Biotechnology and Cleaner Production in Canada

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May 2000

The authors thank the Program for Energy Research and Development (PERD) for providing financial support during the development of this report.

Acknowledgements

The Life Sciences Branch of Industry Canada would like to acknowledge the constructive comments and suggestions provided by federal colleagues from the following departments who formed the steering committee for this project: Environment Canada, National Research Council of Canada, Natural Resources Canada, Agriculture and Agrifood Canada and Industry Canada.

This publication is also available electronically on the World Wide Web at the following address:

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Catalogue No. C47-3/2000E
ISBN 0-662-28957-9
53115E

Aussi disponible en français sous le titre *La biotechnologie au service d'une production plus propre au Canada*.

PRINTED IN CANADA / IMPRIMÉ AU CANADA

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Preface

This study examines the use of biotechnology for cleaner production (i.e., greater energy efficiency as well as reduced emissions of greenhouse gases and toxic substances) in a number of Canadian industry sectors. Both current uses and potential uses are considered.

The overall aim is to build awareness among Canadian stakeholders about applications of biotechnology for cleaner production in key industry sectors. This will lay the foundation for promoting greater use of biotechnology in Canadian industry.

The specific objectives of the study are:

- to develop a better understanding of where biotechnology is or could potentially be used for cleaner production in a number of Canadian industry sectors;
- to examine the capacity of Canada's research community to use biotechnology for developing cleaner industrial process technologies with environmental/economic benefits;
- to assess the receptor capacity in user industries to adopt these cleaner bioprocess technologies and capture the potential environmental/economic benefits; and
- to identify measures for improving Canada's research and receptor capacities including investments in strategic research as well as removal of barriers to innovation so biotechnology can be used more extensively for cleaner industrial production in Canada.

This is by no means the final word on such a broad and diverse field. It is recognized that many Canadian organizations and initiatives have probably been overlooked in this first-time study and therefore the authors would be grateful to receive any additional information which could be used to improve and update this report.

The authors thank the Program for Energy Research and Development (PERD) for providing financial support as well as advice and comments during the development of this report. Also, the authors are grateful for the information and advice provided by the experts consulted during the course of this study. They would also like to acknowledge the constructive comments and suggestions provided by federal colleagues who formed the steering committee for this project:

- Environment Canada;
- The National Research Council;
- Natural Resources Canada;
- Agriculture and Agrifood Canada;
- Industry Canada.

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Executive Summary

Public concern for the Canadian and the global environment is resulting in increased pressure for industry to focus on pollution prevention rather than end-of-pipe cleanup. Industry is responding by modifying existing production processes or developing entirely new ones to achieve cleaner production (i.e., greater energy efficiency as well as reduced emissions of greenhouse gases and toxic substances). Many companies are beginning to find that cleaner production not only reduces environmental liabilities but also reduces costs and increases both productivity and competitiveness.

Recent advances in genomics and biochemistry have made biotechnology one of the key emerging technologies with the potential to solve present environmental problems and prevent future ones in a way that does not set industrial development and environmental protection in opposition.

Basically, biotechnology is the use of living organisms or parts of organisms to produce goods and services. The most familiar applications of biotechnology are in the healthcare sector (e.g. bio-pharmaceuticals) and in the agrifood sector (e.g. genetically engineered crops). However, it is applicable across a wide range of industry sectors where its impact may range from incremental improvements to major paradigm shifts in production processes. When incorporated into an overall industrial process, biotechnology has the potential to contribute to cleaner production in four main ways:

- **biocatalysis** - more efficient processes catalysed by enzymes or microorganisms
- **use of renewable feedstocks** - biomass as the source of renewable energy and chemicals
- **abatement** - limiting the spread of pollution through biologically mediated processes;
- **remediation** - biologically mediated cleanup and restoration of existing contamination.

A number of industry sectors, especially resource processing sectors, could move toward a more sustainable future through biotechnology.

Not all problems associated with achieving cleaner production can be eliminated using biotechnology; nevertheless, biotechnology has proven itself to be a flexible and powerful tool for solving many such problems. As a result, an international trend is developing toward increasing application of biotechnology for cleaner production in a range of industry sectors, some of great importance to the Canadian economy (e.g., Forestry, Pulp & Paper, Chemicals & Plastics, Energy, Mining). According to estimates recently released by the National Climate Change Process[1] , and the National Pollution Release Inventory, these same sectors account for almost 40% of total industrial energy use, 60% of total industrial greenhouse gas emissions and

[1] Canada's Emissions Outlook: An Update. National Climate Change Process, Analysis and Modeling Group. December 1999.

50% of industrial pollutants released to the environment in Canada.

In the Energy Sector, biotechnology has the potential to save energy in petroleum production by helping remove sulfur from natural gas and petroleum as well as helping reduce the viscosity of heavy oil. It also has the potential in future to help decrease fossil fuel consumption for transportation by:

- substituting a portion of gasoline with renewable-source ethanol, and
- providing a biological means of producing methanol as a renewable energy source for fuel cells.

In the Chemicals & Plastics Sector, bioprocesses have been developed which:

- reduce energy consumption of existing chemical processes;
- reduce the production of waste by-products; and
- synthesize specialty chemicals which could not be produced using conventional chemical synthesis.

Bioprocesses are also proving their value in utilizing renewable resources to produce monomers for plastics such as polyester and also to produce biodegradable plastics.

In the Forestry Sector, biotechnology can not only be used as a tool to assess forest biodiversity but also as part of an integrated pest management system. It can be used to select faster growing, disease resistant stock for replanting of harvested forests or to engineer trees which are designed for specific end-uses and which will be grown in intensively managed tree plantations. Biotechnology also has a role to play post-harvest in helping replace or reduce the use of chemical wood preservatives. In the Pulp & Paper Sector, enzymes are used in bioprocesses which help reduce the amounts of energy and chemicals used in treating and bleaching pulp as well as in recycling of paper products.

Biotechnology also has potential in the Mining Sector to help replace high temperature processes such as roasting and smelting with bioleaching and bio-oxidation processes. These bioprocesses are carried out at ambient temperatures and avoid some of the air pollution problems associated with the conventional high-temperature processes.

Industrial applications of modern biotechnology are still in their early days. Nevertheless, it is becoming clear that Canada's economy, environment and the quality of life of its citizens can benefit from the adoption of biotechnology for cleaner production in a number of key industry sectors.

Canada has a strong research base in the chemical and biological sciences as well as in related engineering disciplines. In addition, there is a critical mass of technology development companies with the expertise in biotechnology required to create novel products and the processes for manufacturing them. Major receptor industries are present in the energy, forest, mining, chemicals and plastics sectors. Canada also has major biomass resources and is also recognized as a leader in plant biotechnology. There are programs which can support a full range of activities from basic research to technology demonstration. Thus, Canada has the elements to be the ideal place for developing the next generation of "green" resource, energy and chemical industries which utilize renewable feedstocks and which use biotechnology to achieve the eco-efficiency / productivity required for long term sustainability.

Although the elements for capitalizing on these opportunities are present in Canada, there are also a number of weaknesses and barriers. Some of these were identified during consultations held in 1997-98 which led to the renewal of the Canadian Biotechnology Strategy. There is presently little marketplace demand for cleaner fuels, chemicals or other products derived from cleaner production and/or renewable resources. The receptor capacity in the resource industries is weak for biological technologies and processes. Biotechnology development companies are mostly small and have difficulty attracting investment (except in the bio-pharmaceutical field) or the interest of the resource companies. The multidisciplinary research required to provide the bio-science and bio-technology for a sustainable future is fragmented and there is little consensus on priorities or how to set them. There is also a need for scientifically validated protocols to measure the performance of biotechnologies relative to conventional process technologies and resources are lacking to develop and help apply such protocols. Centrally located, limited access sites are needed to allow for proof of concept and validation work at realistic scale for both cleanup and cleaner production technologies. Finally, coordinated efforts are required to inform the public of the benefits of industrial biotechnology and how potential risks are being managed before the products are in the marketplace to enhance consumer confidence and improve user uptake.

Addressing these weaknesses and barriers so bioprocesses and bioproducts can become an integral part of a clean technology portfolio will require:

- sustained support for strategic research in universities, government laboratories and other research organizations;
- measures to support technology transfer, industrial innovation and skills development in this area;
- a commitment by government and industry to bio-technology demonstration, performance assessment and validation projects;
- increased awareness in industry, government, the investor community, the media and the public about the potential of biotechnology for contributing to clean production and industrial sustainability, and
- leadership by all levels of government.

Other countries are actively investing in biotechnology as part of their cleaner production strategies. In the US, the budget for biomass fuels research is proposed to increase from US$196 million in 2000 to US$436 million in 2001. This spring, Germany is planning to launch a multi-million Mark program on biotechnology and industrial sustainability. The U.K. is also launching an £ 11 M program to stimulate research into environmental applications of genomics.

This document is by no means the final word on such a broad and diverse field. Rather it is a call to recognize the strategic implications and opportunities presented by industrial biotechnology early on in what is predicted to be the 'biotech century'. Canada needs to position itself competitively to seize these opportunities for improving its economy, its environment and the quality of life of its citizens and their future generations.

1. Introduction

Public concern for the Canadian and the global environment is resulting in increased pressures for industry to focus on pollution prevention rather than end-of-pipe cleanup. Industry is responding by modifying existing production processes or developing entirely new ones to achieve cleaner production (i.e., greater energy efficiency as well as reduced emissions of greenhouse gases and toxic substances). Many companies are beginning to find that cleaner production not only reduces environmental liabilities but also reduces costs and increases both productivity and competitiveness.

Recent advances in genomics and bio-chemical sciences have made biotechnology one of the key emerging technologies having the potential to solve present environmental problems and prevent future ones in a way that does not set industrial development and environmental protection in opposition to one another.

Basically, biotechnology is the use of living organisms or parts of organisms to produce goods and services. It is really a set of technologies which are applicable across a wide range of industry sectors where its impact may range from incremental improvements to major paradigm shifts in production processes. Biotechnology is now being used by leading companies to develop approaches to industrial production which not only prevent pollution but also save costs and increase competitiveness. As a result, an international trend is developing toward increasing application of biotechnology for cost savings through cleaner production in a range of industry sectors, some of great importance to the Canadian economy.

When incorporated into an overall industrial process, biotechnology has the potential to contribute to cleaner production in four main ways:

- **biocatalysis** - more efficient processes which are catalyzed by enzymes or microorganisms and which use less inputs (energy and materials) and produce less greenhouse gases and/or less hazardous by-products for the same level of output, compared to conventional process technologies;
- **use of renewable feedstocks** - growing biomass to sequester the greenhouse gas, carbon dioxide, from air and utilizing that biomass as the source of renewable (i.e., greenhouse gas neutral) energy and chemical feedstocks, thus reducing dependence on fossil fuels;
- **abatement** - limiting the spread of pollution through processes such as biological filters for contaminated air or artificial wetlands for contaminated water, both of which save costs and energy as compared to air scrubbers or chemical treatment methods; and
- **remediation** - cleanup and restoration of existing contamination (bioremediation, phytoremediation, ecological reconstruction) often saving costs and energy when used at the contaminated site as compared with removal to a landfill or a treatment facility.

This document will focus primarily on the use of biotechnology to reshape industrial processes to improve energy efficiency, reduce greenhouse gas emissions and prevent or reduce pollution at the source and not so much on cleaning up waste streams or contaminated sites. This does not mean that abatement and remediation are not relevant to cleaner production. In fact, they can provide cost effective means of minimizing the environmental impacts of industrial activity. Also, the microbiological expertise in bioremediation companies can provide the basis to identify microorganisms which metabolize chemicals such as PCBs or produce potentially valuable by-products and these organisms could then be used as the starting biological materials for developing cleaner biocatalytic processes for industrial applications.

The concept of "cleaner technology" has been defined by the Organisation for Economic Cooperation and Development (OECD) as : *"...technologies that extract and use natural resources as efficiently as possible; that generate products with reduced or no potentially harmful components in all stages of their lives; that minimize releases to air, water and soil during fabrication and use of the product; that produce durable products which can be recovered or recycled as far as possible; and are energy efficient."*[2]

One major attractive feature of including biotechnology as a part of a cleaner technology portfolio is that it has the potential to offer both economic[3] and environmental[4] benefits to industries which adopt it as well as societal benefits to countries which learn how to encourage its responsible use. Also, with concern growing over greenhouse gas emissions and climate change, there is increasing recognition of the importance of biotechnology for enabling greater utilization of biomass as a greenhouse-gas-neutral feedstock for producing energy, chemicals and durable consumer goods.

This study aims to build awareness among Canadian stakeholders about applications of biotechnology for cleaner production in key industry sectors and also to lay the foundation for a new direction within the Office of Energy Research and Development - Program on Energy Research and Development (OERD-PERD) that recognizes the considerable potential for the use of bio-processes and bio-products in Canadian industry to increase energy efficiency, reduce greenhouse gas emissions and reduce pollution at source. It will also contribute to development of a policy agenda and strategic plan in this area.

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[2] OECD, Technologies for Cleaner Production and Products (1995).

[3] Cost savings from increased efficiency and reduced environmental liabilities can contribute to increased competitiveness .

[4] Cleanup as well as pollution prevention through cleaner production.

The specific objectives of the study are:

- to develop a better understanding of where biotechnology is or could potentially be used for cleaner production in different industry sectors;
- to examine the capacity of Canada's research community to use biotechnology for developing cleaner industrial process technologies with environmental/economic benefits;
- to assess the receptor capacity in user industries to adopt these cleaner technologies and capture the potential environmental/economic benefits; and
- to identify policies for improving Canada's research and receptor capacities including strategic investments and removal of barriers to innovation so biotechnology can be used more extensively for cleaner industrial production in Canada.

2. Methodology

The approach taken for this study included the following steps:

- Literature sources, including one from the OECD[5], were used to identify key Canadian industry sectors in which biotechnology has the best potential for contributing to clean production. The identified sectors are: Chemicals and Plastics, Forestry and Forest Products, Energy, Mining and Mineral Processing and Food Processing.
- The relative energy consumption and emissions of greenhouse gases and toxic substances in the selected industry sectors as a percent of the total were identified using data from the National Climate Change Process as well as the National Pollution Release Inventory.
- Discussions were held with experts in the identified sectors.
- Searches were carried out for additional information via the Internet.
- The assessment and conclusions were validated through discussions and consultations with industry and the research community (ongoing).

[5] OECD, Biotechnology for Clean Industrial Products and Processes, (1998).

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3. Energy Use and Emissions of Greenhouse Gases and Polluting Substances In Selected Sectors

This section examines the relative contribution of the sectors likely to be impacted by biotechnology to the overall energy use as well as emissions of greenhouse gases and polluting substances in Canada.

3.1 Energy Use

In 1997, the total industrial energy use was 3427.8 petajoules (1 petajoule = 10^{15} joules) while total energy use in transportation was 2401.6 petajoules [6] . Together these two sectors account for 70% of all the energy used in Canada in that year (8313.6 petajoules).

3.1.1 Energy Use in Industry

In 1997, 38% of all the energy consumed by Canadian industry was in industry sectors where biotechnology may contribute to energy savings through cleaner production. The percent of total projected industrial energy use represented by these sectors is estimated to remain roughly constant at 38- 40% out to the year 2020 as shown in the table below. These projections do not factor in any influence from the use biotechnology.

Table 1: Projected Energy Demand in Selected Canadian Industry Sectors (in petajoules)

Sector	**2000**	**2005**	**2010**	**2015**	**2020**
Pulp & Paper Mills	395.5	411	442	477.6	502.8
Forestry	10.4	10.6	11.1	11.4	11.4
Chemical	286.1	307.5	340.7	384	424.8
Mining	150.5	155.8	164.3	177.2	190.3
Smelting and Refining	232.5	262.4	281.4	298.2	311.7
Petroleum Refining	311	290.5	302	318.1	334.6
Total for above	1386	1437.8	1541.5	1666.5	1775.6
Total industrial	3561.3	3734	3963.1	4174.2	4386.5
Ratio of totals (%)	38.9	38.5	38.9	39.9	40.5

3.1.2 Energy Use in Transportation

[6]Data in sections 3.1 and 3.2 are from: "Canada's Emissions Outlook: An Update." National Climate Change Process, Analysis and Modeling Group. December 1999.

In the transportation sector, motor gasoline supplies approximately a constant 53% of the total projected energy demand over the period 2000-2020. This 53% amounts to 1316.9 petajoules in 2000 and 1718 petajoules in 2020, almost the same amount as in the total for the selected industry sectors above. It is not likely that biotechnology will lead to a decrease in overall energy consumption in the transportation sector; however, it could contribute to decreased net greenhouse gas emissions by replacement of fossil fuels with fuels derived from renewable biomass (see Section 3.2).

3.2 Emissions of Greenhouse Gases

In 1997, the total industrial emissions of greenhouse gases were 127 megatons of CO_2 equivalent while total emissions from transportation were 172 megatons of CO_2 equivalent. Together these two sectors account for 44% of all the greenhouse gas emissions in Canada in that year (682 megatons of CO_2 equivalent).

3.2.1 Greenhouse Gas Emissions by Industry

In 1997, 62% of total industrial greenhouse gas emissions in Canada came from industry sectors where biotechnology may contribute to cleaner production. The percent of total projected industrial emissions of greenhouse gases produced by these sectors is estimated to remain roughly constant at 59-60% out to the year 2020 as shown in the table below. These projections do not factor in any influence from the use biotechnology.

Table 2: Projected Greenhouse Gas Emissions in Selected Canadian Industry Sectors (in megatons CO_2 equivalent)

Sector	2000	2005	2010	2015	2020
Pulp & Paper	12.1	12.4	13.3	13.6	13.7
Forestry	0.7	0.7	0.7	0.7	0.7
Chemical	20.2	22.1	23.1	25.3	27
Mining	6.9	7.5	7.7	8	8.5
Smelting and Refining	12.8	12.9	12.6	12.9	13.2
Petroleum Refining	21.3	22.3	23.2	24.9	26.8
Total for above	74	77.9	80.6	85.4	89.9
Total industrial	125.3	130	137.8	144.1	152.5
Ratio of totals (%)	59	60	58.5	59.3	59

3.2.2 Greenhouse Gas Emissions from Transportation

In the transportation sector, motor gasoline accounts for approximately a constant 53% of the total projected greenhouse gas emissions over the period 2000-2020. This 53% amounts to 94.9 megatons of CO_2 in 2000 and 121.6 in 2020, about 30% more than in the respective totals for the selected industry sectors above. While it is not likely that biotechnology will lead to a decease in overall energy consumption in the transportation sector, it is probable that biotechnology will help replace some percent of motor gasoline either with ethanol[7] or by providing some of the fuel (e.g. methanol[8]) used by fuel cells. Both the ethanol and methanol could be produced from renewable resources and could lead to significant reductions in net greenhouse gas emissions.

3.3 Emissions of Polluting Substances

The National Pollution Release Inventory (http://www.ec.gc.ca/pdb/npri/) provides information on releases of pollutants from industrial facilities above a threshold size across Canada. In 1997, the Index reported on 176 pollutants and measured both on-site releases to the environment as well as off-site transfer for disposal. Total on-site releases of the 176 pollutants for all industries were 161,876 tonnes and 51% of this came from industry sectors where biotechnology may contribute to cleaner production. Total off-site transfers for disposal of the 176 pollutants for all industries were 94,341 tonnes and 48% of this came from industry sectors where biotechnology may contribute to cleaner production.

3.4 Relative Importance of Sectors Likely to be Impacted by Biotechnology

Industry sectors where biotechnology may contribute to cleaner production account for about 40% of total energy consumption, 60% of total greenhouse gas emissions and 50% of total pollution released to the environment by all industry sectors in Canada.

In the transportation sector, motor gasoline (which could be partly replaced by ethanol produced through biotechnology) accounts for 53% of total energy consumption and 53% of total greenhouse gas emissions.

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[7]Automobiles are now coming on the market which can run on 85% ethanol 15% gasoline.

[8]Researchers at the University of Illinois have developed a process which uses three enzymes (formate dehydrogenase, formaldehyde dehydrogenase and alcohol dehydrogenase) *in vitro* (i.e., without using living organisms) to convert carbon dioxide into methanol. (Chemical Week, 9 Feb. 2000, page 33). At present the process is uneconomical and it may take years of R&D to make it competitive; nevertheless, it represents a very interesting potential use of biotechnology.

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4. Sectoral Descriptions

4.1 The Canadian Chemicals and Plastics Industry

Decision Resources (http://www.dresources.com/), a major business intelligence and market analysis firm has produced a report[9] on the impact of biotechnology in the global chemicals industry and concluded the following:

- The stage is being set for a biological transformation of the chemical industry in the 21st century.
- The blurring of traditional boundaries separating chemistry and biology in production strategies is a growing trend.
- Leading companies such as DuPont (http://www.dupont.com), Dow Agrosciences (http://www.dowagro.com), AVENTIS (Hoechst and Rhone Poulenc merger), Novartis (http://www.novartis.com) and Monsanto (http://www.monsanto.com/) which will merge with Pharmacia-Upjohn (http://www.pnu.com/) are reinventing themselves as "life sciences" companies or using acquisitions and strategic alliances to take advantage of the increasingly important role of biotechnology.
- Those companies that can stay ahead of the curve in terms of both understanding the strategic pathways coming to light and exploiting these avenues through biotech-based R&D will be the companies that grow and prosper throughout the coming century.

