

Science-Metrix

Canadian R&D Biostrategy

April 2004



Towards a Canadian R&D Strategy
for Bioproducts and Bioprocesses

Prepared for
National Research Council of Canada

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Towards a Canadian R&D Strategy for Bioproducts and Bioprocesses

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Executive summary

Large scale technological metamorphoses are far and few between. They send shockwaves of mass destruction to economic systems, by pushing aside those organizations that fail to position themselves in new technological paradigms. During this century, the world will witness a reversal of 20th-century trends, whereby fossil-based hydrocarbons progressively took over from biomass-based carbohydrates. With fossil-based feedstocks running out, there will be an industry metamorphosis, and biomass-based feedstocks will become essential in providing the basic goods that are currently being produced by the petrochemical complex. Although there is some hope of discovering some inexpensive ways of providing energy by physical means to replace fossil-fuels, it is unlikely that organic chemical products will be made from inorganic substances in the near future, e.g. producing plastics from minerals. The core of the Canadian Biostrategy proposed here is to firmly position the country so that it becomes a key player in the biological conversion of agricultural and forest products into biochemicals, biofuels and versatile bioproducts.

Whereas the concept of the value-chain provides an integrated view of product flow, from suppliers to end-users, Science-Metrix proposes going one step further. It recommends that a Canadian biostrategy consider the concept of value-added cycling, whereby value is added not only from producer to the consumer, but also during the post-consumption stage. The suggestion is to transform liabilities such as wastes into assets, that is, consumer and industrial products. Value-added cycling can be studied by analysing the carbon-cycle of biomass embedded in products and by integrating life-cycle assessment. Optimization in biological value-adding cycling aims to minimize ecological impact and maximize economic value. Canada is ideally positioned to benefit from this paradigm because it has a tremendous natural advantage that can be transformed into a *competitive* advantage. Canada is also one of the western countries that have an urgent need to lower the average ecological footprint of its citizens.

Science-Metrix recommends that the Canadian Biostrategy starts with Canada's natural advantage. In terms of large scale agricultural feedstocks, Canadian strengths include barley, wheat, oat, canola, linseed, and mustard seed. These resources should be harnessed in the short term to develop the production of value-added bioproducts. However, in the medium to long term, it will likely be better to use crops developed specifically for the production of feedstocks with features sought by industry. Hence, part of the Biostrategy is to develop crops for industrial endpoints rather than for feed and food endpoints.

In terms of forestry, Canada has vast resources of tall oil and black liquor that can be transformed into a wide variety of value-added products. Bark is a residue that longs for value-added uses throughout the country. Peat is exceptionally plentiful in Canada compared to other countries, and responsible and sustainable use of this product could prove highly useful, particularly in filtering and in remediation of contaminated sites. Development of agroforestry is promising, particularly where biowaste is used as fertilizer.

There is a clear need to carefully consider the re-entry of human and animal wastes into the value-adding cycle. These feedstocks are potentially potent fertilizers, but, for safety reasons, extra care should be taken that these types of waste not cycle back as human food or animal feed. These forms of biowaste should be managed carefully to not pollute the environment and threaten the health of humans, animals, and ecosystems.

Science-Metrix recommends a strategy centred on biochemical platforms, versatile bioproducts, and bioprocesses. Based on the availability or potential availability of competitively priced biomass in Canada, market potential, and versatility, this report identifies ten biochemical platforms that show tremendous promise as the basis for a strong Canadian biochemical industry. Many of these platforms have a dual function: firstly, in their raw form, they can often be used as fuel, e.g. ethanol can be used directly as a biofuel; secondly, they are so-called precursors, or intermediates, that can be used in the production of other chemicals, e.g. ethanol is a precursor for ethylene glycol and acetic acid, among others. Many of these chemical platforms have synergies with other platforms. For instance, methanol, a platform biochemical, is an important feedstock in the production of another enabling platform, methyl ester. The enabling biochemical platforms are methyl ester (biodiesel), three types of alcohol (methanol, ethanol, glycol), three types of acid (lactic, levulinic, succinic), and three types of biobased gas (methane, syngas, hydrogen).

Science-Metrix also recommends that versatile biomaterials, such as adhesives, lubricants, and composites that are closer to end uses, be developed. The products were selected based on availability of biomass in Canada, market potential, and versatility, which explains why they are called versatile biomaterials. The versatile biomaterials are adhesives and resins, composites, lubricants, pesticides, fertilizers, and plastics. Many of these products can be produced using the aforementioned enabling biochemical platforms as precursors.

