarkable diversity of industrial and consumer goods (Table 8).

3.2.7. Environmental biotechnology

Treatment of municipal wastewater by activated sludge method was perhaps the first major use of biotechnology in bioremediation applications. Activated sludge treatment remains a workhorse technology for controlling pollution of aquatic environment. Similarly, aerobic stabilization of solid organic waste through composting has a long history of use. Both these technologies have undergone considerable improvement. More recently, microorganisms and enzymes have been successfully used in diverse bioremediation applications (Pletsch et al., 1999; Macek et al., 2000; Gavrilescu, 2004b; Jördening and Winter, 2004). Effective and controlled bioremoval of nitrate and phosphate contamination from wastewater has become possible (Khin and Annachhatre, 2004; Liu and Tay, 2004). Biotechnology is already playing a major role in maintaining a clean environment and this role will expand substantially as methods are developed and deployed for bioremediation of all kinds of industrial effluents. Rapid and highly specific detection of numerous pollutants has become possible by using biosensors (Baeumner, 2003; Wolfbeis, 2004).

Table 8
Common products from biomass

Biomass resource	Uses
Corn	Solvents, pharmaceuticals, adhesives, starch, resins, binders, polymers, ethanol
Vegetable oils	Surfactants in soaps and detergents, pharmaceuticals (inactive ingredients), inks, paints, resins, cosmetics, fatty acids, lubricants, biodiesel
Wood	Paper, building materials, cellulose for fibers and polymers, resins, binders, adhesives, coatings, paints, inks, fatty acids, road and roofing pitch

Microorganisms have been isolated, selected, mutated and genetically engineered for effective bioremediation capabilities (Renner, 1997; Pieper and Reineke, 2000) including the ability to degrade recalcitrant pollutants, achieve enhanced rates of degradation of target compounds, and assure better survival and colonization in target polluted niches. Microorganisms and to a lesser degree enzymes have been the main focus of the effort for improving bioremediation capabilities, but use of higher plants in phytoremediation is a significant developing area (Macek et al., 2000; Glick, 2003). Increasing emphasis is being placed on using ecologically integrated mixed bioremediation systems. Bioremediation processes have been established for both in situ and ex situ treatment of contaminated soil and groundwater. When applicable, bioremediation can offer significant cost and environmental benefits in comparison with alternative technologies. In view of the polluting potential of chemical industry, bioremediation technologies (Lee and de Mora, 1999; Jördening and Winter, 2004; Khan et al., 2004) offer the industry significant new tools for enhancing profitability and sustainability.

As with contaminated water and soil, bioremediation has proved useful in reducing emissions of vapors of organic compounds particularly from gaseous effluents that are low in VOCs (Moo-Young and Chisti, 1994; Deshusses, 1997; Jorio and Heitz, 1999; Burgess et al., 2001; Cohen, 2001). VOC emissions are generally produced in processes involving drying of products (Lewandowski and DeFilippi, 1997; Hunter and Oyama, 2000; Penciu and Gavrilescu, 2004). Two main biotechnology processes are available for removing VOCs from gases. In one option, the gaseous effluent is scrubbed with an aqueous medium with or without suspended microorganisms, to absorb the VOCs in the scrub liquid where they are degraded by microbial action (Moo-Young and Chisti, 1994). The VOC containing liquid leaving the scrubber may be recycled through a separate aerated slurry suspension bioreactor where most of the degradation takes place. Alternatively, the VOC containing liquid effluent may be passed over a trickle bed of immobilized microorganisms to achieve degradation of the dissolved pollutants. Another method that is used frequently is direct biofiltration of the effluent gas through a porous bed of soil, or other particulate matter, that supports the VOC degrading microbial community (Moo-Young and Chisti, 1994; Deshusses, 1997; Jorio and Heitz, 1999; Burgess et al., 2001; Cohen, 2001). The moisture content in the bed is controlled by spraying with water and humidification of the gaseous effluent entering the bed.

Appropriately selected biofilters have proved quite effective in removing VOCs. A case in point is the trickling biofilter system installed by the BIP Ltd, UK, for removing and degrading VOCs in its gaseous effluent (Bio-Wise Case Study 7, Department of Trade and Industry, Oxfordshire, UK, 2001). The biofilter achieved compliance with emission legislation in a safe manner and saved the company up to £100,000 annually on running costs compared with the alternative technology of incineration. The capital expense of installing the biofilter was about £500,000 lower compared with the incineration alternative.

3.2.8. Role of transgenic plants and animals

Transgenic animals and plants are potentially versatile chemical factories (Hood and Jilka, 1999; Giri and Narasu, 2000; Larrick and Thomas, 2001; Jaworski and Cahoon, 2003; Wheeler et al., 2003; Mascia and Flavell, 2004). Compared to their conventional

counterparts, transgenic plants offer many advantages, including: superior yields; lower demand for fertilizers and pesticides; better tolerance to adverse environments and pests; improved nutrition and other functional qualities; ability to generate products that a crop does not produce naturally; and reduced cost of production (Bohnert and Jensen, 1996; Murphy, 1996; Hirsch and Sussman, 1999; Jaworski and Cahoon, 2003; Mascia and Flavell, 2004).

In 2003, global acreage planted with biotech crops already amounted to 167 million acres in 18 countries, representing a 15% increase in acreage over 2003. Major transgenic crops cultivated include soybean, maize, cotton, canola, squash and papaya. Dozens of other transgenic crops are expected to enter commerce over the next few years. Some of the major commercial players in plant biotechnology include Syngenta, Monsanto, Bayer CropScience, DuPont/Pioneer Hi-Bred, Dow AgroSciences and BASF. In the United States in 2002, over US$20 billion in crop value was associated with biotech commercial crop varieties. This will increase rapidly as transgenic plants are put to use for "biopharming", or production of pharmaceuticals in plants. Potentially, oil crops can be engineered to produce less toxic and biodegradable industrial lubricant oils, to reduce dependence of the lubricants sector on petroleum derived products. High euricic acid canola oils have found applications as industrial lubricants. By 2003 the levels of adoption of transgenic crops in the US were 40% for corn, 81% for soybeans, 73% for cotton and 70% for canola (Runge and Ryan, 2003).

4. Concluding remarks

The application of biotechnology across various industry sectors has invariably led to both economic and environmental benefits including less expensive processing, enhanced product quality, entirely new products, and environmentally sustainable processing relative to conventional operations. Economic drivers are the main factor for increasing acceptance of bioprocessing and bioproducts, but sustainability considerations are playing an increasing role.

In effect, the application of biotechnology has contributed to an uncoupling of economic growth from adverse environmental impact. Industrial biotechnology is changing the way energy, chemicals, and other products are produced. Through engineered biocatalysis, biotechnology is enabling the use of previously unusable renewable materials and production of novel products. Functionally acceptable products that are less polluting and persistent than conventional counterparts are emerging. All this is being achieved with reduced environmental impact and enhanced sustainability. Undoubtedly, biotechnology is set to transform industrial production to a basis that is more compatible with the biosphere.

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