Advances in three key areas of biotechnology are driving this transformation of the chemical industry:

- **biocatalysis** - the use of microorganisms and especially enzymes to catalyze certain reactions and the use of molecular biology techniques to modify enzymes so they will have specific catalytic properties;
- **metabolic engineering** - genetically engineering plants, animals and especially microorganisms, to have all the biocatalytic steps for production of a particular chemical contained within their cells so that the cells are in effect highly efficient mini reactors; and
- **plant biotechnology** - genetic engineering of plants to have specific characteristics (e.g. lower levels of lignin or higher levels of starch) which increase the efficiency and yield when they are processed into certain products.

In 1995, chemicals and chemical products constituted the fourth largest manufacturing sector in Canada in terms of sales. The Canadian chemicals sector may be divided into the following segments (see http://STRATEGIS.ic.gc.ca, Business Information by Sector, Chemicals):

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[9] Decision Resources, Biotechnology's Impact on the Chemical Industry, (1998).

- Industrial chemicals
- Fine chemicals
- Agricultural chemicals
- Formulated chemicals.

4.1.1 Industrial Chemicals

Industrial chemicals include both inorganic and organic chemicals (petrochemicals and resins) and they account for about 43% of the overall chemical sector in Canada. In 1995, this segment of the industry had about 300 establishments employed 23,000 people and had shipments of $14.4 billion (1.7% of the global market) of which 63% was exported (3% of world exports). Most of the firms in this segment of the industry are Canadian subsidiaries of US and European multinational firms. In the 1980's, restructuring and rationalization of North American production caused Canadian establishments to become more fully integrated into the global operations of the multinational chemical firms where they now specialize in certain products or lines of products based on their capabilities and cost of production.

4.1.1.1 Biotechnology Applications

A) Bioprocessing of petrochemicals to produce industrial chemicals

One example of bioprocessing applied to petrochemicals is the production of polymer-grade ammonium acrylate from acrylonitrile. The conventional chemical process for producing ammonium acrylate is energy intensive and yields by-products which are difficult to remove. For over ten years, Nitto Chemical Company of Tokyo has had a commercial scale process which uses a bacterial enzyme to produce high purity ammonium acrylate. The enzyme biocatalytic process uses less energy and produces less by-products[10].

Bioprocesses to remove sulfur and cleave aromatic rings from heavy oil are used in the Energy Sector (see Section 4.3); however, these energy-saving processes are also relevant for processing industrial petrochemicals and are being pursued by companies such as Bio-Technical Resources[11] (Manitowoc, Wisconsin; URL: http://www.biotechresources.com).

In general, bioprocesses are not yet well adapted to handle non-aqueous organic chemicals derived from petroleum. As a result, most industrial chemicals which are manufactured using biotechnology are derived from renewable biomass feedstock.

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[10]OECD, Biotechnology for Clean Industrial Products and Processes, p. 30 (1998).

[11]Decision Resources, Biotechnology’s Impact on the Chemical Industry, p. 18 (1998).

B) Bioprocessing of biomass to produce industrial chemicals

As mentioned in the Introduction, the use of biomass as a feedstock can promote carbon sequestration, reduce fossil fuel consumption and lead to a net decrease in greenhouse gas emissions. Until the 1930's, most bulk chemicals were produced from biomass such as corn and potatoes by fermentation using selected natural microorganisms. These fermentation processes were largely displaced by developments in chemistry and inorganic catalysis so that chemicals derived from petroleum now dominate the industrial chemicals market. Advances in biocatalysis and metabolic engineering of microorganisms as well as the realization that petrochemical resources are finite have set the stage for reintroducing fermentation of biomass as an economical means of producing many bulk chemicals (see Alper[12]).

Royal Dutch Shell (http://www.shell.com) has predicted that in the first half of the 21st century, biomass will come to supply 30% of worldwide needs for chemicals and fuels, accounting for a market of approximately US $ 150 billion[13] .

In Canada, ethanol derived from grain is presently the only industrial chemical produced at commercial scale using biotechnology. The US also produces fuel ethanol, mostly from corn. Ethanol requires tax concessions in both countries in order to be cost competitive as a replacement for gasoline. (See Section 4.3.2 for more information.)

Iogen is a Canadian company that is a leader in developing bioprocessing methods for producing ethanol from waste cellulosic material rather than grain or corn. Use of waste cellulose to replace grain or corn as starter material promises to improve the economics of ethanol production as well as reduce net greenhouse gas emissions (production of corn requires large inputs of energy and fertilizer). A demonstration project involving Iogen and Petro Canada is currently under way to evaluate the commercial viability of producing ethanol from cellulosic feedstock.

If it were possible to derive valuable co-products (e.g. pharmaceuticals or fine chemicals) as part of the process to produce ethanol, the overall profitability of ethanol production could be made favorable. One study carried out for Agriculture Canada has investigated some of the potential for this (available at URL: http://www.agr.ca/research/cfar/coprod.htm). The concept of a 'bio-refinery' producing fuel ethanol and co-products which include fine chemicals is discussed below in the section on Fine Chemicals.

Other bulk chemicals are also produced at commercial scale from biomass. In the USA, for example these include: cellulose esters and ethers (0.5 billion kg/y), sorbitol (0.19 billion kg/y)

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[12] Alper, J., "Engineering metabolism for commercial gains", Science 283, p. 1625 (1999).

[13] OECD, Biotechnology for Clean Industrial Products and Processes, p. 32 (1998).

and citric acid (0.16 billion kg/y)[14] .

Oak Ridge National Laboratory, the US Department of Energy and Applied CarboChemicals (see http://www.anl.gov/OPA/news96/news961108.html) have developed a fermentation process to produce succinic acid from glucose at lower cost than from conventional petroleum-based methods . Succinic acid is a precursor to compounds such as 1,4-butanediol and tetrahydrofuran which have combined sales of over US$ 1 billion in the US market[15] .

There are a number of other initiatives under way to produce chemical feedstock from biomass, the most notable of which is a US Technology Roadmap for Plant/Crop Based Renewable Resources (available at: http://www.oit.doe.gov/agriculture/).

C) Biological Production of Industrial Resins and Plastics:

It has been known since the 1920's that certain bacteria naturally produce polyhydroxyalkanoic acids (PHA) which are biodegradable plastics. Increasing concern over persistence of conventional plastics in the environment is renewing interest in these types of biologically derived, biodegradable polymers.

Japan’s Institute of Physics and Chemical Research (http://www.riken.go.jp/eng/index.html) has engineered a microorganism with the capacity to produce and store large amounts (up to 96% of its dry weight) of biodegradable plastic[16]. Biotechnology can also be used to metabolically engineer bacteria to modify the structure and properties of the resulting polymers[17]. However, life cycle analysis shows that, depending on the starting material and whether fossil fuel is the source of energy used in the fermentation process, it can take slightly more fossil fuel to produce 1 kg of PHAs than it does to produce 1 kg of polystyrene [18] . This underscores the need to use a systematic approach to assess whether a particular technology is ‘cleaner’ of more ‘sustainable’ and use this as a guide in selecting the technological approach (see Section 7.3). In this case, the problem of fossil fuel consumption can be avoided by engineering plants to produce PHAs directly from carbon dioxide and sunlight, avoiding the use of fossil fuel energy in the fermentation step. Metabolix in Cambridge Massachussets (http://www.metabolix.com) is

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[14]OECD, Biotechnology for Cleaner Industrial Products and Processes, p. 33 (1998).

[15]OECD, Biotechnology for Clean Industrial Products and Processes, p. 34 (1998).

[16]Decision Resources, Biotechnology’s Impact on the Chemical Industry, (1998).

[17]FEMS Microbiology Letters 128, pp. 219-228 (1995).

[18]Nature Biotechnology 17, pp. 541-544 (1999).

pursuing this strategy[19] . This is an example of the power and flexibility of biotechnology.

DuPont (http://www.dupont.com/enggpolymers/news/1998/EP9814.html), through alliances with Genencor International (Rochester, New York) and Pioneer Hybrid (Des Moines, Iowa; http://www.pioneer.com/index_ns.htm) is pioneering the development of biomass as a source of polymer precursors. DuPont and Genencor International have patented a process which utilizes a genetically engineered microorganism (an example of metabolic engineering) to produce 1,3-propanediol (the monomer for an advanced polyester) in a single step from glucose[20]. All liquid effluent from the monomer production process is easily biodegradable and the polymer can be reduced back to the monomer by methanolysis so that it can easily be recycled repeatedly after consumer usage.

4.1.1.2 Research and Development Capacity

During the 1970's and early 1980's Canada had a strong research base for industrial bioprocessing which spanned both government and university laboratories. This was eroded in the late 1980's and early 1990's as programs shifted focus to new priorities. Also, the boom in the biopharmaceutical industry and greater availability of research funds in this field served to attract researchers from industrial bioprocessing into drug discovery and production by fermentation. Industrial bioprocess research continues in government[21] and university[22] but it is largely focused on pharmaceutical and fine chemicals with little development of cross-sectoral and cross-disciplinary networks.

Little information was found on research in Canada relating to bioprocessing of petrochemicals. Some work is being carried out at the University of Calgary and the Biotechnology Research Institute of the National Research Council, but there is almost no demand for such research from petroleum and petrochemical companies. Advances in understanding the performance of enzymes in non-aqueous solvents promise to increase the use of bioprocessing for petrochemicals [23] ; however, little of this research is being carried out in Canada.

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[19]Decision Resources, Biotechnology's Impact on the Chemical Industry, p. 37 (1998).

[20]Decision Resources, Biotechnology's Impact on the Chemical Industry, (1998).

[21]For example: National Research Council (BRI, IBS), Saskatchewan Research Council, Alberta Research Council, Centre Québecois de valorisation de la biomasse.

[22]For example: University of British Columbia, University of Calgary, University of Saskatchewan, Waterloo University, University of Toronto, Ryerson Polytechnical University, Queen's University, McGill, Ecole Polytechnique de Montréal, Université Laval.

[23]OECD, Biotechnology for Clean Industrial Products and Processes, p. 74 (1998).

There is considerable research on production of fuel ethanol and other chemicals from biomass at a number of Canadian universities (University of British Columbia, University of Saskatchewan, Waterloo University, University of Toronto, Ryerson Polytechnical Université, Queen's University, McGill, Ecole Polytechnique, Université Laval) as well as at a number of government research centres (the National Research Council, Alberta Research Council, Saskatchewan Research Council). A research network has recently been proposed in biomass production and biomass utilization for fuels and chemical feedstock (BIOCAP[24]).

4.1.1.3 Receptor Capacity

With few exceptions, the industrial chemicals industry in Canada has little in-house activity relating to biotechnology and bioprocessing, and much of what exists is primarily focused on remediation and abatement. Nevertheless, it is recognized[25] that companies which already use biotechnology, even for end-of-pipe cleanup, are more likely to use it for additional applications[26]. Industrial chemical producers in Canada, have demonstrated a capacity to innovate and attract product mandates (see R&D success stories in the chemicals sector on STRATEGIS at http://www.STRATEGIS.ic.gc.ca under Business Information by Sector - Chemicals). The question is whether these companies can position themselves to benefit from the trend toward increasing use of biotechnology in their industry.

Research consortia such as the Environmental Science and Technology Alliance Canada - ESTAC (http://www.sarnia.com/groups/estac/) have been effective in supporting relevant research at Canadian universities focusing on the chemical and petroleum industry. Research networks such as ESTAC and BIOCAP which is focused on research relating to biomass production and utilization (http://www.biocap.com) could also provide the means for companies in this sector to develop a strategic 'window' on biotechnology and bioprocesses which save costs and reduce environmental impacts.

4.1.2 Fine and Specialty Chemicals

Like industrial chemicals, fine and specialty chemicals can also be separated into inorganic and organic categories. The organic chemicals category includes pharmaceuticals, vitamins, flavours and fragrances, enzymes, chiral intermediates and other specialty chemicals. There are about

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[24]Contact Prof. David Layzell, Queen's University (e-mail: layzelld@biology.queensu.ca)

[25]Statistics Canada, Survey of Biotechnology Use in Canada, (1998). See Section 7.2.

[26]Tembec is an example of one company in which biotechnology migrated from wastewater treatment to production - in this case production of a value-added chemical, ethanol from waste sulfite liquor.

100 firms (including biopharmaceutical firms) in this segment of the Canadian chemical industry, most of which are small and Canadian owned. There are currently no official statistics available on the size and performance of the fine chemical industry in Canada.

The higher value of fine and specialty chemicals and the large global markets associated with some of them provides more latitude for use of biocatalysis and biological starting materials. It is estimated that the worldwide market for fine chemicals which go into pharmaceuticals is around US $24 billion[27].

Decision Resources[28] reported that the global market for non-pharmaceutical fine chemicals produced by fermentation was more than US $ 6 billion in 1996:

- $2.4 billion for amino acids
- $2 billion for vitamins
- $1.2 billion for enzymes
- $0.5 billion for biopolymers.

The Freedonia Group[29] (http://freedonia.imrmall.com) estimated that the demand for fine and specialty chemicals derived from plant sources (flavours, fragrances, botanical extracts, nutraceuticals and pharmaceuticals) would grow at about 9% per year to reach US $ 2.9 billion in 2003. Fermentation processes are under development for a number of these fine chemicals because this would offer greater consistency of quality and supply (e.g. less likely to be affected by weather or natural disasters).

Chiral chemicals are a $ 6 billion business in the US and form a rapidly growing (10% per annum) segment of the fine chemicals market[30] . Chiral chemicals are isomers of asymmetric molecules which have been separated and purified. They are used in synthesis of other chemicals (e.g. pharmaceuticals) which have special properties because they are asymmetric. Conventional separations technologies for producing chiral chemicals are costly and energy intensive because they involve repeated cycles of chromatography or recrystallization. Now over 40% of chiral chemicals are produced through the use of enzymes or microorganisms which selectively break down one of the isomers resulting in a mixture which can easily be separated to yield one isomer in higher purity than could be achieved by conventional processes.

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[27]Genetic Engineering News, Aug. 1999, p. 25.

[28]Decision Resources, Biotechnology's Impact on the Chemical Industry (1998).

[29]Freedonia Group, Plant Derived Chemicals - Market Evaluation (1998).

[30]Freedonia Group, Chiral Chemicals to 2003 (1999).

4.1.2.1 Biotechnology Applications

Fine chemical companies generally produce small volumes of high-value-added chemicals. In general, their activities are associated with much smaller energy consumption or emission of pollutants when compared to the much larger operations of the industrial chemical producers, so potential savings of energy and environmental benefits for this segment of the industry may be relatively small, except on a local scale. However, some of their products, especially enzymes, can contribute very significantly to energy savings and pollution reduction in other industry sectors.

Enzymes form a particularly important class of fine chemicals. They are biological catalysts found in the cells of plants, animals and microorganisms. Many enzymes are now genetically engineered to be produced by industrial fermentation and also to have specific catalytic properties. They are now commonly used to increase energy and material efficiency across a wide range of industries, including energy, chemicals, pharmaceuticals, agriculture, food and feed processing, forestry and pulp & paper, and textiles [31].

Canada has a number of companies which produce fine chemicals, or enzymes, by fermentation or extraction and purification from biological sources. Examples include:

- Iogen (Ottawa, Ontario) is a major producer of enzymes by fermentation for the energy, pulp & paper and textile industries;
- Canadian Inovatech (Abbotsford British Columbia; http://www.inovatech.ca) extracts and purifies enzymes from eggs and animal tissues for use in the agrifood and pharmaceutical industries;
- Kemestrie (Sherbrooke, Québec) is a technology development company which focuses on biomass as a starting material for production of fine chemicals;
- Bioriginal (Saskatoon, Saskatchewan) is a producer and supplier of gamma linolenic acid, an unsaturated fatty acid which is extracted from plants and is used in cosmetics, skin care and nutriceutical products;
- Griffith Laboratories (Scarborough, Ontario) is a producer of enzymes and flavours for the food industry;
- SemBioSys (Calgary, Alberta) is a plant biotechnology company focused on using genetically engineered plants as ‘factories’ to produce high value proteins for the pharmaceutical industry;
- Nexia (Montréal, Québec) is a pioneer in the production of high value proteins in the milk of specially treated goats or cows who have genetically modified mammary cells implanted into their udder;
- Apotex Fermentation Inc. (Winnipeg, Manitoba) is Canada’s largest facility for R&D and production of pharmaceuticals by fermentation and bioprocessing in compliance with

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[31] European Commission Institute for Prospective Technological Studies, Biocatalysis: State of the Art in Europe (1998).

certified Good Manufacturing Practise (cGMP);
- Diagnostic Chemicals (Charlottetown, Prince Edward Island; http://www.dclchem.com) produces advanced pharmaceutical intermediates as well as catalytic enzymes and active compounds extracted from biological sources.

Several Canadian companies are involved in bioprospecting, i.e. screening the biodiversity in nature for plants and microorganisms which produce chemicals with pharmacological activity. Examples include:

- Accutec Technologies (Vancouver, British Columbia);
- Semgen (St. Nicolas, Québec);
- Ecopia Biosciences (Montréal, Québec) .

Such companies also have the capability to identify and isolate specific biocatalytic activities so they could be further developed for use in industrial bioprocesses.

There are also a number of Canadian fine chemical companies specializing in direct organic chemical synthesis but which can also produce fine chemical derivatives of biological source material. Examples include:

- Dalton Chemical Laboratories (Toronto, Ontario; http://www.dalton.com/)
- Raylo Chemicals (Edmonton, Alberta)
- Toronto Research Chemicals (Toronto, Ontario).

4.1.2.2 Research and Development Capacity

There is a strong research capacity in fine chemicals at a number of Canadian universities as indicated by the number of university spinoff companies specializing in this field[32]. The explosion of research in biopharmaceuticals has greatly contributed to this. The growing interaction between researchers in plant biotechnology and in natural products chemistry will add another dimension to the base of capabilities[33]

4.1.2.3 Receptor Capacity

While there are a considerable number of fine chemical companies in Canada, they are mainly focused on servicing the diagnostics and pharmaceutical industries. There has been a lack of ‘pull’ from the traditional chemical industry to attract the attention of technology developers and

[32]For example: Toronto Research Chemicals, Dalton Chemicals, Kemestrie.

[33]There are strengths in plant biotechnology and in natural products chemistry at institutions such as the University of British Columbia, the University of Toronto and in the well networked biotech communities in Saskatchewan and the province of Québec.

financing from the investor community. An initiative such as development of a 'biorefinery' in which high-value fine chemicals contribute to the overall profitability of producing bulk industrial chemicals from biomass could help provide that 'pull'.

4.1.3 Agricultural Chemicals

Agricultural chemicals include **pesticides** and **fertilizers**.

A) Pesticides

Pesticides are used in crop protection, regulation of plant (e.g. weed) growth, control of insects, treatment of seeds, control of algae in swimming pools and preservation of wood and textiles. In 1996, 10 Canadian establishments, mostly subsidiaries of multinational companies, were identified as producers of pesticide chemicals; although, most of the activity in Canada is in formulation and not the development of active ingredients. Uniroyal is the only multinational producing active ingredients in Canada (in this case an antifungal seed treatment). The 10 establishments employed almost 500 people and had shipments of $262 million of which 44% was exported.

Biotechnology products are expected to account for 10% (i.e. approximately US $ 4 billion) of the world pesticide market by 2005[34]. The bulk of the environmental and economic benefits from these biotechnology products will be realized in the agriculture sector and not the chemicals sector. Biotechnology offers considerable advantages in control of pests and is leading to major changes in the pest control industry, for example:

- More rapid and accurate detection of pests using genetic fingerprinting and field test kits based on gene probes will permit earlier identification and response, reducing unnecessary pesticide use, pesticide runoff and energy required for pesticide application;
- Some biological pest control techniques use insect traps baited with pheromones (sex attractants) or insects which act as predators for pests - this reduces pesticide use, pesticide runoff and the energy use associated with transport and application of the pesticide; there are a number of small Canadian companies e.g BioControle Inc.(Ste Foy, Quebec), Coast Agri Inc.(Abbotsford, B.C.), Phero Tech Inc.(Delta, B.C.), Applied Bio-Nomics Ltd (Sidney, B.C.), which specialize in this area;
- Other biological pest control techniques involve the use of (i) bacteria e.g. *Bacillus thuringiensis* (B.t.), (ii) viruses (e.g. some baculoviruses as developed by the Canadian Forest Service) which are toxic to only a very narrow range of insect pests and not to other species or (iii) nematodes which are worm-like organisms effective against a wide range of grubs and weevils (Microkil, Bedford, N.S., http://www.microkil.com).
- Some crops are now genetically engineered to have built-in pesticides which are toxic only to the insect pest and not to humans who eat the crop - this eliminates pesticide runoff and

[34]Decision Resources, Biotechnology's Impact on the Chemical Industry,(1998).

saves the energy associated with synthesis of a conventional chemical pesticide, transportation to the point of use and the fuel used by the farmer in applying the pesticide one or more times to the crop (major multinationals are active in Canada in this field);

- Other crops are genetically engineered to be resistant to a broad spectrum herbicide so that herbicide can be used once after the crop and weeds have emerged - this saves having to use a combination of different herbicides for different weeds as well as the energy required for repeated applications of herbicide (major multinationals are also active in Canada in this field).