The industrial metamorphosis from hydrocarbons to carbohydrates will require a rethinking of process technology. This requires new catalysts; it will therefore become important to invent biocatalysts such as enzymes, bacteria, and other microorganisms. Here, just as much as in the development of crops specific to industrial production, genomics will play a central role. There is also a need to improve fermentation technologies, to develop larger-scale bioreactors, and to integrate these in bio-refineries. Bio-refineries will transform biomass into a wide-range of biochemical intermediates, such as the enabling platforms that are expected to occupy centre stage in the Canadian Biostrategy. These intermediates will then be converted into versatile and end-products using existing physical and chemical processes, but also with bioprocesses that hold the promise of cleaner and safer production because they can be used at atmospheric pressure and room temperature in aqueous environments.

Science-Metrix recommends that R&D projects be oriented toward solving market needs. Environmental regulations are increasing the demand for biodegradable materials. In addition, particularly in Europe, an increasing proportion of the parts used in automobiles are meant to be recyclable. There is a growing demand for products with greater environmental safety. For instance, there is increasing concern about sick-building syndrome, and this increases demands for

construction materials with lower emissions of volatile organic compounds. This report presents several markets where important demands can be expected for bioproducts: the transportation, power generation, construction, pulp and paper, printing, packaging, and environmental industries.

Currently, Canada does not have a strategy for the development of bioproducts and bioprocesses, and R&D in this field is not a priority of funding agencies and government departments. For instance, between 1998 and 2003, the combined grants of the Natural Sciences and Engineering Research Council and the Canadian Foundation for Innovation provided a mere CDN\$50 million in research funds. Additionally, it is very difficult at this time to know precisely how much Agriculture and Agri-Food Canada and Natural Resources Canada are spending in the area, but it is clear that research funds are limited and currently not spent following a well laid-out plan. Compare this to the US, where the Department of Energy and the Department of Agriculture have disposed of a budget in excess of US\$200 million per year since 1998. Europe has also been spending a substantial amount of money within the European Union framework programmes, in addition to country-level efforts in France, the UK, and other countries.

Given these facts, it is not surprising to find that Canada is lagging far behind leading countries in terms of research capability. For instance, between 1998 and 2002, India published more papers (n=1,011) on bioproducts and bioprocesses than Canada (n=887), which seldom happens in other scientific fields. Furthermore, the average growth in number of papers published in this area was 3.8% in Canada during the 1998-2002 period compared to 7.3% at the world level. The most scientific papers in bioproducts and bioprocessing are produced in Ontario, Quebec, and British Columbia at the provincial level and in Montreal, Vancouver, Toronto, and Quebec City at the metropolitan level.

Importantly though, Canada ranks fourth in terms of U.S. patent portfolios. Canada has a greater proportion of patents in bioproducts and bioprocesses than in other fields, which is also the case in Denmark, Finland, and Australia. Although Canada does not have a very strong scientific capability in bioproducts and bioprocesses, it may have a relatively potent receptor capability.

Given the strategic importance of bioproducts and bioprocesses, Science-Metrix recommends that the Canadian Government invest substantial financial resources to support bioproduct and bioprocess R&D. Three financial scenarios are suggested:

- | | |
|-----------------------------------------------------|-----------------------------------------|
| 1) Catching up with the US: | CDN\$425 million between 2005 and 2009; |
| 2) Developing Canada's leadership: | CDN\$650 million between 2005 and 2009; |
| 3) Defining bioproducts as a top national priority: | CDN\$850 million between 2005 and 2009. |

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Abbreviations and acronyms

AAFC	Agriculture and Agri-Food Canada
CO ₂	Carbon dioxide (a greenhouse gas)
DOE	US Department of Energy
eCO ₂	Equivalent carbon dioxide
EU	European Union
GHG	Greenhouse gas
GW	Gigawatt
IEA	International Energy Agency
MTBE	Methyl tertiary butyl ether
MW	Megawatt
NRC	National Research Council
NRCan	Natural Resources Canada
PERD	Panel on Energy Research and Development
PHA	Polyhydroxyalkanoates
PLA	Poly lactide (PLA is also used in the literature to designate polylactic acid)
PJ	Petajoule
VOC	Volatile organic compound
R&D	Research and development
TPC	Technology Partnerships Canada
USDA	US Department of Agriculture

1 Introduction

Back in 1957, practitioners from Bell Laboratories shocked the world of telecommunication switching technology. They demonstrated mock-up computer-controlled switches to engineers from all over the world. One of these switches used a core switching fabric that operated on digital circuits and caught the attention of Canadian and French research engineers. For more than two decades, these practitioners faithfully worked on developing computer-controlled digital switching equipment, in what turned out to be a race against giants.