B) Fertilizers:

Fertilizers include chemicals which can deliver nitrogen, phosphorus, potassium, sulfur and certain other elements which, depending on soil quality, may be needed to achieve optimal plant/crop growth. In 1994, there were 12 primary producers of fertilizers in Canada, with 22 operating facilities which employed 5800 people and exported $2.4 billion worth of product (73% of total shipments). Canada supplies almost 40% of world needs for potassium and sulfur fertilizers and the Canadian fertilizer industry has invested nearly $ 500 million in expanding capacity during 1995-97. Canada is home to some of the world's largest fertilizer companies. Current product research in the industry is focusing on:

- slow release nitrogen formulations
- new sulfur based fertilizers
- more concentrated combination fertilizers
- inclusion of micronutrients such as calcium, magnesium, iron, copper, boron, zinc
- better understanding of soil ecology and microbiology for developing new products.

The first generation of biological fertilizers was based on natural rhizobial bacteria found in the root nodules of legumes (peas, lentils, alfalfa, sweet clover). These bacteria fix nitrogen from the air, providing a source of nitrogen for the plants without the use of chemical fertilizers. Canadian companies such as Premier Tech (Rivière du Loup, Québec), Agrium Biologicals (Saskatoon, Saskatchewan), Philom Bios (Saskatoon, Saskatchewan), MicroBio Rhizogen (Saskatoon, Saskatchewan) and Grow Tech Inc. (Nisku, Alberta) have isolated natural populations of these bacteria which are particularly good at fixing nitrogen and formulate them as biological fertilizers for legumes. Philom Bios also has a similar biological phosphate fertilizer which helps plants take up phosphate already in the soil, reducing the requirement for phosphate fertilizer. When these biological fertilizers are used to coat seeds before planting, the crop will have improved conditions for growth from the time of germination.

Biological fertilizers can reduce the need for nitrogen and phosphorus fertilizers**.** This reduces the potential for fertilizer runoff into lakes and streams where it may contribute to algal blooms and eutrophication. It also means that less fertilizer is used, saving the energy (and associated greenhouse gas emissions) required to produce the fertilizer, transport it and apply it. Efforts are under way to engineer non-leguminous plants to have root nodules so they can also be grown without addition of nitrogen fertilizer.

As understanding of the microbiology of agricultural soils increases, it will be possible to increase the performance of agricultural soils through restoration of the natural microbial consortia which are disrupted by intensive agriculture.

4.1.3.1 Biotechnology Applications

The contribution of biotechnology to cleaner production in the agricultural chemicals is really in providing alternatives to use of chemical pesticides and fertilizers or measures (e.g. rapid pest diagnosis or biological fertilizers as detailed above) which result in less overall use of chemical pesticides or fertilizers.

4.1.3.2 Research and Development Capacity

Canada has a strong research capacity in biological pest control. In addition to networks such as Insect Biotech and research on baculoviruses in the Canadian Forest Service, there is considerable work ongoing at NRC's Plant Biotechnology Institute and Agriculture Canada to engineer pest resistance into major crops such as canola and wheat.

Similarly, there is a strong research capacity in Canada with respect to soil fertility and agricultural practices, including the use of fertilizers, which can help maintain soil fertility. There is also increasing emphasis on low-till agriculture as a means of maintaining natural soil microbial systems and maintaining or increasing the organic content of the soil which is a larger sink for carbon than the standing biomass in forests[35] .

4.1.3.3 Receptor Capacity

In the pesticide field, the receptor capacity is limited. The companies using biologically derived technologies are small, generally serve only regional markets and have difficulty attracting investment. The multinationals which are active in Canada generally formulate existing products developed offshore rather than develop new ones.

With respect to fertilizers, the receptor capacity appears to be much better. As mentioned above, Canada is home to some of the world's largest fertilizer companies and there is a realization that better understanding of soil ecology and microbiology is important for development of more

[35]The BIOCAP Network estimates that the standing biomass in Canada's forests contains approximately 14,500 MT of carbon while an estimated 76,000 MT of carbon is contained in soil, wetlands and peat bogs.

effective and sustainable methods and products for maintaining soil fertility.

4.1.4 Formulated Chemicals

Formulated chemicals is a broad category which includes:

- paints and coatings
- sealants and adhesives
- cosmetics and toiletries
- soaps and detergents, and
- lubricants and other formulations .

Very little information was found on use of biotechnology in these segments of the chemical industry, so discussion of these is very brief.

A) Paints and Coatings

In 1998, the Canadian **paints and coatings** industry included 120 establishments which employed 6600 people and had shipments of $ 1.8 billion of which $251 million were exported. The binder (the base material forming the coating film) in paints used to be formulated using linseed or soybean oils. Now most paints and coatings are based on higher-performance synthetic resins such as alkyds, acrylics, vinyl, epoxies, urethanes, polyesters, phenolics and silicones. As a result of environmental pressures to reduce emissions of volatile organic compounds, there has been a shift to water based formulations where possible. No information was found on R&D or commercial applications involving biotechnology in producing ingredients for paints and coatings.

B) Adhesives and Sealants

The **adhesives and sealants** industry in 1998 included 42 establishments which employed 1790 people and had shipments of $450 million of which $186 million was exported. In this segment of the industry, low-to-medium performance products are often based on natural products such as starch, dextrin, natural rubber or protein; however, there is strong competition from synthetic polymers such as polyvinyl acetate, polyvinyl alcohol, polyesters, acrylics, neoprene, butyl rubber and phenolics. High performance adhesives and sealants have enhanced properties (bond strength, elongation capacity, durability and resistance to weathering or microbiological attack) and products in this segment of the market are exclusively synthetic polymers such as epoxy, polysulfide, cyanoacrylate and silicone.

One interesting use of biocatalysis in the adhesives field is the use of the enzyme peroxidase to replace the toxic chemical formaldehyde in the production of phenolic resins. Enzymol International (Columbus Ohio; http://www.iwaynet.net/~enzy/home.htm) has developed a patented process which uses peroxidase extracted from soybean seed coat to generate the free radicals required to polymerize the phenolic chemicals. A similar process was developed by Forintec and is now used by CanFibre (Vancouver, British Columbia) to replace formaldehyde in the conventional urea-formaldehyde process for manufacturing medium density particle board[36].

The paints and coatings as well as the sealants and adhesives industries are mature and grow on average at the same rate as the overall economy; although, in some specialty areas the growth rates are significantly higher. Most of the Canadian firms in these segments of the industry are subsidiaries of multinational companies and few perform any R&D on raw materials and or formulation but rather depend on their parent companies for R&D and technology. However, they also depend on raw material suppliers for introduction of new technologies. Many of these suppliers are Canadian SMEs and it is through these companies that bioprocesses and renewable biological source materials could enter into common use.

C) Cosmetics and Toiletries:

The **cosmetics and toiletries** industry has traditionally been a major user of biological source materials and fine chemicals. Several small Canadian companies such as Bioriginal (Saskatoon, Saskatchewan), Canamino (Saskatoon, Saskatchewan), Fytochem (Saskatoon, Saskatchewan) and Natunola (Winchester, Ontario) are examples of companies which are suppliers of highly purified plant extracts (oils, starches) for this industry. There is potential to use biotechnology to modify the profile of oils produced by plants to yield products with specific properties; however, no examples of this were identified either at the commercial or R&D stage. Enzymes are also finding use in the cosmetics industry where, for example, laccase is being used in hair dyeing products[37].

D) Soaps and Detergents

The **soaps and detergents** industry also uses biomass derived feedstocks and enzymes. Most soaps are produced from oils and fats derived from plants and animals. No information was found relating to use of biotechnology in production or processing of these materials. Most detergents contain enzymes which help remove stains (lipases for grease, proteases for proteins) or which help prevent pilling of cotton (cellulases). The enzymes are generally produced by fermentation using genetically modified microorganisms and may contribute to secondary energy savings in the use of these products because they enable the use of warm or cold water rather than hot water for washing.

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[36]Information from Industry Canada, Chemicals & Plastics Branch on STRATEGIS (http://strategis.ic.gc.ca).

[37]Decision Resources, Biotechnology's Impact on the Chemical Industry, (1998).

E) Lubricants

The **lubricants** industry is dominated by petroleum derived products. High euricic acid canola oils have found application as industrial lubricants and have the advantage of being more readily biodegradable and less toxic than their petrochemical counterparts. Work in this and related areas is ongoing at the NRC Plant Biotechnology Institute in Saskatoon (http://www.pbi.nrc.ca/).

4.1.5 Sector Assessment

Decision Resources has provided a view of the future for use of biotechnology in the chemical industry:

> "The overall trend of convergence between chemistry and biology can be seen in the increasingly popular strategy of combining chemical and biotechnological production processes. As noted, biotechnology is already used to make intermediates for a number of chemicals, with synthetic processes used for the final products. We envision a long, slow transition in which chemical and biotechnology processes are blended more extensively over time, and during which biotechnology carries increasingly more weight in production responsibility, though probably never entirely supplanting chemical processes."

Barriers to this trend in Canada are interrelated and include cost, lack of investment, and a lack of in-house expertise as well as a lack of cross disciplinary training opportunities in this field for chemists, chemical engineers, biochemists, microbial ecologists, molecular biologists and genome researchers.

The market for most chemicals is very cost sensitive. This remains the major barrier to adoption of biotechnology, especially in the industrial chemicals segment of the industry, until advances in the technology and market demand make its use economically attractive. Regulation can also increase the cost of producing chemicals using biotechnology as compared to existing conventional processes. This is because chemical companies may not have the regulatory affairs expertise to deal with the approval process for products of biotechnology; or, may not want to incur the cost of making a regulatory submission. Instead, many companies driven by cost pressures will continue making or using a conventionally manufactured product for which they already have approval, even if it may be less environmentally friendly.

Lack of in-house R&D expertise in biotechnology is another barrier, especially in the industrial chemicals segment of the industry. Canadian companies, many of which are subsidiaries of multinational corporations, may have difficulty justifying significant investments for in-house R&D in biotechnology. However, if the present trend toward increasing use of biotechnology continues in the global chemical industry, they will likely have greater interest in R&D collaborations with Canadian university/government researchers and strategic alliances with Canadian companies specializing in development of biotechnologies (analogous to what happened in the pharmaceutical industry in the late 1980's). In fact, there may be opportunities to attract investment by European multinational chemical corporations looking to build bioprocessing capabilities but hampered by unfavorable public opinion of biotechnology in Europe[38]. Companies such as DSM (http://www.dsm.nl/) which has a presence in Canada but produces fine chemicals using bioprocesses only in Europe would be an example of such a chemical company. These are good reasons to augment support for science and innovation relating to biotechnology and cleaner production[39] and to target support toward:

- university/government research networks;
- formation of spinoff companies specializing in development of industrial bioprocess technologies; and
- programs which focus on technology development (PERD), technology transfer and industrial R&D (e.g. IRAP) and technology demonstration (e.g. TPC).

This support can foster development of multidisciplinary research networks (including a number of Networks of Centres of Excellence) thus providing the cross disciplinary experiences which are so needed in this field. Linkage of multidisciplinary research in this field with companies can provide fertile ground for combining a knowledge of scientific possibilities with a knowledge of emerging marketplace needs and opportunities through a process known as "Technology Roadmapping".

One promising area for undertaking a technology road map is the development of a 'biorefinery' for ethanol or some other bulk chemical from biomass.

Canada's strength and diversity of companies in the field of fine chemicals support the idea that 'bio-refineries' for ethanol and other bulk chemicals could be made profitable through co-production of fine chemicals and other value-added by-products. This would require a systems approach with strategic alliances among clusters of companies which:

- grow and harvest biomass,
- produce and sell ethanol and/or other bulk industrial chemicals,
- engineer and grow plants to contain valuable fine chemicals,
- extract and sell fragrances, cosmetics, nutraceuticals and pharmaceuticals,
- develop value-added animal feeds,
- produce and sell biological fertilizers and compost from waste organic matter, and
- identify novel chemicals and biocatalysts and the organisms/genes which produce them

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[38]This has already occurred in the ag-bio field.

[39]Other countries are already moving in this direction. In Spring 2000, the German Federal Government will announce an R&D program focusing on biotechnology and cleaner production.

through bioprospecting[40].

The potential for achieving such synergy is particularly high in Saskatchewan, Ontario and Québec where there are significant opportunities for developing demonstration projects because there is a critical mass of researchers and companies which could come together around such a cluster concept..

The chemicals sector will play a key role in moving a broad range of Canadian industries toward cleaner production because it will supply the technology (the biocatalysts, the process chemistries and the chemicals from renewable feedstocks) which will make this possible. The question is whether a large portion of these technologies will come from the Canadian chemical industry or be bought from abroad. The move to cleaner production and renewable resources will lead to many new niche business opportunities and, if the Canadian chemical industry is not a supplier of such technologies, Canada will lose out on these diverse growth opportunities.

The major chemical companies in Canada are mostly subsidiaries of multinational firms. A number of these have demonstrated a strong receptor capacity for conventional chemical technologies as well as the ability to export their products to global markets. However, almost none have in-house expertise relating to bioprocess and bioproduct development. Offsetting this, is a strong bioprocess research base in university/government laboratories and the potential to support a full range of, university-industry, industrial R&D and demonstration projects using existing government assistance programs[41]. This and the Scientific Research and Experimental Development Tax Credit system can provide a strong incentive for chemical companies to use a Canadian base for innovating their way to a future involving cleaner bioprocesses and renewable bioproducts.

Canada's key advantage is its large landmass and associated biomass which can support a major chemicals industry based on renewable feedstocks. Also, there is already an emerging industry in Canada based on novel uses of agricultural and forest biomass to produce fine chemicals, cosmetics, dietary supplements, nutraceuticals, animal feeds, durable composite materials and other value added products. When these factors are combined with the availability of renewable hydroelectric energy, the presence of other resource industries which are major consumers of

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[40]In this regard, the Canadian bioremediation industry already has the expertise to identify microorganisms which can survive in extreme environments and metabolize specific chemicals. The challenge will be linking this expertise with complementary expertise which can screen, select and use these organisms as the starting material for developing novel and cleaner industrial bioprocesses.

[41]For example, the Cooperative R&D Program (Natural Resources and Engineering Council), the Industrial Research Assistance Program (National Research Council), the Program for Energy Research and Development (Natural Resources Canada) and Technology Partnerships Canada (Industry Canada).

chemicals and generous incentives for industrial R&D, the case can be made that Canada is an ideal location to develop the next generation of chemical industries which will be based on renewable feedstocks.

4.2 The Canadian Forest Sector

Canada's forest sector includes two main groups: the forestry industry and the manufacturers of forest products (which includes the paper and allied industries and the wood products industry). The forestry industry involves a diverse range of players, such as woodland operations of companies operating under licence on Crown land, nursery and silviculture companies (forestry biotechnology service companies are part of this group) and hundreds of private woodlot producers. Canada's forest product manufacturers are technologically very distinct, but are closely linked in that they share a common source of raw material, often from the same land base[42].

Canada's forests cover 45 per cent of the country (total land base: 977 million hectares). Canada has 10 per cent of the world's forest. Of the 418 million hectares of forest in Canada, 245 million hectares are considered to be commercial forests capable of timber production. About 119 million hectares of the commercial forests is available for timber production at present. Canada's forest is predominantly publicly owned (provinces: 71 per cent; federal: 23 per cent). The remaining 6 per cent is privately owned (425,000 private owners of forest land range from small individual land owners who predominate much of the Atlantic provinces to large scale forest company owners in British Columbia.

The 1997 annual allowable cut was 236.5 million cubic metres: 175.6 million m^3 in softwoods and 61 million m^3 in hardwoods. Annually, Canada harvests less than half of one per cent (1,023,680 hectares, 187.8 million m^3 in 1997). In 1997, 4 million hectares were affected by insect defoliation and 0.6 million hectares were lost due to forest fires. By 1997, only 16 per cent of all forest land, that had been harvested in Canada since 1975, needed further treatment to become regenerated with commercial species. By comparison, in 1990, 25 per cent of all forest land, harvested since 1975, needed further treatment. In 1997, 433,826 hectares were planted with 642 million seedlings and 24,812 hectares were seeded. In the same year, revenues from the sale of timber from provincial Crown land generated a revenue of $2.6 billion.

Canada's forests support a wide range of industrial, commercial, cultural and recreational uses. Non-timber and recreational activities generate significant economic benefits in terms of jobs, income, contribution to GDP and government revenues. These activities are important to the economic well-being of many rural communities. In 1996, expenditures by Canadians on nature-related activities in Canada amounted to $11.0 billion.

The forest sector is one of the largest and most geographically diverse industry in the country, with operations in all provinces and territories. It is Canada's largest non-urban employer, supports hundreds of rural communities, is Canada's largest net exporter, and makes an overwhelming contribution to the country's merchandise trade balance. In 1998, the forest

[42] Canadian Forest Service - Natural Resources Canada, National Climate Change Forest Sector Table Options Report (1999).

sector's contribution to the Canadian economy (i.e., GDP) was 2.4 per cent, or $18.2 billion. Total employment (i.e., direct and indirect) was 877,000 people (Quebec: 200,000; British Columbia: 175,000; Ontario: 174,000; Other: 328,000). Direct employment was 384,000 (or 2.7 per cent of total employment in Canada): wood industries: 180,000; paper and allied industries: 128,000; logging: 62,000; forestry services: 14,000). For 1997, wages and salaries for direct employment were estimated to be $11.8 billion, and shipments were estimated to be $70.3 billion. Compared to 1997, in 1998, shipments of pulp and paper decreased by 1 per cent to 29.1 million tonnes. Production of lumber remained at 1997's record level of 27.6 million cubic metres. In 1998, new investment (i.e., capital only) totaled $3.7 billion: paper and allied products: $2.5 billion (68 per cent); wood industries: $0.8 billion (23 per cent); logging:: $0.3 billion (9 per cent).

Internationally, Canada is the world's largest forest products exporter (i.e., 19 per cent global market share). In 1998, forest products were the largest contributor's to Canada's surplus balance of trade, contributing $31.7 billion. The total value of Canadian exports rose by 2.1 per cent in 1998 for a total of $39.7 billion: British Columbia: $13.2 billion (33 per cent); Quebec: $10.8 billion (27 per cent); Ontario: $8.1 billion (20 per cent; other provinces: $7.6 billion (20 per cent).

The forest-sector biotechnology industry is composed of those companies which provide biotechnology products and/or services to the forest industry. This industry cannot be described using the Standard Industrial Classification (SIC) system; although, elements of it are found in the following SIC categories:

- nursery products and services (SIC 0163),
- pest control products and services (SIC 0222),
- forestry (i.e., logging - SIC 04; forestry services - SIC 051),
- pulp and paper and allied products (SIC 27),
- wood products (SIC 25),
- energy / bio-fuels / chemicals from forest biomass (i.e., newly emerging industries with SICs not being available yet at this time).

Biotechnology can reduce energy consumption and environmental pollution in the Forest Industry by contributing tools for:

- More sustainable and efficient forest management, regeneration and protection (more wood for less input of energy and chemicals)
- Improvement of tree genetics, either through selection of natural species with desirable traits or through genetic engineering (e.g., faster growth or altered lignin for easier processing into pulp)
- Post harvest protection of trees and lumber from disease and pests (less loss of wood feedstock; higher quality feedstock because it is not damaged or degraded)
- Development of more efficient technologies for bioprocessing and waste water reuse
- More effective recycling of forest products (e.g. post consumer lumber and paper products; greater efficiency of conversion into recycled products).

4.2.1 Forestry and the Forest Resource Industry

In 1996, the logging and forestry industries contributed about $4 billion to Canada's GDP and employed about 79,000 people, with a distribution of 80 per cent in logging and 20 per cent in forestry services. The incomes earned by these workers tend to be much higher than the Canadian average. There are significant regional differences in the importance of these industries for employment, with British Columbia, Saskatchewan, Quebec and Atlantic Canada being more dependent on logging and forestry services than the rest of the country. Rural communities are especially dependent on these sources of employment in parts of the country.

In addition to providing an economic value and the raw material for the forest products industry, Canada's forest resources also have a social and environmental value since they provide space for recreational activities, and contact with nature as well as help maintain water purity, bio-diversity, prevent soil erosion, provide habitat for wildlife and help recycle carbon, oxygen and other life-sustaining substances.

4.2.1.1 Biotechnology Applications

Biotechnology can contribute to sustainable management of forests. It provides tools to assess the genetic diversity of tree populations as well as soil microorganisms. It can also be used to increase the quality of seedling stocks used in forest regeneration and plantation forest management or it can be used for enhanced forest protection through biological pest control. Biotechnology can help mitigate climate change by enhancing the capacity of forests to act as carbon sinks (e.g. by timely maintenance of first growth forest, by management of secondary growth forests, and by contributing to the productivity of intensively managed plantation forests)[43,44,45]

Biotechnology applications relating to forestry and the forest resource can be divided into the three categories of forest protection, forest regeneration and tree improvement:

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[43] World Wildlife Foundation, GM technology in the forest sector. A scoping study, (1999).

[44] Wright, J.D., Future directions and research needs of the pulp and paper industry. In 7th International Conference on Biotechnology in the Pulp and Paper Industry, Vol. A: A3-A6 (1998)

[45] Advances in Biochemical Engineering Biotechnology, Volume 57 (Biotechnology in the pulp and paper industry) Springer-Verlag (1997).

A) Forest Protection

DNA markers[46] are used to assess biological diversity of tree species (so measures can be taken to maintain genetic diversity of forest trees) and can also be used to identify traits such as disease resistance.

Pheromone[47]-baited insect traps can provide an early warning capability for insect pests so measures can be taken when required, reducing unnecessary pesticide spraying and saving energy and cost. Sex pheromones and related semiochemicals are versatile natural products tools for insect pest management in Canadian forests. Phero-Tech Inc. (http://www.pherotech.com), a Canadian biotechnology company located in Delta, British Columbia, is a recognized leader in the commercial development of research done by Canadian organisations such as the Canadian Forest Service (http://www.nrcan.gc.ca/cfs/), University of British Columbia (http://newview.ubc.ca), Simon Fraser University (http://www.sfu.ca).

Biological control of forest pests is an attractive alternative to use of broad spectrum chemical insecticides which can kill both beneficial and harmful insects. Chemical insecticides are used less and less due to health, safety and environmental concerns. Almost 30 million acres of Canada's forests are subject to moderate to severe defoliation by insects and it is estimated that at least 10% of this area could benefit from biopesticide treatment. *Bacillus thuringiensis* (a bacterial biopesticide, also known as B.t.) is presently the only significant biopesticide used in forestry. Annual sales of B.t. are estimated to be of $40 million per year in North America. This represents less than 1% of a $5 billion potential market worldwide for biopesticides, which gives an indication of the potential economic value of developing other similar products. Other biopesticides such as insect viruses have been developed and registered by the Canadian Forest Service for the gypsy moth (*Lymantria dispar*), the Douglas-fir tussock moth (*Orgyia pseudotsugata*), and the redheaded pine sawfly (*Neodiprion lecontei*). A fungal bioherbicide for vegetation management is being commercialized by Mycologic and the estimated annual market in North America is $48 million[48] .

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[46]DNA markers are segments of DNA which are associated with specific traits or characteristics of an organism.

[46] Pheromones are chemicals which act as insect sex attractants. They are species specific and even very small quantities can be used as bait in insect traps.

[48]Renewal of the Canadian Biotechnology Strategy (1998) Key Messages Received from the Forest Sector Consultation. Canadian Forest Service, Science Branch, Natural Resources Canada. Ottawa.

B) Forest Regeneration

About 700 million seedlings are planted annually in Canada to regenerate forests on 0.5 million ha of land. Less than 10% of these seedlings are from propagules which have been selected or genetically improved for better survival and growth. This replanted area represents less than 0.2% of the productive forest and just over 0.1% of the total forested area. In the United States of America, 1.9 billion trees are planted annually on 1.2 million ha. On a global basis, there are around 11 billion trees planted annually.

Failure of planted seedlings leads to less than optimal forest regeneration and sometimes requires replanting which increases costs and energy consumption. Estimates of biomass gains (and of increased carbon sequestration) from genetic enhancement of trees ranges from 10% to 100% per generation. To capture these potential gains, tissue culture is used for micro propagation of selected naturally occurring conifers at a commercial scale in New Brunswick (J.D. Irving Co, http://www.ifdn.com/irning.htm), Quebec (Ministry of Natural Resources, http://www.mrn.gouv.qc.ca) and British Columbia (BCRI Inc., http://www.bcr.bc.ca ; Silvagen Inc., http://www.silvagen.com/ ; Pacific Biotechnologies Inc.). For instance, BCRI is producing 600 000 seedlings of weevil-resistant Sitka spruce (*Picea sitchensis*)[49]. Companies such as Agrium Biologicals (http://www.agrium.com/) are also involved in the development of bio-fertilizers (e.g., plant growth promoting rhizobia) to support the growth of seedlings in forest nurseries.

The economic value of biotechnology-derived products in forest protection and forest regeneration goes beyond the value of direct sales because of the multiplier effect for end-users resulting from increased productivity of the forest sector. In addition to the primary direct benefits to forestry, spin-off benefits of forest biotechnology could also impact other sectors, where the technologies and products developed for forestry applications could be exploited for other means (e.g. production of vaccines or pharmaceutical compounds using baculovirus expression vectors in insect colonies).

C) Tree Improvement*:*

(i) Selection of Superior Natural Strains

Biotechnology provides efficient tools for identification of tree genotypes with desirable traits by the use of DNA marker techniques. It also provides the means to conserve rare or endangered tree species using tissue culture and cryopreservation.

[49] Unfortunately, many of these trees were destroyed by environmental activists who thought that they were genetically engineered trees.

(ii) Genetic Engineering of Trees for Forestry

Genetically engineered forest trees are intended for use in intensively managed forests and in plantation forests where management practices can help deliver the productivity increases which make the use of such tree stock economically viable. Work in this area is necessarily long term in nature because most trees of economic interest have long life cycles and many years are required to evaluate their performance in the field.

Genes of interest in genetic engineering of trees come almost exclusively from other trees or plants and can be divided into two categories. The first category includes genes that govern agronomic traits or the ability of trees to grow rapidly. This category includes genes for resistance to disease, herbicide and pests or for tolerance to environmental stresses such as cold, drought, salt and flooding. Most efforts in this area have focussed on improving agronomic traits, including herbicide tolerance for stand establishment, insect resistance with *Bacillus thuringensis* toxins and protease inhibitors, bacterial soft-rot resistance, and male sterility to inhibit transfer of genes from engineered trees into the natural tree population. The second category includes genes for value added traits that improve production efficiency, product quality, or product value. These genes increase the value of the wood. Genes in this category include those that reduce or modify lignin content so it is more easily removed during pulping (leading to savings of energy and chemicals) as well as genes that improve fibre characteristics for specific applications (e.g. fibrillation for stronger paper).

4.2.2 Pulp and Paper Industry

The pulp and paper industry spans a complex set of material flows that run from the resource base to the post-consumer recycling of waste paper. Canada's large forest resource and relatively small population continues to make it the world's leading exporter of pulp, paper and paperboard products. In terms of capacity, Canada's share of global wood pulp capacity was roughly 15 per cent in 1998, ranking it second only to the U.S. in the production of paper grade pulp. By 2001, Canada's total pulp production capacity is expected to amount to 28.3 million tonnes[50] (http://www.open.doors.cppa.ca/english/index.htm) .

The pulp and paper and allied products industry accounts for approximately 89% of the total energy used to manufacture forest products in Canada. Most of this energy is used to produce the large quantities of steam and power to debark and chip wood, produce pulp, bleach it, and produce and dry paper and paper board. In the 1990's, the Canadian pulp and paper industry has achieved an impressive track record in its attempt to become a "environmentally cleaner" industry. For instance, now this industry self-generates over half of its energy needs from renewable resources. It is estimated that the industry could meet the Kyoto commitment of 6% reduction in energy

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[50] Canadian Pulp and Paper Association (1999). Canadian Pulp and Paper Capacity 1998-2001.

consumption from 1990 levels through co-generation alone (see footnote 44).

4.2.2.1 Biotechnology Applications

There are at least four major areas where biotechnology has a role to play in cleaner production and energy efficiency in the pulp and paper industry:

A) Fibre and Product Quality

Forestry biotechnology and improved silviculture allow for tailoring of future fibre resources to match required end product properties. This has the potential to yield superior products and process savings in terms of decreased requirements for energy and chemical inputs. The ability to produce fibres with optimal papermaking properties through genetic engineering is a long-term objective that will require a better understanding of biosynthesis in woody tissues to be achieved.

B) Bio-pulping

Bio-pulping, is the treatment of wood chips with lignin-degrading fungi prior to pulping. It is an experimental process that has been researched extensively during the past eight years, mainly as a pretreatment for mechanical pulping. Bio-pulping improves penetration and performance of chemicals during the 'cooking' of wood chips to separate the wood fibres from the lignin. It has been found to reduce the requirements for chemicals and energy (which is the major cost in mechanical pulping), improve paper quality, and decrease the environmental impact of pulping operations[51].

C) Enzyme-Aided Processing

The world market for industrial enzymes isolated from microorganisms is estimated at US $1.4 - 1.6 billion a year with an expected compound annual growth of 10%[52]. Applications in the pulp and paper industry account for 2% of this market, and this is expected to grow at 15% a year. Areas where enzymes have quickly moved from research to commercialization include: bio-bleaching to reduce chlorine consumption; pulp de-watering and de-inking; pitch removal; removal of dissolved and colloidal materials in the concentrated effluents of mills; enhanced fibrillation to give stronger paper[53]. In most of these applications the driving forces for adoption

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[51]Pullman, G.S., Cairney, J., Peter, G., Clonal forestry and genetic engineering: where we stand, future prospects and potential impacts on mill operations. TAPPI Journal 81(2): pp. 57-63, (1998).

[52]Genetic Engineering News, Vol 20, p. 3 (2000).

[53]Biotechnology in the Pulp and Paper Industry. *In:* Advances in Biochemical Engineering Biotechnology. Springer-Verlag (1997).

are cost savings (in terms of reduced inputs of energy and chemicals) and improved product quality.

(i) Enzymes in Kraft Pulping

In kraft pulping, bleaching is still one of the most expensive operations in the pulp mill and therefore a prime target for cost reduction. North American mills have moved towards ECF (Elemental Chlorine Free) bleaching which has increased operating costs even further. In Canada, about 10 per cent of bleached kraft pulp is now manufactured with xylanase treatment to reduce the amount and cost of chlorine dioxide used. Current research on oxidative enzymes (e.g. laccase) holds promise for even greater chemical savings, and is compatible with system closure options (see Subsection D below). Another important target in kraft pulping is yield improvement.

(ii) Enzymes in Paper and Board Manufacturing

Enzymes have been applied in a number of paper and board manufacturing processes. Lipase has been found to reduce pitch deposits, cellulase improves dewatering rates, and pectinase decreases cationic demand in whitewater where bleached mechanical pulp is part of the furnish. These enzymes must function efficiently in an environment which is increasingly complex chemically, and at higher temperature, as efforts continue to conserve water in the papermaking operation. One challenge for biotechnology is therefore to provide such enzymes at reasonable cost. In the longer term, it may be possible to manufacture unique paper products by targeting enzymes to fibre components which control end product properties. One example is the hydrophobicity of fibre surfaces which is altered by the enzyme laccase[54].

D) Mill System Closure (Zero Discharge)

Biological treatment of mill effluent plays a key role in water conservation. Pulp and paper mills in Canada are moving toward total effluent reuse after secondary and tertiary treatment. This has the potential of saving costs and energy required for treatment of input water as well as costs of minimizing the environmental impacts of effluent disposal. A challenge to bio-treatment operators will be to tailor their operations to changing effluent characteristics as mills evolve through progressive stages of system closure. The in-plant biotreatment process ideally removes dissolved and colloidal organic material and metal ions in order to prevent deposit and slime problems. These areas are the subject of current research efforts.

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[54]Wright, J.D., Future directions and research needs of the pulp and paper industry. In 7th International Conference on Biotechnology in the Pulp and Paper Industry, Vol. A: A3-A6 (1998).

E) Biotechnology for Paper Recycling

Recycling is not a new or recent phenomenon in Canada. The first Canadian paper mill recycled linen and cotton rags to make paper in 1805. Today, approximately 71 per cent of the fibre used to make Canadian pulp and paper comes from saw mill residues and recovered papers that used to go into land fills. Over 90 per cent of paper-based packaging is made from recycled fibre or sawmill residues.

In 1989, there was only one mill in Canada that could manufacture recycled-content newsprint. Today, there are some 23 of them. Since 1989, the Canadian industry has invested over $1.7 billion in facilities to use various grades of recovered paper to manufacture recycled-content paper and packaging. By-products from some recycling operations that used to go to landfills are now mixed with other ingredients and used as a soil conditioner.

The recovered paper market is a global one. Consequently, Canadian mills must compete in world markets to obtain enough recovered paper to meet their needs. Canada is the world's largest importer of recovered paper and paperboard; it is also a leading exporter of recycled-content paper and paperboard. In 1997, the Canadian industry used 4.7 million tonnes of recovered paper to manufacture recycled-content paper and packaging. Some 2.6 million tonnes, or 55 per cent of recovered paper used in Canada, came from domestic sources. The other 2.1 million tonnes was imported from the US. In 1997, the recovery rate in Canada was 45 per cent (i.e., 45 per cent of the paper consumed in Canada was recovered to make new paper and paperboard products). While recovered fibre is expected to supply an increasing amount of the paper industry's raw material, a reliable supply of virgin wood fibre will always be essential to meet the demands of consumers for high value-added quality paper and paperboard products [55].

Newspaper recycling is one of the most popular recycling processes feeding the pulp and paper industry. It can potentially reduce municipal solid waste volume by as much as 4%. Historically, newspaper recycling has also been profitable. However, in some cases, the newspaper recycling industry has been a victim of its own success. So much newspaper is being recycled (often encouraged by mandatory consumer recycling legislation) that the price has fallen. Once, raw newspaper could be sold to processors. Now, processors may charge a fee to accept newspaper.

Before recycled newspapers can be used to make white paper (including new newsprint), the recycled newspaper pulp must be deinked. A chemical-based deinking process, currently widely used, uses sodium hydroxide and a variety of flocculants, dispersants, and surfactants. These chemicals can yellow the resulting pulp, and hydrogen peroxide must be used to bleach the deinked pulp. These chemicals can also create environmental problems.

Scientists working at the North Carolina State University (http://www.ncsu.edu) are developing an

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[55] Guide to the Paper Recycling Mills in Canada, Canadian Pulp and Paper Association. (http://www.cppa.org/english/wood/guide/factse.htm).

alternative to chemical deinking, based on microbial enzymes. The research is still in the lab bench stage, and significant work must be done before commercial scale-up. Nevertheless, the process could revolutionize how paper is recycled. In laboratory demonstrations, the cellulase and hemicellulase enzymes are mixed with the paper pulp. They digest the paper's sugar molecular units, including those to which the organic ink particles are bound. Then, when the pulp is washed and drained, most of the ink particles are removed. Any remaining ink particles are removed during the standard flotation step. It is not necessary to treat the pulp with caustic soda, so it does not need to be bleached before it is made into paper. Any remaining enzymes are destroyed when the paper is dried [56].

4.2.3 Wood Products Industry

The Canadian wood products industry includes two main groups:

- producers of lumber and logs, and
- manufacturers of wood-based panel products (softwood plywood, oriented strand board, particleboard, medium density fibreboard, hardwood veneer and plywood).

The output of Canadian sawn softwood was 64.1 million cubic metres (m^3) in 1998. Domestic demand was 17.0 million m^3 and the strong economy and healthy housing market in the US in 1998 pushed exports of sawn softwood to the US to 42.1 million m^3, an increase of 1.4 million m^3 over 1997 and accounting for two thirds of Canadian sawn softwood production. In 1998, coniferous log exports reached 1 million m^3 with exports to the US doubling to 616 thousand cubic metres.

An increasing trend is more efficient use of the wood resource to make new generation, value-added building materials from the residual wood (including what was once considered waste material) once the high grade lumber has been extracted. This involves development of wood composite materials and this has spawned the wood-based panel industry (softwood plywood, oriented strand board, particleboard, medium density fibreboard, hardwood veneer and plywood). In 1996, the wood-based panel industry had total shipments of $3.7 billion of which $2.1 billion were exported. The largest panel sectors are oriented strand board (OSB) and softwood plywood, each of which shipped products worth $1 billion in 1996. The panel industry in Canada is located in all provinces of the country except Newfoundland and Prince Edward Island, and it is a significant supporter of rural economies.

4.2.3.1 Biotechnology Applications

The two main applications of biotechnology for cleaner production in the wood products industry are in wood preservation and in preventing sapstain.

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[56] Bioremediation of Hazardous Wastes, Wastewater, and Municipal Waste. In: Business Communications Company, Inc., Report Number: C-110U (1999).

A) Wood Preservation

In order to prolong their service lifetime and durability, lumber and panel products, which are used in construction to make buildings, decks, fences and other wood-based items, need to be protected against damage caused by decay and insect pests (decay is the big problem with exterior wood products used in Canada, whereas termites are the big problem in countries with warmer climates which import Canadian wood). Current methods of treatment use chemicals (e.g. chromate-copper-arsenate, boron, creosote). One biotechnology-based solution to prevent damage by termites which could be explored would be examining plant species which may contain chemicals repugnant to termites, extracting such chemicals and developing them for commercial use. A US organization recently applied for a patent on nootkatone, a chemical found in yellow cypress, as a termite repellent. Alternatively, researching the gene(s) responsible for producing these chemicals in plant species and transferring them through genetic engineering to other tree species could make these trees resistant to termites. To date, these kinds of work against termite-induced damage have yet to be done.

B) Prevention of Sapstain

Sapstain fungi cause a characteristic staining of sapwood, resulting in a blue, black, grey, or brown discolouration of the wood. Common sapstain fungi found on softwoods include many fungi of the genera: *Ophiostoma* and *Ceratocystis* (including their anamorphs such as *Leptographium*). Sapstain fungi can rapidly colonize the sapwood of logs, lumber and wood chips. These fungi grow mainly in ray parenchyma cells and are capable of deeply penetrating sapwood. In addition, these fungi can grow within resin canals, tracheids, and fibre cells, and penetrate simple and bordered pits, occasionally forming boreholes through the wood cell walls.

An informal network of Canadian research organizations led by Forintek Canada Corporation (http://www.forintek.ca) and the Department of Wood Sciences at the University of British Columbia[57] (http://wood.ubc.ca) are working together on minimizing the loss of value of Canadian softwood logs and lumber from fungi, which cause sapstain damage, by biotechnological methods. While chemicals can be used on freshly cut lumber in sawmills, they cannot be used on logs in the forest (because of environmental concerns such as soil and water contamination through chemical leaching). Research is ongoing to counteract the impact of dark-pigmented staining fungi species by developing albino (non-pigmented) fungi of the same type and inoculating felled trees with these in an effort to prevent the pigmented fungi from getting established. Some of this research work has reached the field trial stage.

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[57]Other network members include the University of Northern British Columbia (http://www.unbc.ca/), University of Laval (http://www.ulaval.ca), Canadian Forest Service, Agriculture and Agri-Food Canada (http://www.agr.ca), Forest Engineering Research Institute of Canada - FERIC, Phero-Tech Inc., Clariant Corporation and Mycologic.

4.2.4 Research and Development Capacity

One of Canada's recognized strengths in the forest sector is its excellent knowledge resources. Canada is a world leader in applied and basic research in forest biotechnology. The extramural R&D infrastructure includes universities, research institutes and Networks of Centres of Excellence. Led by the Canadian Forest Service, Natural Resources Canada (http://www.nrcan.gc.ca/cfs/), the Pulp and Paper Research Institute of Canada (PAPRICAN) (http://www.paprican.ca) , Forintek Canada Corporation (http://www.forintek.ca), and the Forest Engineering Research Institute of Canada (FERIC) (http://www.feric.ca/en/index.htm), Canada has a strong R&D position in a number of key niches of forest sector biotechnology, including:

- Forest Regeneration
- Forest Protection
- Treestock Development
- Biological Control Agents
- Sustainable Industrial Development
- Environmental Management
- Quality Control Strategies
- Risk Management and Policy Analysis.

Networks of Centres of Excellence like the Sustainable Forest Management Network, based in the University of Alberta, Edmonton, Alberta (http://web.cs.ualberta.ca/UAlberta.html) , and an extensive variety of educational and research institutes participating in training, education and investigations complement the eight subsectors.

4.2.5 Receptor Capacity

A key element in translating biotechnology research into products and services is the presence of technology development companies which bridge the gap between university/government research and the user industry. There are approximately 50 of these biotechnology development companies listed in the forest sector of the Canadian Biotechnology Directory 1999 (http://ContactCanada.com) . About 40% provide forest regeneration and forest protection products and/or services, another 10% provide products and/or services to the pulp and paper manufacturing industry, and the rest provide products and/or services for environmental protection (e.g., waste treatment biotechnologies). Most of them are small, employing 50 or less biotechnology staff and having revenues of $ 1-5 million. The total R&D expenditures by Canadian companies having a forest biotechnology component were estimated to be $42 million in 1998[58].

It should be noted that most of the revenues generated by Canadian forest-sector biotechnology firms have been generated in foreign markets, especially in the USA. This is because the

[58]Magazine of the Canadian Biotechnology Network, Biotech (June/July 1999).

Canadian forest products industry is conservative in its approach to novel technologies and relatively few biotechnology products have been taken through the demonstration phase in Canada. The Canadian forest industry is one of the most capital intensive industries in Canada and is a major user of high technology, especially informatics and intelligent systems. The Canadian forest products industry has adopted biotechnology derived products and processes where there are clear economic benefits, mostly in the areas of pest management (e.g. Bacillus thuringiensis) forest regeneration (e.g., DNA markers) and pulp and paper processing (e.g., xylanase in pulp bleaching). However, there are very few forest products companies such as Tembec which has in-house biotechnology R&D and uses biotechnology to transform waste by-products into value-added materials (e.g. ethanol from waste sulfite liquor).