At the time, the world of telecommunication switching equipment was dominated by AT&T Bell Laboratories, which performed research, Western Electric, which built telecommunications equipment for the US as part of the huge AT&T family, and ITT and its research laboratories in Belgium, France and Germany, which dominated the world's markets. In the 1970s, the Canadians and the French swiftly outmanoeuvred these giants by introducing the first functional digital telephone exchange. These efforts led to the current situation in which Nortel and Alcatel are both strongly positioned in the telecommunications industry and ITT has virtually disappeared from the telecommunications industry world map.

Technological metamorphoses of this degree of magnitude are far and few between. They send shockwaves of mass destruction to economic systems by pruning out older firms that lack the vision and the willpower to work for a number of decades simply to position themselves in a new technological paradigm. They also allow younger and bolder organizations to encroach upon the position of the former giants. We will undoubtedly witness a technological metamorphosis of another kind, one that will alter industrial structures throughout the world, sometime this century. During this century, the world will see a reversal of the trends observed in the 20th century, whereby fossil-based hydrocarbons progressively took over from biomass-based carbohydrates. Although the mutation towards hydrocarbons was not a complete metamorphosis since carbohydrates were never displaced completely, the next wave of technological change will run higher, deeper and wider and will sweep away the old petroleum economy—although that will no doubt take a very long time.

Before the 20th century, industrialized countries did not rely on petroleum- and hydrocarbon-based products. Biomass and minerals were all that humans harnessed, and they used them to create great civilizations. During the 20th century, hydrocarbons and organic chemistry progressively pushed aside biological products. This happened in a matter of decades, not years. The same will happen with the bioeconomy. Biomass will regain some of the ground it once occupied in the production of industrial and consumer goods. It may be hard to imagine, but consumer demand will no doubt be a decisive factor in this change. For instance, in the 1960s and the following decade, clothes and fabrics were increasingly made of synthetic fibres in Western countries. There was an important change in the 1980s and 1990s, whereby consumers increasingly bought garments and fabrics made of natural fibres such as cotton and wool. While cotton and wool are not going to replace synthetic fibres tomorrow, they will certainly continue to obtain an important market share.

Interestingly, fibres are now being made from biomass, but are undergoing such a complex set of transformations that they can be considered synthetic as well. These fibres match or even exceed the specifications of petroleum-derived fibres, yet have the advantages of natural fibres such as their softness and the fact that they are made from renewable resources. A Canadian innovation policy should be designed to assist evolution and to catalyze the process of change; it should not attempt to revolutionize industry by negating the strengths of hydrocarbons. The metamorphosis is ineluctable but will take several decades, and one therefore has to tackle it in an *evolutionary* rather than a *revolutionary* way.

Thus, Canada has to undergo an important transformation to favour a gradual shift from an economy dominated by hydrocarbons to one dominated by carbohydrates. This may be a long shot, but a systematic approach will guarantee that Canada will not experience a crisis when resources start rarefying to the point that shockwaves are sent throughout the world economy. Part of a sound R&D strategy should entail the development of products that do not have equivalents in the hydrocarbon-based economy, but a substantial part of the strategy should also aim to find substitutes for hydrocarbon-based products. This also means developing processes to transform biomass into energy and chemical stocks.

No one can say for sure how long the metamorphosis currently underway will take, but it is certain that, since hydrocarbons are non-renewable, one day humans will have exploited all the petroleum, coal and natural gas that are economically usable. That day, the world economy will have known a complete metamorphosis. That day, renewable resources will no doubt play a large part in the planet's energy balance-sheet and, most likely, highly efficient and non-polluting ways of producing energy will have surfaced. Even though it is difficult to estimate how much of the energy needs will be met by biomass, a large number of chemicals currently derived from hydrocarbons will be produced from biomass feedstock. This explains why chemical platforms play such an important role in this proposed framework for a Canadian policy on R&D in bioproducts and bioprocesses.

Important definitions

Biomass

The term biomass is used to describe any organic carbon-based materials that are available on a renewable or recurring basis and that can be used in place of fossil-fuel sources to develop value-added products such as power, heat, industrial chemicals and consumer goods. Biomass sources can be found in agriculture (plant, animal), water, forests and even municipal waste streams.

Bioenergy

The term bioenergy is used to describe the energy produced from biomass (electricity; liquid, solid and gaseous fuels; heat).

Biobased industries

The term biobased industries is used to describe emerging businesses which use a broad range of biomass and bioprocessing technologies to output bioproducts.

Bioproducts

The term bioproducts is used to describe a commercial or industrial product (other than food and feed) that is generated from biomass. These products include biopower (heat and electricity), biofuels (ethanol and biodiesel), industrial biochemicals and a broad range of other bioproducts like agri-fibre panels, textiles made from flax and hemp and bioplastics made from corn starch.

Source: http://www.agr.gc.ca/misb/spcrops/sc-cs_e.php?page=bioproducts-bioproducts

Canada's natural advantages and not so natural weaknesses

Canada is one of the most atypical countries on the planet. It has the world's second largest total landmass—nearly 10 million square km—and the third largest forest area—nearly 2.4 million square km. Although Canada is blessed with 7.4% of the earth's landmass, as of 2000 it had only 0.5% of the world's population (ranking 34th) and 1.9% of the planet's GDP at purchasing power parity (ranking 13th overall). Although Canada accounts for only 0.5% of the world's population, it is responsible for 1.9% of global CO₂ emissions. If everyone on the planet was responsible for the same quantity of CO₂ emissions as an average Canadian in 2001, worldwide emissions would be 140 billion tons of CO₂-equivalent - whereas this figure is currently in the 25-30 billion ton range. Clearly, this is an unsustainable situation, and the pressure on the environment is growing due to the rapid industrialization currently occurring in a number of highly populated countries, which will only put more pressure on the more wasteful countries to lower their "ecological footprint".

Canada clearly has a tremendous natural advantage. Importantly though, practitioners from the National Research Council and Industry Canada as well as from a mounting number of Canadian organizations are bringing home the message that we have to create greater value from Canada's natural resources. There is a good reason why so many informed Canadians are pushing for the production of more value-added goods: Canada clearly has a weakness and an increasing lack of competitiveness in high-technology manufacturing. Whereas Canada's exports of natural resources post a positive commercial balance in agriculture, forestry and energy, the country is not performing very well in terms of industrial products. In fact, Canada has a paltry performance in terms of balance of trade of industrial machinery and an alarmingly bad performance in trade of consumer goods (Figure 1).

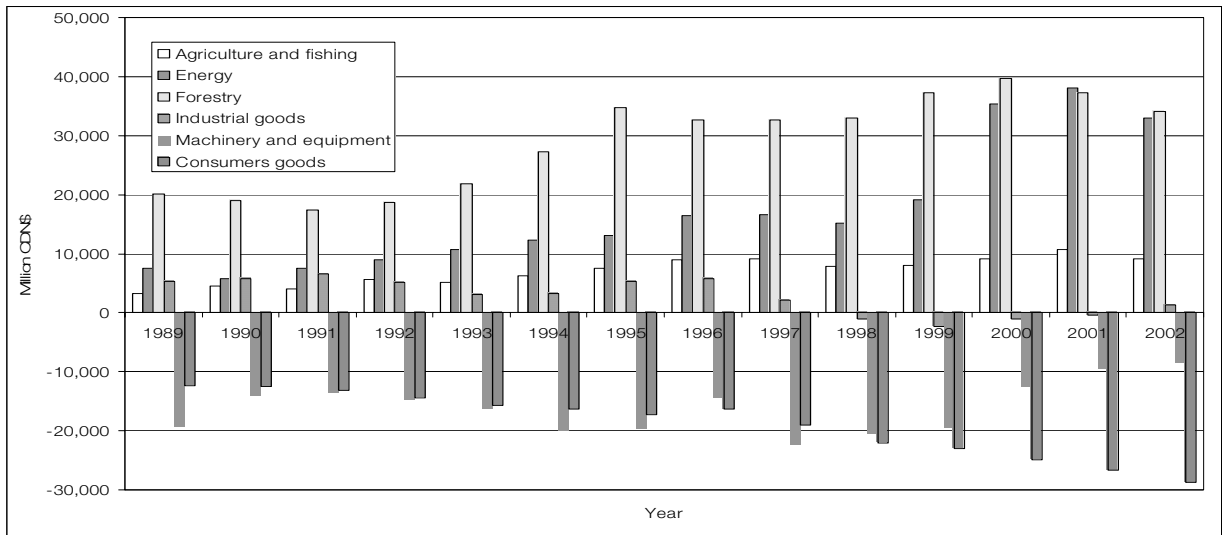


Figure 1 Canada's merchandise trade by selected product type, balance of payments basis, CDN\$ million

Source: Statistics Canada, Canadian International Merchandise Trade, Catalogue no. 65-001

This sends a serious message that Canada has to somehow find the means and the willingness to make the most of its natural resources and to modernize its industrial fabric to better serve the needs of industry and customers alike. Because of this situation, one of the most important missions of Canadian industry and governments should be to transform Canada's tremendous natural advantage into an equally tremendous competitive advantage.