Several initiatives (see below) have recently been launched to improve the receptor capacity of the forest products industry for technologies relating to intensive forestry.

Leading forestry research organizations in North Carolina and other regions of the US are encouraging US forestry companies to use biotechnology to grow more wood on less land and to produce hardier trees with better traits. In support of this, the North Carolina Biotechnology Centre (http://www.ncbiotech.org), in 1999, created an Advisory Committee on Forest Biotechnology, which will look at strengthening US forest biotechnology endeavours.

The concept of intensive forestry (i.e., equitable to the concept of plantation forestry) has only quite recently emerged as an activity that is worthwhile to be pursued in Canada. Intensive forest management and intensive forestry are two concepts which are being investigated as a tool for the future in Canada. Initiatives will be taken to look at gaps and provide innovative solutions to address growing concerns over long-term security of wood supply.

4.2.6 Sector Assessment

A) Forestry

World demand for forest products is forecast to increase significantly in the coming decades. According to FAO (http://www.fao.org/forestry/) estimates, world demand for wood will increase by 50 percent by the year 2010 and will double by the year 2020 from present levels. At the same time, a worldwide shortage of wood and wood products is expected at beginning of this millennium. This poses both a threat and a tremendous opportunity for Canada[59] .

As the global demand for wood continues to increase, maintaining healthy and productive forests to enhance the competitiveness of this industry becomes a priority. Canada's historical advantage in forest products due to its substantial natural forest endowment is rapidly diminishing.

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[59]Canadian Forest Service - Natural Resources Canada, National Climate Change Forest Sector Table . Foundation paper (1998).

Countries such as the US, Brazil, Chile, Malaysia, Indonesia and New Zealand are developing plantation forests which can be harvested after 7-10 years for hardwood pulp logs and after 20 to 30 years for softwood sawlogs. In Canada, by comparison, typical harvest rotations are 60 or more years.

An important opportunity for Canada to meet the increasing global demand for wood is to develop marginal agricultural land (which may have originally been forested) using intensely managed commercial forest plantations that incorporate trees with faster seedling-to-harvest cycles and also avoid the disease and pest problems associated with monoculture. This would help meet increasing demand for wood products without depleting Canada's overall forest resources and would also permit retention and protection of much of the remaining old growth forests. Genetic engineering technology for enhancing seedling survival, disease resistance and growth rates will be commercially available within the next decade. Multinational companies such as Fletcher Challenge Forests (http://www.fcl.co.nz), International Paper (http://www.internationalpaper.com), Westvaco (http://www.westvaco.com) and Monsanto (http://monsanto.com) have recognized the potential of biotechnology in this regard and have formed a joint venture to work with Genesis Research and Development Corporation Limited, a biotechnology company based in New Zealand, on tree improvements of this nature.

Financing and access to capital, support for R&D and technology transfer, efficient regulatory systems, effective patent protection and developing and retaining skilled human resources are potential barriers to growth and productivity improvement which the Canadian forest biotechnology industry shares with other high technology sectors. In addition, the forest biotechnology industry faces its own unique challenges. One example of a policy which could be seen as a barrier to investment and innovation in the forest industry sector relates to land tenure. Reforestation and sustainable forest management practices are significantly influenced by the form of forest tenure, and readiness to increase investment and pursue innovation in this field is fostered by more secure forms of land tenure (i.e. the ability to harvest what has been planted).

B) Wood, Pulp & Paper Products

Globally, there is increasing pressure on wood, pulp and paper manufacturing companies to use cleaner and more energy efficient production processes to reduce operating costs and minimize their discharge of environmentally toxic pollutants and greenhouse gases. Biopulping using fungal pretreatments can save energy in mechanical pulp operations. Pretreatment of kraft pulps with certain enzymes such and xylanases and hemicellulases, increases the effectiveness of subsequent chemical bleaching, and decreases the amount of chemical bleaching agents required. Other enzymes improve pulp dewatering rates, saving energy (see Section 4.2.2.1). Multinational companies such as Novartis (http://www.novartis.com), Genencor (http://www.genencor.com) and Clariant are actively pursuing opportunities in this market.

Genetic engineering of trees provides an alternative way to achieve cleaner manufacturing processes and increased energy efficiency by allowing the feedstock to be tailored to the end use. Companies like Zeneca Plant Sciences and Nippon Paper (http://www.npaper.co.jp/) are working together to genetically engineer trees in such a way as to make the lignin easier to separate from the cellulose. The companies expect their product will reduce lignin content by 20-30 per cent in conifers and 15-20 per cent in broadleaf trees. Adoption of these genetically modified trees could reduce the requirement for chemical pulping and bleaching agents by up to 30%.

C) Conclusion

The forest industry is a key contributor to Canada's economy. It is also a key source of biomass which could be used as a renewable feedstock for production of greenhouse-gas-neutral fuels and chemicals. While Canada's large landmass and forest resources have been the basis for competitive advantage, this advantage is being eroded by competition from countries with intensively managed forests. In order to maintain the competitive position of the existing forest industry and to open the way to an economy based more on renewable resources it is necessary that ways be found to increase forest yield sustainably and biotechnology has a role to play in making this possible.

Canada has a strong research base in forest biotechnology. This is recognized internationally and foreign companies such as Stora (a Swedish forest products company) have begun to establish a presence in Canada to link with these research capabilities. There is also a growing forest biotechnology industry in Canada composed of innovative small companies which can help translate research and technology developed in university and government laboratories into commercial products and services for the forest and forest products industry.

The forest and forest products industry is technology intensive but conservative when it comes to adopting novel technologies. Also, it has had to make major investments in pollution reduction technologies to meet air and water quality objectives so it is reluctant to undertake more investment unless it is in proven technologies with clear economic benefits. Over the last few years, the industry has reduced its in-house R&D capacity, preferring to buy technology as turnkey systems. As a result, when it comes to biotechnology, the Canadian forest and forest products industry is expected to be a technology follower rather than leader[60].

Given this preference to buy rather than develop technology, one strategy would be to help reduce the time from first commercial application of a biotechnology anywhere in the world to when it is applied in Canadian firms through an international technology watch coupled with a fast-response technology demonstration/validation program. Alternately, the move toward biotechnology may be initiated by a chemical or energy company which might form an alliance with a forest company or acquire it to obtain carbon credits or access to biomass as a renewable feedstock. In this regard, it is possible there will be a convergence among forest, chemical & plastic, energy and agricultural companies when it becomes economically attractive to make renewable fuels and chemicals from biomass.

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[60]Although there are companies like Tembec which is highly innovative in its use of biotechnology to produce ethanol and possibly other chemicals from pulp and paper waste.

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4.3 The Canadian Energy Sector

The energy sector, which includes oil and gas, electric utilities, refined petroleum and coal products, coal and uranium, contributes $52 billion to the Canadian GDP and directly employs about 200,000 people (http://strategis.ic.gc.ca/SSG/bh00208e.html).

According to the National Energy Board[61], primary domestic energy production in Canada was 16,276 Petajoules (PJ)[62] in 1997. The main sources of energy were natural gas (42%), oil (30%), coal and coke (18%), hydro (7%), nuclear (6%) and renewables (4%). About half of this primary production is exported (7, 942 PJ), the main exports being oil (42%) and natural gas (38%). Total Canadian secondary (end use) energy demand was reported to be 8,482 petajoules (PJ) in 1997. Of this, 38% was met by oil products (e.g. gasoline, diesel, heavy fuel oil), 29% by natural gas, 20% by electricity, 7% by renewable energy sources (e.g. pulping liquor, wood, hog fuel and solar energy) and 6% by other fuels (e.g. coal and coke). This secondary demand came primarily from the following sectors: industrial (34%), transportation (25%), residential (19%), commercial (12%) and non energy use of hydrocarbons (10%) (http://www.neb.gc.ca/energy/sd99/index.htm).

Greenhouse gas emissions from the production and consumption of energy in 1997 were reported to be 572 megatonnes (Mt) of CO2 equivalent. These emissions originated from: the transportation sector (28%), fossil fuel production (18%), industrial sector (19%), electricity generation (19%), residential sector (10%), commercial sector (5%).

Since Canada's economy depends heavily on non renewable fossil fuels that are major greenhouse gas emitters, government and industry (http://www.cppi.ca/en/library/issues/issues.asp) have been actively looking for ways to achieve a sustainable production and use of energy. After several decades of research and development, biotechnology is emerging as a tool that can play an important role in the cleaner utilization of fossil fuels and also in the production of fuels from renewable biomass resources.

4.3.1 Fossil Fuels

4.3.1 1 Biotechnology Applications

A) Microbial enhanced oil recovery (MEOR)

Microbial enhanced oil recovery (MEOR) or microbial improved oil recovery (MIOR) is a secondary / tertiary oil recovery process whereby microorganisms are used to extract oil from wells through several mechanisms including:

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[61] National Energy Board, Canadian Energy - Supply and Demand to 2005 (1999).

[62] One petajoule (10^{15} Joules) is approximately equivalent to 165,000 barrels of oil.

- Increasing the solubility of residual oil in crude oil formations by biosurfactants produced by oil-degrading bacteria;
- Controlling the viscosity of flood solutions during secondary oil recovery by polymers produced by bacteria;
- Repressurizing and redirecting the oil flow in wells as a result of carbon dioxide produced by the growth of bacteria injected in the well;
- Reducing the viscosity of the oil by injection of microbes that can metabolise long chain alkanes (e.g. waxes) in the well.

Current MEOR applications use naturally occurring microorganisms which under the appropriate oil well conditions, (e.g. salinity, pressure, permeability and temperature), may provide economic and environmental advantages compared to conventional recovery methods that are based on waterflooding and injection of chemical agents into the well. The economic advantages result from the lower initial and follow-up costs of implementing a MEOR process and also from relatively high oil recovery rates. The environmental advantages result from the fact that conventional injection processes are more energy intensive and use chemicals such as acids.

B) Biological upgrading and refining of fossil fuels

Oil extraction is usually followed by upgrading (primary and secondary) and refining steps. Upgrading involves thermal cracking processes that reduce the viscosity of heavy crude (through aromatic/cycloparafinnic ring opening) as well as other energy intensive processes for removal of sulphur and nitrogen. In refining, catalysts are used to convert the crude oil to various product streams. The potential of using biotechnology in both upgrading and refining has been recognized for several years. In the areas of biodesulphurisation (BDS), research has been going on for over 60 years and this has led to a good understanding of the enzymes and genes that play key roles in the transformation of inorganic and organic sulphur into water soluble products. This interest in biodesulphurisation is primarily driven by a desire to move away from the conventional hydrodesulphurisation (HDS) process which is:

- expensive (capital cost of about $ US 50 - 80 million),
- energy intensive (HDS requires high temperature, pressure and hydrogen) and
- relatively inefficient for deep desulphurisation (HDS is cost effective on low molecular weight compounds) .

Some of the environmental and economic advantages claimed by Energy Biosystems Corporation (http://www.energybiosystems.com) regarding its biodesulphurisation process over the hydrodesulphurisation process include:

- Energy savings and a reduction of greenhouse gas emissions of 70% - 80%;
- Safer operating conditions;
- Effective removal of sulfur in aromatic ring structures;
- Capital cost savings of approximately 50%;
- Operating cost savings of about 10% - 20%;

- More rapid engineering and construction time (12 - 18 months for BDS versus 24 -36 months for HDS).

Besides biodesulphurisation, other bioupgrading opportunities include converting ring structures into less viscous branched or chain paraffins that are more desirable as transportation fuels, easier to ship and require less energy to refine. In the refining sector, there are opportunities to develop biocatalysts for niche applications where conventional catalysts are inadequate.

It is important to note that the success of these potential applications will heavily depend on where they are being applied. In upgrading and refining plants, production rates are of the order of 200,000 barrels per day and this could be too much of a challenge for bioprocesses[63]. However at well sites where production is of the order of 20,000 barrels or less and the oil has a residence time of about 7 days from the day it is extracted to its transport in pipelines, biotechnology applications are more realistic.

4.3.1.2 Research and Development Capacity

In Canada, research and development on the applications of biotechnology in the fossil fuels sector has been concentrated mostly on the bioremediation of contaminated sites. As a result, Canada has developed world class expertise in this area, for example at the NRC's Biotechnology Research Institute (http://www.bri.nrc.ca/bri-1c.htm), the University of Alberta (http://www.biology.ualberta.ca/), and École Polytechnique de Montréal (http://www.biopro.polymtl.ca). However, besides bioremediation, R&D on the applications of biotechnology in the production, upgrading or refining sectors of the fossil fuel industry has been relatively limited.

A) Microbial Enhanced Oil Recovery

The Alberta Oil Sands Technology and Research Authority (AOSTRA) has funded work on MEOR in 1989 which led to a patent (US 4800959) for a microbial process for selectively plugging a subterranean formation. No field trial using this process has however been reported. Imperial Oil and more recently Husky Oil also have done some exploratory work on MEOR but there is currently no reported activity in Canada. Current efforts to improve oil recovery, for example at the Petroleum Recovery Institute (http://www.pri.ab.ca/intro.html), have been focussed primarily on improving traditional recovery techniques such as waterflooding and injection of chemical agents.

In the U.S., leading research in the area of the novel biosurfactants is being carried out at the

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[63] Presentation by Dr. Heather Dettman of the National Centre for Upgrading Technology (http://www.ncut.com) at the Environmental Biotechnology for Sustainable Industrial Forum in Montreal, February 2, 2000.

University of Oklahoma (http://www.ou.edu/cas/botany-micro/faculty/mcinerne.html). R&D is also being done by several companies such as:

- Micro-Bac International (http://www.micro-bac.com/alternative.html),
- Environmental BioTechnologies (http://www.e-b-t.com/meor.htm),
- U.S. Microbics Inc. (http://www.bugsatwork.com/prod05.htm),
- Oppenheimer Biotechnology Inc. (http://www.obio.com/meor.htm) and
- the Atech CTI Group (http://www.atech-cti.com/about.html).

Many of these companies are start-ups that also offer bioremediation services. Scientists and engineers at the Idaho Engineering and Environmental Laboratory (INEEL) are supporting these companies by developing economical methods to use microbes to increase oil production rates, reduce water intrusion, and decrease sour fluids (http://www.inel.gov/engineering/oilsub.html). MEOR has also been investigated in several countries such as Russia, Rumania and China.

B) Biological upgrading of fossil fuels

In Canada, R&D on the biodesulphurization of fossil fuels has focussed mainly on:

- Anaerobic desulphurization of hydrocarbons by sulphate reducing bacteria, especially *Desulfovibrio vulgaris* (http://www.ucalgary.ca/UofC/faculties/SC/BI/cmmb/voordouw.html);
- Biodegradation of dibenzothiophenes by pure and mixed bacterial cultures, specially *Pseudomonas* isolates (http://www.biology.ualberta.ca/fedorak.hp/fedorak.html);
- Development of *Rhodococcus* strains with high desulphurization capacity of bitumen and related compounds (http://www.bri.nrc.ca).

Most of the biodesulphurisation research peaked in the mid nineties and today the level of activity is lower as a result of limited funding. However, recently, under the Strategic Technologies Application of Genomics in the Environment (STAGE) program funded by Environment Canada, the Biotechnology Research Institute has been investigating the full coding capacity and biocatalytic potential of a biodesulphurization plasmid (http://www.bri.nrc.ca). Research in other areas of biological upgrading of fossil fuels is being carried out mainly in Alberta for example at the University of Alberta (http://www.biology.ualberta.ca/foght.hp/foght.html), (http://www.ualberta.ca/CHEMENG/gray/), the National Centre for Upgrading Technology (http://www.ncut.com) and the Alberta Research Council (http://www.biotech.arc.ab.ca/).

Outside Canada, Texas based Energy Biosystems Corporation has publicized extensively its activities on the biodesulphurisation of a wide range of petroleum streams. It has achieved a 400 fold increase in the catalytic efficiency of some *Rhodococcus* bacteria since 1992 through genetic engineering with the result that the cost of biodesulphurisation of one gallon of diesel has decreased from about $400 to about $0.14 . The current objective is to further improve the biocatalyst and reduce the cost of biodesulphurisation to the order of $0.02 – $0.03 per gallon in order to make it a commercially attractive option. Research is also being carried out on the biodesulphurisation of natural gas and other industrial gaseous emissions in Japan (BIO-SR process), the Netherlands (http://www.paques.nl/) and the U.S.(http://www.arctech.com).

The Oak Ridge National Laboratory (ORNL) and Lawrence Berkeley National Laboratory (LBNL) are also carrying out research in biological upgrading of heavy oils, for example reducing the viscosity of heavy oils by using bacterial enzymes capable of partially transforming polycyclic aromatic hydrocarbons (PAH) (http://www.energylan.sandia.gov/ngotp/ngotp.htm). Since the U.S. derives about 56% of its electricity from coal, there has been an interest in developing technologies that combine microbial action with a physical method to separate pyrite and other minerals containing sulfur, arsenic, mercury, selenium, and other pollutants from coal before it is burned (http://www.inel.gov/engineering/coalsub.html).

4.3.1.3 Receptor Capacity

A) Microbial Enhanced Oil Recovery

Microbial enhanced oil recovery tests that were carried out in the 1980s were not successful in Canada. The inappropriate physical characteristics of Canadian oil wells (e.g depth and shape), the type of oil found in Canada (Alberta oil consist primarily of aromatic ring structures and not long chain alkanes which can be metabolized by microbes) and limited microbiological expertise among petroleum engineers are some of the key factors that have hindered the development and adoption of this technology.

MEOR operations have however been successful in several oil fields in the USA, Venezuela and China (http://www.micro-bac.com/alternative.html). For example, since 1993, Texas based Advanced Technologies is reported to have injected microorganisms into more than 2,500 wells in Lake Maracaibo in Venezuela (http://www.atech-cti.com/meor.html).

B) Bio-upgrading of fossil fuels

Barriers to the adoption of bio-upgrading technologies such as biodesulphurisation, include technical limitations (e.g. inefficient at high flow rates) and poor financial returns. In a few cases, where bioprocesses can compete with conventional physical/chemical processes, (e.g. removal of hydrogen sulphide from sour gas), a lack of demonstration projects and previous capital investments have been considerable barriers to adoption. The recent licensing of the Shell-Paques biodesulphurisation technology to remove sulphur from natural gas and sour gas flares by New Paradigm Gas Processing Ltd, a subsidiary of CCR Technologies Ltd could lead to the first commercial exploitation of such technologies in Canada (http://www.reclaim.com/new/).

The timing of government regulations can also act as a barrier to the adoption of innovative bioprocesses. For example, the introduction of regulations in Canada to lower the level of sulphur in gasoline from an average of 350 ppm to 30 ppm by January 2005 should drive the development and adoption of innovative technologies by the Canadian oil refineries. However since biodesulphurisation is currently not a mature technology, it is unlikely that it will be considered by the Canadian petroleum industry to meet its targets by 2005.

In other parts of the world, commercial plants featuring bioprocesses for removal of hydrogen sulphide from natural gas have been built in Japan (BIO-SR process) and the Netherlands (http://www.paques.nl/). Energy Biosystems is building a pilot plant, in collaboration with Petro Star in Alaska, to demonstrate the biodesulphurisation of crude oils. Major refiners such as Total/Elf of France and Texaco have also been collaborating with Energy Biosystems.

4.3.1.4 Sector Assessment

As fossil fuel resources become depleted, efficient secondary/tertiary oil recovery techniques as well as technologies that can upgrade the vast reserves of high sulphur and high viscosity bitumen in Canada will become increasingly important. The economic and environmental benefits of using biotechnology for both oil recovery and upgrading have been recognized and investigated in many countries, including Canada. At the present time, there is limited interest and expertise to carry out microbial enhanced oil recovery (MEOR) operations in Canada, primarily as a result of poor field trials in the 1980s attributed to the characteristics of the oil wells and the fact that petroleum engineers are not trained in the area of microbiology. However, since 70% of the oil that is discovered in Canada cannot be recovered using conventional recovery techniques and that in the past decade some companies have claimed excellent recovery using MEOR in different parts of the world, Canadian oil companies and bioremediation companies which offer clean-up services to the petroleum industry should still minimally keep a window on this technology. Major breakthroughs in other parts of the world using this technology could rekindle Canadian interest in this area.

In the area of bio-upgrading of fossil fuels, niche areas where biotechnology can play an important role are being identified and investigated when resources are allocated. So far, these resources, both human and financial, have been quite limited. In fact, few Canadian scientists have expertise in bio-upgrading technologies and more importantly the financial resources required to conduct long term strategic R&D have not been available. Since very promising bio-upgrading technologies are being developed as a result of long term R&D commitment, (e.g. Energy Biosystems in the U.S.A. has been able to reduce the cost of biodesulphurisation of one gallon of diesel from about $400 in 1992 to about $0.14 today), it is worth re-evaluating the level of support that has been allocated to this field in Canada. Areas that could be addressed include:

- Financing strategic R&D that brings together expertise from complementary disciplines (e.g microbiology and chemical engineering). Examples of such R&D teams can be found at the University of Alberta;
- Financing demonstration projects that allow companies to refine their technology;
- Bridging the cultural differences between engineers and microbiologists, for example by providing microbiology courses as part of the engineering curriculum.

4.3.2 Energy production from renewable biomass resources

4.3.2.1 Biotechnology Applications

The bioconversion of renewable biomass feedstocks such as agricultural and wood wastes into ethanol or other fuels can yield major environmental and economic benefits. The blending of gasoline with bio-ethanol leads to lower emissions of greenhouse gases, volatile organic compounds, nitrous oxides, benzene and other particulates compared to gasoline. For example a 10% ethanol blend with gasoline results in a 2 - 3 % reduction in carbon monoxide and a 6-10 % reduction in carbon dioxide (http://www.greenfuels.org/envirobenefits.html). Similarly, bio-diesel is biodegradable and has lower emissions of carbon monoxide, hydrocarbons, particulates and especially sulfur compared to petrodiesel. According to the U.S. based National Biodiesel Board, in the presence of an oxidation catalyst, a 20% biodiesel blend with petrodiesel results in at least a 40 % reduction of particulate matter, carbon monoxide and total hydrocarbons (http://www.nbb.org/faq.htm). In addition to these environmental benefits, the conversion of waste biomass into value-added products can also lead to increased employment and economic diversification in the forestry or agricultural sectors. Opportunities for the use of biomass to produce energy are specially interesting because, although in energy terms annual land production of biomass is about five times the global energy production, only one percent of commercial energy originates from biomass[64].

Organic wastes from landfill sites or farms can also be converted to energy through anaerobic digestion[65] to yield biogas (approximately 55% methane and 45% carbon dioxide). Landfill sites account for 26% of the man-made methane emissions from Canadian sources http://www.ec.gc.ca/nopp/lfg/bulletin/indexe.htm). Annually, about 25 Megatonnes of CO_2 equivalent are generated from these sites. The collection and utilization of these landfill gases can result in significant economic and environmental benefits such as energy recovery, greenhouse gas reductions and the elimination of problems such as odors and pathogens in the neighborhood. The anaerobic digestion of farm wastes such as swine, dairy and poultry manure slurries is another source of biogas. However, the economics of producing biogas from farm waste are not as favourable and these types of operations often require subsidies to become viable. The potential of reducing GHGs through landfill site management has been fully reviewed as part of the National Climate Change Process (http://www.nccp.ca).

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[64]OECD, Biotechnology for Clean Industrial Products and Processes, p. 30 (1998).

[65]The decomposition of organic material by microorganisms in the absence of oxygen.

4.3.2.2 Research and Development Capacity

A) Bio-Ethanol Production

Canada has considerable expertise in the conversion of various forms of biomass, e.g. agricultural substrates and forestry wastes into ethanol. In the area of enzymatic conversion of agricultural residues and hardwood to ethanol, Iogen Corporation, (http://www.iogen.ca), has developed world class expertise as a result of sustained R&D for over 20 years. Other promising technologies for production of ethanol include the Acid Catalyzed Organosolv Saccharification (ACOS) process developed at the University of British Columbia in the 1980's (http://www.wood.ubc.ca/people/faculty/paszner.html)[66] . This process involves the solubilization of lignocellulose with a concentrated solution of acetone containing a small amount of acid and there have been claims that it can be used on a wide variety of feedstocks. There has also been R&D in improving the fermentation of various sugars to ethanol, for example extractive fermentation at Queen's University (http://www.chemeng.queensu.ca/ajd) and very high gravity fermentation at the University of Saskatchewan (http://www.ag.usask.ca/departments/amfs/faculty/ingledew/index.html). Expertise in the conversion of biomass to ethanol is also present within Agriculture and Agri-Food Canada (http://res.agr.ca/neri/ethanol/ethatabl.htm), the National Research Council (http://www.sao.nrc.ca/ibs/vaccine_e.html), the University of British Columbia (http://www.wood.ubc.ca/people/faculty/saddler.html),and the University of Toronto (http://bioinfo.med.utoronto.ca/Brochure/Lawford.html) .

In the United States, the Office of Fuels Development (OFD) of the Department of Energy sponsors the National Biofuels Program which consists of the Regional Biomass Energy Program (RBEP), the Bioenergy Feedstock Development Program (BFDP) and the Biofuels Program (http://www.biofuels.doe.gov/research.html).The goal of the Bioenergy Feedstock Development Program (BFDP) managed by the Oak Ridge National Laboratory (ORNL) is to develop and demonstrate environmentally acceptable crops and cropping systems for producing large quantities of low-cost, high quality biomass feedstocks (http://bioenergy.ornl.gov/bfdpmain.html). The Biofuels Program managed by the National Renewable Energy Laboratory (NREL) consists of two main projects, one on Bio-Ethanol and another on Bio-diesel. Research and development in the Bio-Ethanol project is being driven by the desire to make bioethanol competitive in the marketplace when tax incentives end in 2007. As a result, NREL is focusing its efforts primarily on cellulase technology research[67]. In order to reach the target of producing bioethanol at

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[66]The patents surrounding this technology have been the subject of dispute between Canadian and Brazilian organisations and as a result the technology has not yet been proven at a commercial scale.

[67]It is expected that future cost reductions are likely to be four times greater for the cellulase process than for the concentrated acid process, and three times greater than for the dilute acid process.

US$0.40 per gallon (CDN$0.16 per litre), research is targeted at improving the activity of cellulases by at least ten-fold and developing fermentation organisms that are able to ferment non glucose sugars or convert cellulose directly to ethanol (http://www.biofuels.doe.gov/bioethanol.html). The United States Department of Agriculture also has R&D activities in this area, however the focus is primarily on the conversion of agricultural crops to ethanol (http://www.nal.usda.gov/ttic/biofuels.htm). Promising R&D aimed at developing xylose fermenting *Saccharomyces* strains is being carried out at the Laboratory of Renewable Resources Engineering (LORRE) of Purdue University (http://IIES.www.ecn.purdue.edu/IIES/LORRE/).

In France and Italy, the technologies used to produce bio-ethanol from agricultural crops such as sugar beets, wheat and sweet sorghum are well understood and only limited R&D is being done in these areas. However, European countries, especially Sweden and Finland, through collaborative research projects such as the EU Cellulase project, (http://alpha2.bmc.uu.se/~cellulase/) are considered world leaders in gathering fundamental knowledge on cellulase enzymes that could have applications in a wide range of industries such as energy, pulp and paper, textile, food and feed processing.

B) Biodiesel Production

The potential of producing biodiesel from refuse and heated canola oil has been investigated by the Saskatoon Research Centre of Agriculture and Agri-Food Canada (http://res.agr.ca/sask/fuel.html) in the mid nineties with support from the Saskatchewan Canola Development Corporation (http://www.canolainfo.org/scdc/html/researchlist.html). Research carried out at the CANMET Energy Technology Centre of Natural Resources Canada led to the conversion of canola and tall oils into a high cetane component of diesel fuel (http://www.nrcan.gc.ca/es/etb/cetc/facts/cetc02hc.htm). More recently, there has been considerable progresss in increasing the rate of base-catalysed transesterification of vegetable oils to biodiesel (http://www.chem-eng.utoronto.ca/faculty/boocock.html). R&D targeted at improving the oil content in crops is being carried out the Plant Biotechnology Institute of the National Research Council of Canada (http://www.pbi.nrc.ca/fact98/somg.html) and this could have an impact on the economics of biodiesel production.

In the U.S., R&D on biodiesel is being carried out (although not to the same extent as in bio-ethanol) within the National Biofuels Program and the United States Department Of Agriculture (see previous section). The focus of the R&D is to make biodiesel cost competitive with petroleum diesel. Present cost of producing biodiesel from soya oil is estimated at US $2.00 to $3.00 per gallon at the plant gate and the goal is to reduce the production cost to less than US $1.00 per gallon. Current research includes enzymatic approaches using lipases to produce biodiesel from inexpensive feedstocks such as animal fats, recycled restaurant grease and low value co-products from vegetable oil processing (http://www.nal.usda.gov/ttic/biofuels.htm), improvements in soybean crushing and esterification process, development of oil seeds with higher oil content and improving cold weather performance of biodiesel.

In Europe, research on biodiesel has been supported through the FAIR Programme of the European Commission (EC). Between 1985 and 1996, 44 MEcu were spent on 70 biodiesel projects, most of them targeting esterification research, with France, Italy and Germany taking leadership roles (http://europa.eu.int/en/comm/dg17/atlas/htmlu/lbrtdc.html).

C) Biogas Production

Research and development in the area of biogas production from wastes (e.g. landfill, industrial, farm) is increasing in Canada. Eastern Power Ltd (Toronto, Ontario) is currently in the process of developing and demonstrating an enhanced two-stage anaerobic digestion system for treating non-recyclable municipal solid waste (http://strategis.ic.gc.ca/SSG/tp00158e.html). The Dairy and Swine Research and Development Centre of Agriculture Canada (http://res.agr.ca/lennox/home.htm) and the University of Ottawa (http://by.genie.uottawa.ca/profs/droste/droste.htm) recently obtained a US patent (US5863434) for the development of an anaerobic treatment of farm wastes. The Biotechnology Research Institute has been involved in the anaerobic digestion of industrial wastes, specially those resulting from the pulp and paper industry (http://www.bri.nrc.ca).

A description of biogas R&D being done in several European countries is provided through the Anaerobic Digestion Network (http://www.ad-nett.org/). Biogas production using manure digesters is considered a mature technology in Europe and R&D is now targeted mainly at solid waste digesters. In the USA, the National Renewable Energy Laboratory (NREL) (http://www.nrel.gov/) of the Department of Energy spent about ten years developing a technology for the anaerobic digestion of organic matter with high solids content. This technology has been transferred to Pinnacle Biotechnologies Inc (Evergreen, Colorado) (http://www.pinnaclebiotech.com/) which is demonstrating its commercial applications.

4.3.2.3 Receptor Capacity

A) Bio-ethanol

In Canada, annual production of bio-ethanol derived from corn or wheat using established fermentation technology is around 220 million litres [68] and most of it is used in fuel blends (http://www.greenfuels.org/ethaprod.html). In addition, Tembec Inc. also produces about 14 million litres of high purity ethanol (used primarily in food processing and pharmaceuticals) from

[68] Companies involved with commercial scale production of ethanol in Canada include: Commercial Alcohols (Chatham, ON.), Mohawk (Minnedosa, MB), Pound-Maker Agventures Ltd.(Lanigan, SK), API Grain Processors (Red Deer, AB) and Tembec(Témiscamingue, QC).

spent sulfite liquor[69]. Other companies that have shown an interest in building bio-ethanol plants using corn or wheat include Seaway Valley Farmers, Canadian Agra and Metalore Resources.

Technologies that are being developed to convert agricultural or forestry residues to ethanol are currently at or near demonstration stage. For example, Iogen, in partnership with Petro-Canada and Technology Partnerships Canada, is currently building a plant in Ottawa to demonstrate that ethanol can be cost-effectively produced from agricultural feedstock such as oat hulls, straw and corn stovers. Tembec has also been testing xylose fermenting *Saccharomyces* strains developed at Purdue University to increase ethanol yields from spent sulfite liquor. Further adoption of these technologies will depend on the success of the demonstration plants.

In the U.S., there are about fifty ethanol producers which produce about 3.5 million tonnes of ethanol, mostly from corn. Receptor capacity for novel technologies has also been increasing in the U.S.. Arkenol which holds a series of patents on the use of concentrated acid to produce ethanol is collaborating with the Department of Energy to build a commercial facility to convert rice straw to ethanol in Sacramento County, California. Masada Resource Group is also collaborating with DOE to build a municipal solid waste (MSW)-to-ethanol plant in Orange County, New York and BC International is building a plant in Louisiana for the conversion of sugar cane bagasse to ethanol using dilute acid hydrolysis (http://www.biofuels.doe.gov/bioethanol.html). The potential of genetically modified yeasts developed at Purdue University to convert corn and wheat stover into ethanol is being evaluated by Swan Biomass Inc., an affiliate of Amoco, in collaboration with several partners (http://www.agcom.purdue.edu/AgCom/news/backgrd/9808.Ho.yeast.html).

In Europe government regulations and subsidies have led to the growth of the bioethanol industry. Total production in 1995 was 350,000 tonnes with France accounting for 200,000 tonnes and Italy 120,000 tonnes. According to the EU commission biofuels are expected to reach a 5% share of the total fuel consumption in 2005 (http://www.biodiesel.de/biodiesel2000.htm).

B) Biodiesel

An analysis of selected markets for diesel in Canada concluded that three main factors will drive the penetration of biodiesel in Canada : price, perception and compatibilty of diesel with a given industry (http://res.agr.ca/sask/fuel.html) . Although biodiesel has been tested in many locations in Canada, it is not yet available commercially because it cannot compete with petrodiesel on a cost basis.

In other countries where the biodiesel industry has grown, government regulations, subsidies as well as public support have played key roles. For example some European countries have supported the construction of pilot or demonstration plants with capital grants and have provided

[69] Presentation by Dr. David Cameron of Tembec Inc. at the Environmental Biotechnology for Sustainable Industrial Development Forum in Montreal, February 2, 2000.

tax relief on the biodiesel produced. In 1995, biodiesel production in Europe was about 500,000 tonnes with Italy (186,000 tonnes) and France (160,000) tonnes as major producers (http://europa.eu.int/encomm/dg17/atlas/htmlu/lbpot1.html).

In the U.S., government regulations and subsidies are also needed to increase the viability of the biodiesel industry. Before an amendment to the U.S. Energy Policy Act of 1992 (EPACT) in late 1998, there were 7 registered biodiesel producers operating at about 10% of the total capacity of 50 million gallons. The amendment which allows fleet managers to comply with EPACT requirements by using an 20% biodiesel blend (B20) will likely stimulate the market for biodiesel in the U.S. (http://www.oilseeds.org/asa/asatemp/biodcong.htm) .

C) Biogas

An appropriate financial return is a primary condition for any biogas-to-energy installation. In the absence of incentives such as tax credits in Canada, it is difficult for landfill site developers to compete with other power generating stations with better economies of scale and lower production costs. As a result, there are only about 13 landfill sites in Canada that have been converting the emissions into energy. A description of six of these sites is provided at http://www.ec.gc.ca/nopp/lfg/bulletin/indexe.htm.

In the United States, financial incentives in the form of tax credits and regulations for collecting greenhouse gases have facilitated the energy production from landfill sites (http://www.epa.gov.outreach/lmop/products.html). The impact of these incentives is clearly demonstrated by the fact that Ontario based Comcor, although having no generating facilities in Canada, has been exploiting about 30 landfill gas sites in the United States totaling approximately 130 MW.

In the area of biogas production from farm wastes, a number of demonstration projects run in Canada from 1973-86 failed because of system instability, intensive labour requirements and poor economics (http://www.ad-nett.org/home5.htm). Currently, the main driving forces for anaerobic digestion of farm wastes in Canada are environmental regulations, energy recovery and the desire of the farming community to eliminate problems such as odors and pathogens in its neighborhood. Bio-Terre Systèmes Inc in collaboration with the Dairy and Swine Research and Development Centre of Agriculture Canada (http://res.agr.ca/lennox/home.htm) is currently testing anaerobic digestion systems using psychrophilic micro-organisms (micro-organisms adapted to low temperatures) in Quebec swine farms.

Farm based anaerobic digestion systems in the United States have also been plagued by some of the problems encountered in Canada, e.g. technological and economic barriers. Overall about 65% of anaerobic digestion projects failed with regions such as Michigan experiencing failure rates of over 85% (http://www.msu.edu/~rozdilsk/adpaper.htm).

In the mid eighties European farm based biogas production also ran into technical and economic barriers in spite of very generous government subsidies. Since then many of the technical problems have been resolved, and as a result of continuous government subsidies for biogas installations about 200 new plants have been built in Germany in the past two years (http://www.ad-nett.org/home5.htm).

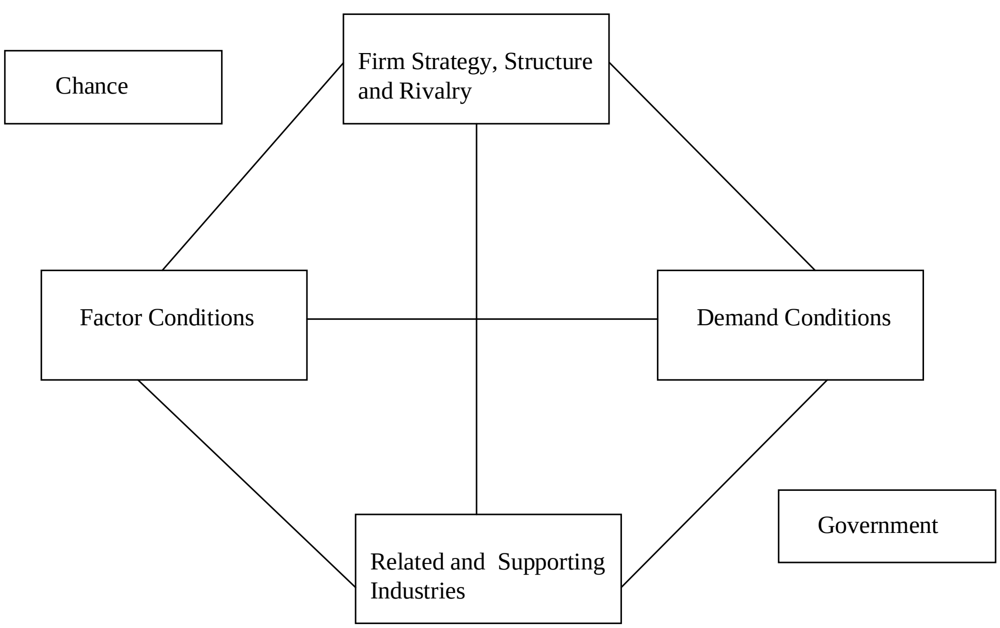
4.3.2.4 Sector Assessment

The "Diamond" model developed by Michael Porter will be used to assess Canada's ability to compete in the bioethanol, biodiesel and biogas (landfill) industries. This model (Figure 1) contends that regions develop a competitive advantage based on their ability to innnovate. The determinants that influence innovation include:

- Factor conditions, such as a specialized labour pool, natural resources and infrastructure;
- Demand conditions from local customers who push companies to innovate;
- Related and supporting industries which create business infrastructure and spin off industries;
- Firm strategy, structure and rivalry.

In addition to these factors, chance and government action play also very important roles, especially in the early development of an industry.

Figure 1: Porter's Diamond Model[70]



[70]Porter, Michael, Competitive Advantage of Nations, Free Press, New York (1990).

A) Bioethanol

Factor conditions for sustaining a bio-ethanol industry in Canada are generally very good and include:

- Excellent research and development capacities in industry, universities and government laboratories in the conversion of lignocellulosic biomass to ethanol.
- Excellent renewable agricultural and forestry biomass resources across the country.
- Existing transportation fuel distribution infrastructure that supports the integration of ethanol in the fuel mix.

On the demand side, agricultural associations, environmental and government organisations have been the major proponents of bio-ethanol. Key players in the current value chain of the Canadian fuel transportation industry, e.g. gasoline producers, consider ethanol as an alternative to several oxygenates that they can produce. Thus there is no guaranteed demand on their part except if the other oxygenates are banned on environmental or health concerns or there is regulated use of bio-ethanol. On the consumer side, there has also been limited demand as a result of a lack of awareness about bio-ethanol.

In the area of related and supporting industries, contrary to the supply of corn or wheat to ethanol producers, a reliable system for supplying agricultural and forestry residues to processors is not yet established and this could become a major barrier. The fact that advances in fuel cell technology have focused mainly on the use of methanol as fuel source could also considerably limit the growth of the bio-ethanol industry, especially in countries like Canada that can readily produce methanol.

Strategies adopted by Canadian organisations pursuing the production of ethanol from biomass have contributed significantly to the development of the industry. These strategies include:

- Developing leading edge lignocellulosic conversion technology;
- Improving the overall profitability of ethanol production by producing valuable co-products;
- Gaining first mover advantages by demonstrating the commercial feasibility of their technology;
- Securing adequate feedstock supplies;
- Developing strategic alliances with key partners that can market and distribute the ethanol produced.

As expected, governments have also played a key role in the development of the Canadian bio-ethanol industry. Examples of government initiatives include:

- Exemption of federal excise tax and provincial taxes[71] on ethanol blended fuels;
- Creation of the National Biomass Ethanol Program that offers a repayable line of credit guaranteed by the federal government in the event of a future reduction or elimination of the federal excise tax exemption for ethanol (http://www.agr.ca/progser/aafnbep.html)
- Allocation of funding for research and development in the production of ethanol from biomass.
- Provincial financial incentives in Manitoba and Saskatchewan that have led to the construction of ethanol plants from grains. For example, the Poundmaker ethanol plant, at Lanigan Saskatchewan, has received assistance of 40 cents/litre for the initial years of operation of the plant for product sold into the Saskatchewan market, (http://www.agr.ca/pfra/sidcpub/sidcft3.htm)

In summary, favorable factor conditions, good strategic decisions on the part of companies and government initiatives have been the major determinants that have allowed Canada to become a world class competitor in the conversion of cellulosic biomass into ethanol. Besides the plant being built in Ottawa by Iogen Corporation, interesting opportunities exist in other parts of the country , especially in British Columbia where softwood supplies are considerable. However, besides demonstrating the cost-effectiveness of a process, the following barriers or threats will need to be addressed in order for the bioethanol industry to be fully developed in Canada:

- A feedstock supply system is not yet in place to provide agricultural and forestry residues to the processors;
- Gasoline producers consider ethanol as an alternative to several other oxygenates and may not represent a substantial market for ethanol;
- Tax incentives from governments may be reduced or eliminated;
- Lack of financial resources to demonstrate other promising technologies (e.g. technology that could be used to convert softwoods to ethanol)
- Lack of awareness among consumers and fleet managers about bio-ethanol;
- Fuel cells may not be commercially designed to use ethanol as a fuel source .