However, being party to the Kyoto Accord, Canada has to develop its industrial capabilities without increasing its dependence on greenhouse gas (GHG) producing technology. This is where the biobased industry comes into play: Canada can continue to industrialize without creating additional burden in terms of GHG while at the same time increasing its capability to manufacture high-tech goods. In addition, Canada has to make the most out of its natural resources while tackling head first the liabilities associated with both industry and the modern way of life that Canadians have come to expect.

The development of a bioeconomic policy for Canada will ideally be associated with a gradual transformation of attitudes to facilitate the adoption of schemes, habits and practices that tend toward the creation of value-added products, that is, products that have the same value and use less natural resources or products with much greater value using the same amount of resources. The framework for this system centres on matching Canada's natural strengths with the liabilities that take the form of pollution to create products that could be sold, with a view to reducing waste and increasing turnover within the Canadian economy. The suggestion is to transform Canada from a country that exploits natural resources into one that leverages them using smart production processes, many of which are based on metabolic processes found in living organisms (bioprocesses), in order to offer the market smart products based on renewable or organic waste matter (bioproducts).

Hence, it appears that it is essential for Canada to define and implement an R&D strategy to position itself in the carbohydrate economy and to increase the added value of its natural resources. In a world where sustainable development has become a necessity, Canada has to have two interconnected missions in the years to come:

- *Transform* Canada's natural advantage into a competitive advantage through the *transformation* of biomass into value-added biomaterials and bioproducts;
- *Transform* liabilities such as waste and pollution into assets such as exportable high-tech green products.

Transformations and the concept of value-added cycling

The concept of transformation is really a central aspect of an R&D strategy for bioproducts and bioprocesses since most of the developments that have to be undertaken centre on operations that are in fact transformations. Indeed, physical and chemical processes such as fractionation and separation and biological processes such as enzymatic conversion and fermentation all transform matter.

The reason why transformations are so important can be apprehended partly by the concept of the value chain, but it must also be realized that the existing model falls short of the expectations of sustainable development. Typically, a value chain is defined as a connected series of organizations, resources and knowledge streams involved in the creation and delivery of value to end-customers. Value systems integrate supply-chain activities, from the determination of customer needs to the development of products and services, and going on to production, operations and distribution, including a series of tiered suppliers. The objective of value systems is to position organizations in the supply chain to achieve the highest levels of customer satisfaction and value while effectively exploiting the competencies of all organizations in the supply chain. One of the limitations of this approach is that traditionally, it has been seen as a linear process. Furthermore, it is customer-centric and does not take into account the need to optimize the use of existing resources or deal with waste and pollution created within the value chain and after consumption. These last two factors have to be factored in to create a sustainable approach to industrial development, thus the notion of *value-adding cycle*. Biomass should cycle through the system and be used to the maximum extent possible, with waste being transformed from liabilities into assets through several stages of value-adding cycles. In addition, this has to be an ecologically sensible system that takes into account the carbon-cycle and attempts to fix carbon into durable value-added objects rather than release carbon in the atmosphere. This is a complex optimization game whereby the life-cycle assessment must take into account both the carbon-cycle assessment and the value-adding cycle assessment. An economical-ecological approach is therefore needed.

Intermediate products are subsequently transformed, e.g. moulded or packaged, to offer end-products to the market. The Canadian bioeconomy R&D strategy also deals with the bioprocessing of hydrocarbons and inorganic matter. Hydrocarbons and inorganic matter will usually produce intermediate materials that will undergo subsequent stages of transformation, biobased or not. Before delivery to the customer, intermediate materials undergo one or more transformations during which they are shaped or packaged to fit the “form” that “follows functions”. The strategy would not support sustainable development if it ended there. The strategy should therefore also encourage the recycling of biobased products when reduction and reusing are not possible. The use of biological, chemical and physical processes to recycle biological materials produced by intermediate transformations and consumption has to be incorporated in the R&D strategy. Moreover, the use of biological processes to recycle non-biological materials has to be supported too. Figure 2 shows how green processes and green products interact with other types of materials and processes.

Value cycling starts by identifying the biomass that is already present in large quantities in this country and that meets two additional conditions: it is currently sold with little value added (profit margins are low), and some sizeable parts of production are being wasted in the form of surpluses or insufficient use of the biomass. If a market exists (present or potential) for speciality products, R&D could be undertaken to leverage the biomass. A life-cycle approach must be used as much as possible, and liabilities must be reduced to a minimum while by-products must be used to the maximum.

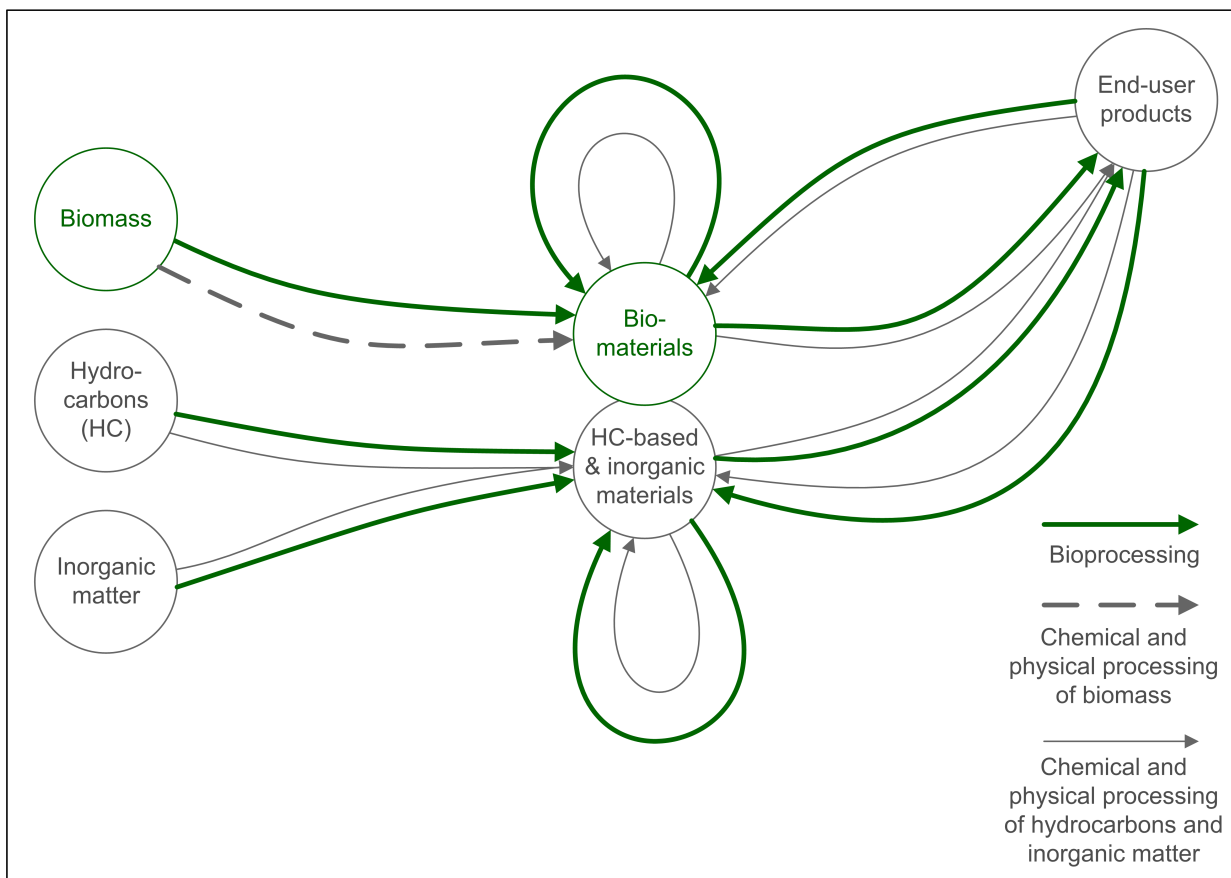


Figure 2 Value-added cycling in the bioeconomy

Source: Science-Metrix

In the transition towards a sustainable, or at least a more efficient economy, using biobased feedstocks presents important advantages. One of them is that, compared to fossil-based feedstocks, which require a high temperature and high pressure to be converted into desired intermediate materials, the bonds of biomass are normally easier to break. This means that transformation can often occur at or near room temperature and at close to atmospheric pressure (Paster, Pellegrino and Carole 2003). In other words, not only does the use of biomass translate into lower energy expenditures, it also means that production plants are cheaper to build and safer to operate. These are some of the key advantages associated with a green economy—there is an intrinsic "virtuous circle" built-in.