B) Biodiesel

Just as in the case of bio-ethanol, factor conditions for biodiesel production in Canada are excellent since Canada is a major producer and exporter of vegetable oils (e.g canola or soya) and the technology as well as the skilled labour that is required to convert oils into biodiesel are readily available.

Canadian demand for biodiesel has however been limited because of its high price compared to petrodiesel or other renewable fuels such as ethanol. In 1997 the cost of biodiesel was about $1.2 per litre. Since targeted industries (e.g mining or marine) that were most likely to adopt biodiesel

[71] Ontario, Manitoba, Alberta and Quebec (Jan. 2000) are currently providing tax incentives. B.C. will provide incentives once an ethanol plant is operational in B.C.

because of its environmental benefits were at most willing to pay a premium of about 10% for biodiesel instead of petrodiesel (20-50 cents per litre), demand is not expected to rise unless there are considerable reductions in the price of biodiesel. Thus, in the short to medium term, the best opportunity for biodiesel is likely to be as an additive (up to 4%) that can reduce the sulphur content of petrodiesel and improve its lubricity properties without adding significantly to the price.

The development of the Canadian biodiesel industry has also been hampered by the fact that government support has been very limited compared to what the U.S. and specially some European countries have been providing. Without further government involvement in Canada, e.g. tougher environmental regulations in the area of sulphur emissions and tax incentives, it will be difficult for biodiesel to penetrate the diesel market.

In summary, the best near term opportunity for biodiesel in Canada is as an additive that can reduce sulphur emissions and improve the lubricity properties of petrodiesel. For this opportunity to materialize, reduction in production costs and government regulations will be key determinants.

C) Biogas (Landfill / Municipal Solid Waste) Industry

Factor conditions are in place to allow the development of the landfill industry in Canada. In fact, several Canadian consulting engineering companies have expertise in this area, promising R&D is being done in industry in the area of solid waste digestion and there are approximately 100 landfill gas sites that could be exploited.

However, with the relatively cheap price of energy in Canada, energy recovery from landfill gases has been limited. With limited local demand, Canadian companies have been selling their services in other countries such as the U.S. where environmental concerns are driving the industry. This is expected to continue unless financial incentives, in the form of tax credits and greenhouse gas emission credits for landfill gas site developers, that are already in place in the U.S.become available in Canada.

4.4 The Canadian Mining Sector

The mining industry is a important contributor to the Canadian economy. In 1997, the mining and mineral processing industries contributed $26.2 billion to the economy, an amount equal to about 3.8% of the Canadian GDP, and employed 368,000 Canadians. Canada is among the top four producers of several metals (e.g. uranium, zinc, cadmium, nickel, aluminum, copper, gold) and minerals (e.g. potash, asbestos and gypsum). The four most important metals produced in 1997 were gold ($2.50 billion), copper ($2.07 billion), zinc ($1.88 billion) and nickel ($1.77 billion).

One of the main challenges of the mining industry has been to extract and process mineral and metal resources with minimal disruption to the ecosystem. According to the 1998 annual environmental progress report published by the Mining Association of Canada (http://www.mining.ca/english/publications/index.html) the main environmental issues that the mining community is currently tackling are:

- Tailings management;
- Metals in the environment;
- Energy efficiency;
- Water issues;
- Improved estimations of industry releases.

The development and adoption of new technologies, including biotechnology, will play a key role in addressing these issues.

4.4.1 Biotechnology Applications

The contribution of biotechnology to cleaner production in the mining sector is mainly in the area of metal extraction in various types of ores by bioleaching or biooxidation and in the prevention of acid mine drainage (AMD). Since bioleaching or biooxidation is carried out at ambient or mild temperature and pressure, there are lower GHG emissions and potential energy savings compared to roasting and smelting which are high-temperature processes. It is worth noting however that smelting is an exothermic process and that energy savings resulting from bioleaching/biooxdation may not be a major issue. Instead, the main drivers for the adoption of bioleaching/biooxidation have been the lower capital and operating costs.

The prevention of acid mine drainage (AMD) or acid rock drainage (ARD) is another area where biotechnology can contribute to cleaner production. The exposure of mining by-products such as sulphide-bearing waste rock to oxygen and water generate acidic effluents that can leach heavy metals and contaminate the soil and water. Biological systems that are being developed to control or prevent AMD are integrated with the mining operation, require little maintenance and are designed to treat tailings impacted groundwater before generation of acidic drainage. This is in contrast with conventional processes, such as lime treatment, that generate considerable amounts of sludge as a result of the collection and treatment of the acidic water. Biotechnology can also play an important role in the treatment of other mine effluents, for example in the removal of metals in wastewater using plants or wetlands (http://www.ec.gc.ca/science/sandemar99/article1_e.html), (http://www.microbialtech.com/index.html), (http://www.nrcan.gc.ca/mets/biominet/). These applications will however not be covered in the following sections since they are considered "end-of pipe treatment" and not part of the cleaner production process.

4.4.2 Research and Development Capacity

Canada has promoted R&D and utilization of biotechnology in the mining sector for about forty years. This has led to many breakthroughs which have found application around the world. Most of the R&D capacity resides in government laboratories, universities, consulting engineering firms and to a lesser extent mining companies.

A) Bioleaching / Biooxidation

The Industrial Research Chair in Biohydrometallurgy established within the Department of Metals and Materials Engineering of the University of British Columbia (http://www.interchange.ubc.ca/hydromet/hydropage.html), has programs in the following categories: bacterial culture development, biooxidation of refractory gold/silver ores, enhanced bioleaching of chalcopyrite, bioreactor design and scale-up and bioleaching of low-grade ores and tailings. Expertise relating to the mechanism of sulfur, iron and ammonia oxidation by autotrophic bacteria as well as bacterial leaching of metals from sulfide ores can also be found at the University of Manitoba (http://www.umanitoba.ca/faculties/science/microbiology/staff.html). The CANMET Mining and Minerals Sciences Laboratory (MMSL) of Natural Resources Canada (http://www.nrcan.gc.ca/mets/biominet/) and BC Research Inc. (http://www.bcr.bc.ca/default.htm) have also investigated the potential of bioleaching/biooxidation.

In other countries, considerable R&D is being carried out on the bioleaching of copper minerals and biooxidation of refractory gold concentrates, e.g., at the Centro de Investigacion Minera y Metalurgica (CIMM) in Chile (http://www.cimm.cl/english/index.html), Mintek, South Africa’s national minerals research organisation (http://www.mintek.ac.za), the chemical engineering department of the University of Cape Town (http://www.chemeng.uct.ac.za/research/) and the Idaho National Engineering and Environmental Laboratory (INEEL) (http://www.inel.gov/capabilities/biotech/Biohydro.html). Expertise in these areas has also been developed within companies such as Billiton (London, U.K.) (http://www.billiton.com) and BacTech Metallurgical Solutions Ltd (Belmont, Western Australia) (http://www.bactech.com). Billiton which has operations in several countries, including Canada has developed, in collaboration with South African based Gencor, the BIOX process which is commercially proven for the recovery of gold from refractory sulphides. It is now focusing its efforts on demonstrating the BioNic process for the treatment of low-grade and chemically difficult nickel ores as well as the BioCop process for the extraction of copper. BacTech which also has a subsidiary in Canada has commercially proven technology for the pre-treatment of gold concentrates. In April 1997, BacTech Australia entered into a joint venture agreement with Mintek for the development of bioleaching technology especially for copper concentrates.

B) Acid mine drainage

With the liability related to AMD estimated to be between $ 2 -5 billion in Canada, several prevention or treatment processes have been developed in the past ten years (http://mend2000.nrcan.gc.ca/introduction.htm). Biological processes that have been developed to control or prevent AMD include:

- Development of porous reactors containing reactive organic solids that are installed below the ground surface in the path of migrating tailings-impacted water. These reactors enhance biologically mediated sulphate reduction and as a result, tailings impacted groundwater is treated before it contributes to the generation of acidic drainage. (http://www.science.uwaterloo.ca/earth/blowes.html);
- Testing the effectiveness of various organic covers (e.g. waste materials from the pulp and paper industries, compost, peat) on top of mine tailings (http://mend2000.nrcan.gc.ca/reports/2253es_e.htm), (http://www.lakefield.com). These layers of fibrous organic material prevent the generation of AMD by retaining water and starving the mine tailings of oxygen.

Biological treatments for AMD that have been developed include the biosulphide process (http://www.direct.ca/ntbc/) and the construction of wetlands (Boojum Research Ltd, Toronto). A first Canadian study on the microbial consortia of an AMD water seepage path conducted by the Biotechnology Research Institute in collaboration with Boojum Research will also help in developing solutions for AMD.

4.4.3 Receptor Capacity

A) Bioleaching / Biooxidation

Although Canada pioneered many breakthroughs in mining biotechnology, the uptake of biotechnology by the mining industry in Canada has been very limited. In the area of bioleaching, there have been two commercial applications: uranium bioleaching facility at Denison Mines and a secondary copper heap bioleaching in Gibraltar, British Columbia. Some of the main barriers to the adoption of bioleaching/biooxidation that have been reported in Canada include:

- Overcapacity in Canadian facilities using conventional processing technologies such as roasting and smelting. In other parts of the world where there is no overcapacity, Canadian companies have been adopting bioleaching technology, for example Cominco has licenced Chilean technology for exploiting a copper mine in Chile.
- Lack of funding for resolving particular difficulties related to the conditions specific to the Canadian climate. These difficulties are however not major and it has been reported that with modest improvements in the kinetics and efficiency of bioleaching processes, about

10 new mineral deposits could be exploited within the next 10 years.

- Lack of awareness among industry leading to a perception that biological processes are not reliable.
- Bioleaching/biooxidation processes did not meet expectations when they were first tested in Canada.

Bioleaching/biooxidation processes have however been successful in other countries, specially Chile, Australia and South Africa. For example, the BIOX process is being used for the pre-treatment of gold concentrates at five facilities and the BacTech process is being used at one facility[72] . Demonstration plants are being planned for the BioCop and BioNic processes (http://www.billiton.com).

B) Prevention of AMD (Acid Mine Drainage)

The porous reactors and organic covers described earlier are currently being tested by Falconbridge at some Canadian sites in collaboration with the University of Waterloo. (http://www.nserc.ca/news/p991014_b5.htm). The adoption of such biological processes over competing processes will depend on the following:

- Demonstration of the cost-effectiveness of the bioprocesses on a full scale. This can often be a major barrier because technology developers have difficulties finding appropriate industrial partners that are willing to share some of the risks and participate financially in the commercial demonstration of a particular technology. Current demonstration plants featuring the porous reactors indicate that they are likely to be cost-effective and this bodes very well for the technology;
- Perception of biotechnology within the mining industry. Mining companies are becoming less skeptic about the potential of biotechnology but there is still a great need for information transfer;
- The status of environmental regulations. Bioprocesses that are more efficient than conventional processes may not be considered if regulations do not require use of best available technology.

4.4.4 Sector Assessment

Biotechnology can play an important role in helping the mining community address its environmental issues on a cost-effective basis. Bioleaching/biooxidation processes are not only energy efficient but require much less capital and operational investments compared to smelters and roasters. In Canada, although there has been R&D work in government labs and universities for about four decades, the adoption of bioleaching/biooxidation processes has been limited. Overcapacity in conventional roasters and smelters as well as some technical difficulties related to

[72] OECD, Biotechnology for Clean Industrial Products and Processes, p. 151 (1998).

the cold climate have been the main barriers to the adoption. These technical barriers are however not considered major and it has been reported that with modest improvements in the kinetics and efficiency of the process, about ten mineral sites could be exploited over the next ten years (http://envirolab.NRCan.gc.ca/biotech.htm). The resolution of these technical difficulties therefore represents a great opportunity for mining companies, government laboratories and other R&D organisations to take a leadership role and ensure that Canada does not keep falling behind other mineral rich countries (e.g. South Africa, Australia and Chile) in its ability to develop and adopt innovative bioprocesses with both environmental and economic benefits.

In the area of acid mine drainage prevention, Canada is considered a world leader and current R&D work indicates that bioreactors can provide a cost-effective and elegant option. Since receptor capacity for these bioreactors will depend on the results of pilot or full scale demonstration projects, it is critical that adequate financial resources become available to demonstrate the commercial viability of the projects. As mining companies are becoming less skeptic about the potential of biotechnology, bioprocesses that are cost effective, technologically proven and integrated with the mining operations could very well compete with conventional or other novel processes. More demanding environmental standards can also help the adoption of bioprocesses, specially in cases where biological processes are more efficient and generate less waste than conventional processes.

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4.5 The Canadian Food and Beverage Processing Sector

The Canadian food and beverage processing industry accounts for about 2% of Canada's GDP. Some of the major industries within the food and beverage processing industry include: meat and meat products (SIC-E 1011), dairy (SIC-E 1049 and SIC-E 1041), poultry products (SIC-E 1012), fish products (SIC-E 1021), frozen fruits and vegetables (SIC-E 1032), bread and other bakery products (SIC-E 1072), brewery products (SIC-E 1131) and feed (SIC-E-1053). Details about the industries that make up the food and beverages processing industries can be accessed on Industry Canada's Strategis web site at (http://strategis.ic.gc.ca/SSG/tm00025e.html).

The main environmental issues facing these industries include the conversion/treatment of liquid and solid wastes as well as the reduction in use of toxic chemicals such as chlorine. Overall, these industries are not considered very energy intensive; however, energy efficient alternatives are sought for some processes which require considerable amounts of energy (such as blanching of vegetables). Some of the ways in which biotechnology can be used to manage the environmental and energy issues in these industries are discussed in the following sections.

4.5.1 Biotechnology Applications

Fermentation, has been used in food processing for centuries as a means to preserve or enhance the qualities of food. Examples of such fermented foods include cheese, pickles, sausages, beer and bread. More recently, the potential of using biotechnology as a tool for cleaner production in the food processing sector has also attracted attention, specially in industrialized countries. Some examples of how biotechnology has been contributing to cleaner production and economic gains in the food processing sector include:

- Conversion of wastes into valuable products, resulting in less wastes transferred to landfill sites and less GHG emissions;
- Reduction of the output of manure, nitrogen and phosphorus from farm animals by developing and using feed enzymes such as endoxylanases and phytases which enhance feed efficiency and reduce pollution;
- Replace relatively low yield chemical processes that require high temperature, high pressure and acids with milder enzymatic processes.

Note that bioprocesses that have been developed to treat solid and liquid wastes before disposal will not be covered in the following sections because they are considered "end-of-pipe" processes.

4.5.2 Research and Development Capacity

A) Conversion of wastes streams

Expertise in the area of conversion of food processing wastes into higher value products can be found in universities, government labs, innovative SMEs and specialized centres such as the

Guelph Food Technology Centre (http://www.gftc.ca).

Some of the research on the conversion of seafood wastes include the production of:

- N,O-Carboxymethylchitosan (NOCC), a biopolymer derived from crustacean wastes (http://www.chitogenics.ns.ca). This biopolymer has been evaluated for use in medical devices and agricultural products;
- Biodegradable plastic films from chitosan (http://www.agrenv.mcgill.ca/foodscience/staff/simpson/simpson2.htm);
- Preservative coating and biofungicide from chitosan for the preservation of fresh fruits and vegetables (http://www.ulaval.ca/vrr/rech/Cherc/177924.html).

Fundamental research on the antimicrobial properties of chitosan and the chitosanase enzyme is also being carried out at Laval University (http://www.ulaval.ca/vrr/rech/Cherc/159135.html) and Sherbrooke University (http://www.usherb.ca/SCES/BIO/brerys.html) respectively.

Dairy wastes or by-products as well as other food wastes or effluents have also been upgraded as indicated by the following projects:

- the production of nutraceuticals and functional bioingredients from dairy by-products such as cheese whey (http://res.agr.ca/sthya/engrech.htm#lait); (http://alpha.eru.ulaval.ca/stelawww/donnees/membres/francais/christophe_lacroix.html);
- the development of biodegradable packing materials from casein salts derived from dairy by-products (http://www.bioenvelop.com);
- the development of high value polyesters for niche cosmetic/biomedical applications by the fermentation of potato starch or dairy by-products (http://www.bri.nrc.ca);
- the development of Fibrimex, a natural fresh meat binding medium (http://www.mtgplace.com/com/fna/1154S278.HTM);
- the use of thermophilic microbes to process food wastes into organic fertilizer products (http://www.ibrcorp.com);
- the development of processes for the conversion of food wastes containing large quantities of fat or oil into soil conditioners (http://www.nationalchallenge.com);
- the production of biopesticides from waste effluents (http://www.inrs-eau.uquebec.ca/activites/repertoire/rajeshwar_dayal_tyagi/infocv.htm);
- the production of the alpha amylase enzyme by the solid substrate fermentation of waste potato peel instead of expensive submerged fermentation that generates large amounts of wastewater (http://www.agrenv.mcgill.ca/agreng/STAFF/sheppard/index.htm)
- the conversion of fish breeding effluents into feed by cyanobacteria (http://www.ulaval.ca/vrr/rech/Regr/00056.html) are other reported examples of waste conversion.

Since enzymes are often key elements of the conversion process, it is worth mentioning that there is also considerable activity in developing techniques that modify the properties of the enzymes. Chemical modification, site directed mutagenesis, the use of crosslinked enzyme crystals and hybrid enzymes are some of the means by which enzymes with novel properties can be developed. Canada has expertise in this area, specially within the Protein Engineering Network of Centre of Excellence (http://www.pence.ualberta.ca/pence/english/team_e.htm) and the University of Toronto (http://www.chem.utoronto.ca/people/academic/jonesj.html). Developments of acid tolerant, thermostable variants of *B. licheniformis* alpha-amylase for the starch industry and improvements of glucoamylase for thermostability and susbstrate specificity are examples that have been reported[73]

Some of the activities that have been reported in other countries include:[74]

- corn cobs as a substrate for citric acid;
- cranberry waste as a substrate for fungal bioinoculants;
- production of kluyveromyces and other lactose fermenting yeasts as flavouring ingredients from cheese whey.

In the U.S., the Food Manufacturing Coalition (FMC) technology transfer program formed in 1996 is the primary vehicle to identify innovative technologies which address the common problems of the industry relative to environmental quality and processing efficiency. The FMC which is supported by the U.S. Environmental Protection Agency and the U.S. Department of Agriculture has identified several generic technology needs for the food processing industry and is searching for technologies from a wide variety of research centres (http://foodsci.unl.edu/fmc/fmc-00.htm).

B) Feed enzyme technology

The Lethbridge Research Centre (http://res.agr.ca/leth/livestoc/livesum.htm#RUMNUT) of Agriculture and Agri-Food Canada has considerable expertise in various aspects of feed enzyme technology. Enzymes that can improve feed efficiency and thereby reduce pollution, for example xylanases, cellulases, phytases and proteases have been isolated from rumen microorganisms and are being tested as feed additives for nonruminant animals. Research is also being done to enhance the activity of the enzymes either through direct alteration of gene structure or by the use of enzyme enhancers that promote binding of enzymes to the substrates. There is also considerable expertise in this area at the Department of Animal Science of the University of Manitoba (http://www.umanitoba.ca/afs/animal_science/). Since the use of enzymes, especially recombinant enzymes in the feed industry is still in the early stages, research is also being carried out to develop more sensitive and accurate enzyme assays and to investigate the site of action of enzymes. Some priorities have been identified for future research on the use of enzymes in animal feeds can be accessed from (http://www.idrc.ca/books/focus/821/chp12.html).

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[73]Current Opinion in Biotechnology, Vol. 10, pp. 321-323 (1999).

[74]OECD, Biotechnology for Clean Industrial Products and Processes, p. 47 (1998).

4.5.3 Receptor Capacity

A) Conversion of wastes streams

Canadian food processing companies tend to focus solely on their core businesses and most of them are not inclined to develop or acquire technologies that can convert their wastes into valuable by-products. Disposal or sales of the wastes to specialized waste management companies are two options commonly considered by food processing companies. Technology developers in universities or government laboratories thus usually transfer their know-how to these specialized waste management companies or create spin-off companies when clear economic and environmental benefits have been demonstrated. Technologies have been adopted for the production of biodegradable plastics (http://www.bioenvelop.com), biopolymers (http://www.chitogenics.ns.ca), fertilizers and soil conditioners (http://www.ibrcorp.com), (http://www.nationalchallenge.com) and meat binding mediums (http://www.mtgplace.com/com/fna/1154S278.HTM).