In addition, there are clearly some cases where non-biological natural resources are currently used in a sub-optimum manner, that is, little value-added is created and too much liability exists because of pollution. Areas where a market already exists and where a bioprocess could be used to increase efficiency should be targeted.

The strategy suggested in this study centres on the production of intermediate materials and products, which is what most bioprocesses and physical and chemical transformation of biomass provide. For instance, biomass processing can produce a number of intermediate chemicals including ethylene glycol, adipic acid, ethanol, acetic acid, isopropanol, acetone, butanol, citric acid, 1,4-butanediol, methyl ethyl ketone, N-butanol, succinic acid, itaconic acid, lactic acid, fumaric acid, and propionic acid. These intermediate chemicals have uses in the manufacture of polymers such as nylon, polyester and urethane, of various plastics and high-strength composites and of solvents, coatings, and antifreeze (NRC 2000). Although these are often called bioproducts, it is often the case that this notion reflects the origin of the product rather than a fundamental difference from products obtained from fossil-based feedstocks. For instance, methanol has exactly the same chemical structure whether it is produced from natural gas or from so-called syngas which is derived from biomass.

Scope of the bioprocesses and bioproducts R&D strategy

What is included?

Industrial bioproducts such as fine and specialty chemicals and materials produced from biomass including novel textiles, natural fibre composite materials and bio-composites generally, biopolymers, and bio-plastics. Sources of energy such as biofuels (e.g. biodiesel, ethanol). Bioproducts derived from municipal and industrial effluents, landfill and other types of pollution. Bioprocesses based on enzymes and other biocatalysts.

What is excluded?

Traditional forest products (lumber, paper, oriented strand board and plywood), food, food ingredients, agricultural feed, nutraceuticals, flavour ingredients, pharmaceuticals, burning of raw materials.

One may ask, why not include the health and food and feed sectors in a strategy to spur the development of the Canadian bioeconomy? After all, these are the principal areas of application of biotechnology to date. This is precisely why they are not included: health biotechnology, food and feed have already received a lot of attention and is very well supported by Canadian organizations of all types. These fields are striving whereas the aspects covered by this report still have to realize their full potential. As argued by Minns (2003):

The benefits of biotechnology in health and pharmaceuticals are well established. However, a principal feature of the emerging BBE [biobased economy] is the application of biotechnology, often in partnership with conventional chemical technology, to produce clean commodity products such as biofuels, biochemicals and materials. It is in this capacity that the BBE will potentially have its greatest impact on sustainable development.

Although Canada is often seen as a land of natural resources, Section 2 shows that in comparison with comparable countries, the percentage of its surface comprising agricultural and forest lands is relatively small. Because of the relatively small proportion of Canada's land mass where biomass can be harvested economically and ecologically, it should be treated with care and diligence. Given the high level of pollutant emissions by Canada, a great deal of emphasis should be placed on finding ways to make economical and smart use of Canadian natural resources. These are only two of the multiple reasons why the development of the bioeconomy must be pursued in a thoughtful manner.

To sum up, the typical case for investment in R&D would 1) involve a resource which is comparatively abundant in Canada; 2) exploitation of this resource would currently directly or indirectly lead to extensive pollution; 3) the resource would currently be transformed into products using relatively inefficient methods; 4) the market would be important; 5) this whole system would currently create little value added locally.

Research should not be undertaken with a view to maximizing exploitation of biomass; on the contrary, research should provide wisdom as to how to exploit the Canadian biomass within the framework of sustainability. Research projects that aim to optimize the use of biomass and to minimize the risks associated with the depletion of resources should be an integral part of a bioeconomic policy. This means that life-cycle assessment methods, carbon-cycle assessments, value-adding cycle assessments and the development of robust agronomic, forest and waste management practices must be brought to the fore.

This report is divided as follows:

- Section 2 shows that agriculture, forestry, peat bogs and urban waste represent a major source of readily available complex proteins, oils, fatty acids and sugars that can be used as feedstocks.
- Section 3 examines the types of platform products and specialty products that could be developed in priority within a Canadian R&D strategy for the bioeconomy.
- Section 4 examines the main types of bioprocesses under development, but also notes that chemical and physical transformation of biomass should be part of a robust R&D strategy.
- Section 5 examines some of the most important markets that are likely to use bioproducts and bioprocesses.
- Section 6 compares Canada's scientific and technological output in bioproduct and bioprocess to that of other leading countries.
- Section 7 examines programs aimed at supporting R&D in bioproducts and bioprocesses in Europe, the US and Canada.
- Section 8 recommends a structure and priorities for a Canadian R&D strategy.