B) Feed Enzyme Technology

The farming community and the feed industry have been very receptive to feed enzyme technology because of the demonstrated economic and environmental benefits. The research activities being done at AAFC's Lethbridge Research Centre have led to several patents on enzyme application technology for the beef and dairy industry. Some of the technology has been licenced to U.S. based companies (http://res.agr.ca/leth/rep1027.htm) indicating that there may be a lack of Canadian companies that could exploit and market the technology on a global basis. Receptor capacity for feed enzymes targeted at the swine and poultry industries is also expected to be quite high.

4.5.4 Sector Assessment

Biotechnology can potentially contribute to cleaner production in the food processing industries in three main ways: waste conversion, waste reduction and the replacement of chemical processes with milder enzymatic processes. Contrary to other sectors (e.g pulp and paper or energy) the environmental benefits of biotechnology in the food processing sector are however not the driving factors. Enzymes and bioprocesses are being developed primarily to enhance the quality of foods or to improve process yields but there are often associated environmental benefits since enzymatic processes generally require lower temperatures and pressures compared to chemical processes.

The large amounts of organic wastes generated by the food processing and feed industry are however important environmental concerns and several government and university laboratories have been considering biotechnology as a tool for waste conversion / reduction. Promising technologies have been developed but there has been limited receptor capacity for them primarily because major food processors do not generally consider waste conversion as part of their core business. As a result, technologies with the best economic potential have been transferred to a few companies that focus on upgrading wastes or to spin-off companies. This trend is expected to continue and will be influenced by the following factors: efficient technology transfer between R&D and receptor organisations, favorable environmental regulations that can be followed by companies without substantial amounts of time and money, capital for demonstration of promising technologies and start-up companies, access to incubators that can offer managerial and scientific guidance in the early stages of the start-ups and collaboration / strategic alliances between waste producers and users.

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5. Government Programs and Strategies

The three main driving forces for cleaner industrial bio-products and bio-processes are developments in science and technology, marketplace economics and government initiatives. The OECD[75] has concluded that "Government policies to enhance cleanliness of industrial products and processes can be the single most decisive factor in the development and use of clean biotechnological processes". This section examines some of the federal government's programs and strategies which relate to cleaner production and biotechnology from a systems perspective (i.e., do they or can they work in concert, allowing biotechnology to make its full contribution to saving energy and reducing emissions of greenhouse gases and toxic substances in Canada ?).

5.1 Programs Supporting Scientific Research and Technological Innovation

A number of federal programs support different aspects of science and innovation relating to biotechnology and cleaner production[76] :

- basic and applied research in science and engineering (NSERC);
- university-industry cooperative R&D (NSERC);
- Networks of Centres of Excellence (NSERC);
- funding for university research infrastructure (Canadian Foundation for Innovation - CFI);
- genomics research funding and infrastructure (Genome Canada);
- industrial R&D (NRC-IRAP; federal science based departments);
- industrial technology development, scale-up and demonstration (IC-TPC);
- sustainable technologies (Sustainable Development Technology Fund - SDTF);
- energy related research and development (PERD);
- climate change mitigation/adaptation technologies (Climate Change Action Fund);
- environmental technology validation (EC, NRC);
- regional technology initiatives, e.g. industry clustering (Atlantic Canada Opportunities Agency, Economic Development Canada, Western Economic Diversification);
- technology transfer to developing countries (Canadian International Development Agency - CIDA).

In addition, some agencies such as the National Research Council have internal programs to support their employees in spinoff of new companies. There are also tax incentives promoting formation of labour sponsored venture capital.

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[75]OECD, Biotechnology for Clean Industrial Products and processes, p. 11 (1998).

[76]NSERC is the Natural Sciences and Engineering Research Council; NRC is the National Research Council; IRAP is the Industrial Research Assistance Program; EC is Environment Canada; IC is Industry Canada; TPC is Technology Partnerships Canada; PERD is the Program for Energy Research and Development of Natural Resources Canada.

While there are programs supporting a full spectrum of activities from basic research to scaleup and demonstration, there is need to strengthen the links between programs and the mechanisms for handoff from one to another. At present, it is difficult to set priorities across the entire system (research, development, technology demonstration and validation).

Another issue concerning programs is that the budgets in other countries which are targeted for R&D and technology demonstration in the area of cleaner production and renewable energy/chemical are projected to increase significantly. In the US, President Clinton is proposing a US$2.4 billion package of funding increases and tax incentives to combat global warming as part of his 2001 budget[77] . Development of clean, low-emissions technologies is targeted. It is also proposed to increase funding for biomass fuels research from the current US$196 million to US$436 million, a net increase of over 120%. Also included are a US$2.1 billion tax credit plan for companies that produce clean-burning fuels. This spring Germany is planning to launch a multi-million Mark program focused on biotechnology and industrial sustainability**.** The U.K. is launching an £ 11 M program to stimulate research and development into environmental applications of genomics.

5.2 Risk Assessment and Risk Management

Novel products need to be assessed for potential risks to human health and the environment and if risks are identified, these need to be managed. The Canadian Environmental Protection Act (CEPA) administered by Environment Canada is a comprehensive instrument which the federal government has for assessing novel products and managing the risk from their use. The Seeds Act, administered by Agriculture and Agrifood Canada provides the authority for assessing and managing risk relating to novel plants and trees such as might be used in intensively managed forests and in plantations for biomass production. Other Acts and Regulations may also pertain to the use of biotechnology for cleaner production and these can be identified using tools such as BRAVO (Biotechnology Regulatory Affairs Virtual Office; http://BRAVO.ic.gc.ca).

Environmental regulations generally include penalties (negative incentives) to ensure that companies meet certain emission standards. However, there are few fiscal incentives for companies to replace older dirtier products and processes with cleaner ones. Furthermore, the cost and time incurred for making a regulatory submission can constitute a real barrier especially to small companies trying to attract investment and compete in a rapidly moving field such as biotechnology.

There is a requirement to assess the potential environment impact resulting from projects which receive federal funding. It would be desirable to include a "design for environment" approach to measurement of environmental performance and impact as an integral part of technology development and demonstration (especially for biotechnologies which claim to be cleaner). If this were done, programs could partly cover the cost of gathering experimental data for a regulatory

[77]Chemical Week, "Clinton Releases Green Budget Plans", 9 Feb 2000, p. 5.

submission, making regulation less of a disincentive for adopting newer, cleaner products and processes. This would also provide a more robust tool for managing the development of bioproducts and bioprocesses so that potential negative environmental impacts are identified early when the amount invested in the technology and cost of modifying the technology is still relatively low.

5.3 Canadian Biotechnology Strategy

Under the Canadian Biotechnology Strategy (CBS), seven federal ministers[78] have agreed to cooperate in coordinating federal initiatives relating to biotechnology. A number of federal interdepartmental working groups have been established focusing on R&D, regulation, communication with the public, international market access etc. and senior managers in the seven portfolios are responsible for managing the overall process. Some of these senior managers are also involved in the Canadian Climate Change Process. The CBS working groups and the management structure provide an improved basis for coordination at the federal level and also between the federal and provincial government. However, an issue such as biotechnology for cleaner industrial production cuts across many of these working groups and, as yet, mechanisms are not yet well established for identifying and effectively managing such cross-cutting issues. Also, there is presently little cross-talk among such major strategies as Biotechnology, Climate Change and Sustainable Development which could potentially support one another during their evolution and implementation.

5.4 Climate Change Strategy

The Canadian Climate Change Process (http://www.nccp.ca) was established to develop a national strategy and implementation plan for Canada to achieve its greenhouse gas emissions targets. The climate change issue provides a strong impetus and a timeline for moving toward cleaner and more energy efficient industrial processes as well as toward an economy based increasingly on renewable feedstocks. Biotechnology has been identified as an important aspect of the innovation component of the Climate Change strategy. Significant opportunities exist to link up with the Canadian Biotechnology Strategy and develop a common approach. One example of where this linkage is needed is in international negotiations on what will qualify as carbon sinks as this will strongly affect investment in biotechnology for biomass production and utilization. Another example is in the use of the Clean Development Mechanism where Canadian companies or organizations would obtain carbon credits in return for transfer of cleaner biotechnology process technology to developing countries.

5.5 Sustainable Development Strategy

The federal government has made a commitment to improve its performance with respect to

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[78]Ministers of Industry, Agriculture and Agri-Food, Environment, Health, Natural Resources, Fisheries and Oceans, and Foreign Affairs and International Trade.

sustainable development. Each department and agency is required to develop its own strategy, objectives and targets and an interdepartmental committee has been established to coordinate the overall effort. While the implications of biotechnology for industrial sustainability are beginning to be understood, this is not widespread and, as mentioned above, there are significant opportunities to establish linkages between the groups working on the Canadian Biotechnology Strategy and on the Sustainable Development Strategy.

5.6 Building Public Awareness

More than ever before, the public wants to be consulted on issues which affect health, safety and the environment. In addition to economic factors, public concern for the environment is an important force which drives industry to research, develop and adopt cleaner production technologies, including biotechnology. Research indicates that public opinion is generally favourable toward environmental applications of biotechnology for pollution cleanup and prevention. Indeed, public concern over eutrophication of lakes and streams led to development and market acceptance of detergent formulations where phosphate is replaced by enzymes produced through biotechnology. In this case, the benefits were not only to the environment but also to the consumer who could wash clothes in cold water and save the cost of heating water for washing. Even organizations such as the German Green Party, which has generally disfavoured biotechnology, are supportive of the use of biotechnology where clear environmental benefits can be demonstrated (e.g. licencing of the Novartis-Biochemie plant in Frankfurt, Germany for production of cephalosporin using enzymes derived from genetically modified organisms).

A key element in citizen engagement is availability of objective scientific data which provides a balanced perspective on the benefits and drawbacks of biotechnology used for cleaner production (energy efficiency, materials efficiency, reduction of hazardous byproducts, utilization of renewable resources). Government can contribute to public understanding and acceptance of cleaner industrial bioprocesses and bioproducts, not only by supporting R&D on cleaner, more energy efficient industrial bioprocesses, but also by providing information to the public on the potential economic, environmental and societal impacts of such projects. Also, if assessment of biotechnology for economic, environmental and societal impacts and use of a design-for-environment approach were an integral part of project management and reporting, this would help provide scientifically validated data for communication to the public regarding progress in this field.

5.7 Opportunities for Improved Coordination

The federal government has a number of programs and strategies which could help biotechnology to make its full contribution to cleaner production and energy savings in Canada. There is strong potential and wide scope for synergy, especially among the major strategies mentioned above, and biotechnology for cleaner production and industrial sustainability provides an opportunity to tap this potential.

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6. Assessment and Proposed Future Steps for PERD

6.1 Assessment

It is clear that Canada's economy, environment and the quality of life of its citizens can benefit from the research, development and utilization of biotechnology for cleaner production and energy saving in a number of key industry sectors. However, it will take continued advances in science and technology as well as policies supportive of innovation to bring this about.

Canada has a strong research base in the chemical and biological sciences as well as in related engineering disciplines. There are government programs with funding which can support a full range of activities from basic research to technology demonstration (see Section 5.1). There is also a critical mass of technology development companies with the expertise in biotechnology required to produce novel products and the processes for manufacturing them. Major receptor industries are present in the energy, forest, chemicals and plastics sectors. Canada has major biomass resources and is also recognized as a leader in plant biotechnology. Thus, Canada is ideally positioned to be the place to develop the next generation "green" resource and chemical industries which are based on renewable biomass feedstocks and which use biotechnology to achieve the eco-efficiency / productivity required for long term sustainability.

Although the elements for capitalizing on these opportunities are present, there are also a number of weaknesses and barriers. There is presently little marketplace demand for cleaner fuels or chemicals derived from renewable biomass feedstocks[79]. The receptor capacity in the resource industries is weak for biological technologies and processes. The biotechnology development companies are mostly small and have difficulty attracting investment or the interest of the resource companies. The multidisciplinary research required to provide the bio-science and bio-technology for a sustainable future is fragmented and there is little consensus on priorities or how to set them.

Consultations with industry and other stakeholders were held on environmental applications of biotechnology during the renewal of the Canadian Biotechnology Strategy in 1997-98. These consultations identified the following issues[80] which need to be resolved to make the innovation system for industrial biotechnology function more effectively :

- Greater support for technology demonstration and validation is needed so it will be possible to measure the economic and environmental performance of novel bio-processes and bio-products at a realistic scale. This is key for engaging the interest and buy-in of

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[79]In the US, the announcement by President Clinton on August 12, 1999 set targets for greater use of renewable biomass in production of energy and chemicals, effectively stimulating the development of a market for fuels/chemicals from biomass and for related biotechnologies.

[80]Many of these issues were raised at a regional workshop on Biotechnology for Industrial Sustainability held on 2 February 2000 at the NRC Biotechnology Research Institute .

user industries.

- Scientifically validated protocols need to be developed for assessing the environmental impacts/benefits and the sustainability of cleaner bioproducts and bioprocesses implemented as an integral part of the innovation process.
- Strategic research needs to be encouraged and supported and the priorities for this need to be established using both the research community's knowledge of trends and developments in science and technology as well as the industry's knowledge of trends and developments in global markets.
- Skill sets of engineers and technical personnel in user industries need upgrading to enable adoption and adaptation of bioprocess technologies in these industries. This implies development of retraining programs as well as changes to existing educational programs to include relevant biological training opportunities.
- The public needs to be informed of the benefits of industrial biotechnology and how the risks are being managed before products are in the marketplace in order to build consumer understanding and confidence.

6.2 Proposed Future Steps for PERD

A) More Focused Consultations

There is a need for more focused consultations with industry, the research community and with the public which would look specifically at biotechnology and energy efficiency, greenhouse gas emissions and cleaner production as well as build on the issues already identified. These discussions would aim to set a more focused R&D and technology demonstration agenda which has broad support. A series of regional/provincial workshops is planned for fiscal year 2000-01 to hold such discussions and focus on applications of cleaner biotechnology which are relevant to the regional/provincial economy and environment.

B) Review of International Developments

To engage in such consultations, there is a need to complement the present study, which focuses more on Canada, with a more systematic overview of international developments in cleaner biotechnology (i.e. increased energy efficiency and reduced emissions of greenhouse gases and toxic substances) as well as an inventory of documented case studies where such benefits have been achieved.

C) Technology Roadmapping

The regional/provincial consultations will help identify representatives from industry and from the research community which could then meet at a national workshop to set more detailed research priorities using the Technology Roadmap process which has been pioneered by the US Department of Energy. The "Technology Roadmap for Plant/Crop-Based Renewable Resources 2020" (http:///www.oit.doe.gov/agriculture) could form the basis for such a Canadian roadmap (or possibly a series of sectoral roadmaps) which would then take into account the differences between the US and Canadian situations.

D) Development of a Plan of Work

The regional/provincial consultations would help in the development and validation of a 4-year plan of work under the bioprocessing element of OERD-PERD. Key elements of this plan could include:

- promoting multidisciplinary and multisectoral R&D and pilot projects in biotechnology and cleaner production;
- fostering the growth of emerging technology development companies spinning out in this field from university and government laboratories through support for strategic alliance projects;
- promoting pilot projects involving clusters of companies which could cooperate in developing and producing different types of products from the same streams of renewable resources; and,
- stimulating international collaborative R&D to help access any essential expertise and/or technology not available in Canada.

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7. APPENDICES

7.1 OECD Task Force on Biotechnology for Sustainable Industrial Development

This appendix provides an overview of the Task Force initiative.

A) Background:

"Industrial biotechnology has come of age." [81]

" The stage is being set for a biological transformation of the chemical industry in the 21st century." [82]

The timing is right for an initiative to support the diffusion of environmentally friendly biotechnologies into industry. Progress of such an initiative depends on understanding and using three driving forces for the adoption of cleaner bioproducts and bioprocesses:

- Advances in science and technology;
- Marketplace economics; and
- Government policies as influenced by public opinion.

Success will depend on making the three driving forces work in concert both at the country level and at the international level. This is a complex problem which requires different solutions for different countries as well as international policy coordination. The Task Force on Biotechnology for Sustainable Industrial Development has taken on the role of developing and implementing a plan of work to develop initiatives as well as policy recommendations to governments which will help advance the research, development, demonstration, assessment and uptake of biotechnology for cleaner industrial products and processes in both developed and developing countries.

B) Strategic Approach:

The Task Force has identified four key projects:

- **Country Profile –** identification of key players in industry, the research community and the government policy community to stimulate development of international networking;
- **Technology Assessment for Sustainability –** development of the methodology to assess whether specific biotechnologies are "cleaner" and more "sustainable" than their conventional technology counterparts;
- **Communication and Education –** development of a guidebook providing a "checklist" for establishing national plans in this area; and

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[81] OECD, Biotechnology for Clean Industrial Products and Processes (1998).
[82] Decision Resources, Biotechnology's Impact on the Chemical Industry (1998).

- **Policy Implications –** identification of how a set of policy measures could be identified and implemented in each country for supporting diffusion of environmentally friendly biotechnologies into industry as well as identification of what international policy coordination is required regarding certain international agreements (e.g. biosafety protocol, international trade, climate change etc.)

The four projects are meant to enable and support one another:

- A profile of key players in industry, the research community and the government policy community is necessary to understand the status of biotechnology for cleaner production in that country as well as to identify opportunities and potential national or international collaborations to advance these applications of biotechnology.
- An efficient method for assessing the environmental and economic performance of biotechnologies and guidance on how to use such a method is necessary for identifying which are the promising biotechnologies and for communicating the opportunities and benefits associated with adopting such technologies.
- Effective communication of the environmental and economic benefits from cleaner biotechnologies requires convincing information from technology assessment as well as a strategy and collaborators to inform industry, investors, the government and the public.
- Effective policy advice from stakeholders is necessary to engage policy makers in governments in removing barriers to advancement of these technologies and in making strategic investments in these technologies to benefit the quality of life of their people.

C) Deliverables:

By 2001 the Task Force is aiming to produce the following deliverables:

- A web based information gateway to the country profiles and other information;
- A guidebook in simple language on how to maximize the benefits of adopting biotechnologies for increased efficiency and cleaner production;
- A guidebook serving as a checklist for development of national communication and education plans;
- A document for government policy makers on policy considerations and options for increasing the uptake and use of cleaner biotechnologies by industry.

7.2 Statistics Canada Survey of Biotechnology Use in Canadian Industry

In 1997, Statistics Canada published the results of the Survey of Biotechnology Use in Canadian Industry[83] for the year 1996. The survey included all companies in Canada which had annual sales of $5 M or more and which fell within the following standard industry classifications (SIC):

- forestry
- mining
- crude petroleum and gas
- food
- beverages
- tobacco
- leather products
- primary textiles
- textile products
- wood products
- paper and allied products
- printing and publishing
- fabricated metal products
- refined petroleum and coal
- other (including scientific instruments).

Firms were asked about their use of 22 carefully defined biotechnologies ranging from recombinant DNA to classical breeding of plants and animals. The following were key findings:

- 14% or 271 firms responded that they used one or more biotechnologies;
- two sectors accounted for 52% of biotechnology use (food; paper and allied products)
- environmental biotechnology was used by 25% of all resource firms;
- the average time of biotechnology use ranged from 17 years for food companies to 2.8 years for mining companies;
- very few firms planned to adopt biotechnology in the next 2 years;
- environmental biotechnology was the most likely to be adopted of any biotechnologies;
- key barriers to adoption for non-users were lack of information, scientific expertise or lack of biotechnologies commercially available in that sector;
- key barriers to the adoption for users were high equipment costs, regulations, lack of financial justification and lack of biotechnologies commercially available in that sector;
- of firms which use biotechnology, 88% invested in biotechnology in 1996;
- of firms which use environmental biotechnology, 72% reported the major benefit was reduction of environmental damage, 45% reported lower costs and 36% reported increased productivity.

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[83]Data from: "Diffusion of Biotechnologies in Canada", Statistics Canada Research Paper #88F0017MPB No. 6, Feb. 1999.

7.3 Assessment of Bioprocesses and Bioproducts for Sustainability

Technology, including biotechnology, when used for cleaner production can yield economic, environmental and societal benefits; however, it is important to assess the performance of any technology at different stages of development to ensure that these benefits are achieved.

Assessment of technology has evolved beyond considering only economic benefits. Ideally technology assessment should provide the tools to guide optimizing the performance of a technology in three dimensions - economic, environmental and societal - which comprise the basis for assessing sustainability. In a particular country, the optimum achieved using these tools will depend on the relative value attached to the specific economic, environmental and societal benefits/impacts of a given technology.

Tools to assess the economic impact of a technology are well developed and accounting systems exist which provide the framework for such analysis.

Environmental assessment tools have more recently become highly developed[84] and life cycle analysis is currently considered the best tool for assessing the cleanliness of an industrial product or process[85] ; however, more work must be done to make this tool more easily applicable for biotechnologies.

Assessment of societal impacts of technology is still a developing science and there is little consensus on endpoints or criteria.

In Canada, a working group including representatives from Environment Canada, the National Research Council and Industry Canada has begun to explore ways to adapt existing methodologies for developing such an integrated assessment tool[86].

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[84]There are now a number of international standards and organizations, such as ISO which focus on environmental assessment and standards.

[85]OECD, Biotechnology for Cleaner Industrial Products and Processes, p.11 (1998).

[86]For more information contact Terry McIntyre of Environment Canada (terry.mcintyre@ec.gc.ca) or Dave Minns of NRC (dave.minns@nrc.ca).