2 Sources of biological feedstock

Canada certainly is a resource-rich country by several standards, but a detailed comparison with similar countries shows that it should cherish its natural resources. This is particularly the case for its agricultural and forested lands, since they do not make up a very high proportion of Canada's total area, at least when compared to comparable countries. Table I shows countries that are comparable to Canada in various respects: like Canada, they are also among the world's powers (Russian Federation, US, China, Brazil, Australia); they are economic competitors (G7 countries); they are also members of NAFTA (US, Mexico); or they occupy a northern location (Sweden, Finland, Norway).

Table I Areas of Canada and comparable countries in terms of agricultural and forested areas, thousand hectares

Country	Agricultural area	% Agricultural	Forest area	% Forest	Total area	% Biomass area
Russian Federation	216 861	13%	851 400	50%	1 707 540	63%
Canada	74 880	8%	244 600	25%	997 061	32%
United States of America	411 259	43%	226 000	23%	962 909	66%
China	555 276	58%	163 500	17%	959 805	75%
Brazil	263 465	31%	532 500	62%	854 740	93%
Australia	455 500	59%	158 100	20%	774 122	79%
Mexico	107 300	55%	55 200	28%	195 820	83%
France	29 631	54%	15 300	28%	55 150	81%
Sweden	3 144	7%	27 100	60%	44 996	67%
Japan	5 199	14%	24 100	64%	37 780	78%
Germany	17 033	48%	10 700	30%	35 703	78%
Finland	2 219	7%	21 900	65%	33 815	71%
Norway	1 042	3%	8 900	27%	32 388	31%
Italy	15 355	51%	10 000	33%	30 134	84%
United Kingdom	16 954	70%	2 600	11%	24 291	80%
Total Group	2 175 118	32%	2 351 900	35%	6 746 254	67%
World	5 021 734	37%	3 861 600	29%	13 431 258	66%

Source: Compiled by Science-Metrix from Faostat data.

Canada is a large producer of agricultural products. For instance, it ranks 8th in the world in terms of cereal production and accounts for 2.4% of the world's output (FAO statistics, average for 1995-2002¹). Importantly though, although Canada has a sizeable proportion of the earth's landmass, only 7.5% of Canada's surface is made up of agricultural lands. This is quite different from many large countries. For instance, 43% of US area is agricultural land, 58% in the case of China, 31% in the case of Brazil and 59% in the case of Australia. Large proportions of the areas of G7 countries tend to be what is considered agricultural land: France 54%, Germany 48%, Italy 51% and the UK 70%. In this respect, Canada is similar to other countries which find themselves in a northern location: 13% of the Russian Federation is composed of agricultural land, 7% of Sweden and Finland and only 3% of Norway. However, with the exception of Norway, other Nordic countries differ

¹ <http://apps.fao.org/default.htm>

significantly from Canada, given the fact that a substantial proportion of their area is composed of forest (65% of Finland is made up of forest, 60% of Sweden and 50% of the Russian Federation). Even within the G7, most countries (France, Germany, Italy and Japan) have a larger proportion of forested area than Canada does.

Another interesting figure is the proportion of land that is amenable to agriculture or that is covered by forests. Among the list of 15 countries presented in Table II, Canada has the second lowest proportion of area that is covered by biomass area, second only to Norway. Whereas only a third of Canada is covered by forest and agricultural lands, the world and the 15 competitor countries have, on average, two-thirds of their respective areas covered by biomass that can be economically exploited. Hence, Canada is a huge country, but compared to other competitors, it is relatively sparse in terms of the proportion of biomass of its total area.

Hence, in terms of total landmass, Canada's natural resources are sparser than those of competing countries in terms of regularly used areas for biomass harvesting. One may ask though what purpose the two-thirds of land area not composed of agricultural land and forests serve. Part of it is made up of lakes: Canada is covered by lakes, which greatly helps its biodiversity, and makes it one of the largest reservoirs of drinkable water on the planet. In addition, large parts of Canada are made up of mires and peatland. These are precious areas. Peat bogs cover nearly 12% of Canada's surface, and the country possesses, by far, the largest peatland area on Earth (Table II).

Table II Areas of peatland in countries with the largest peat resources, 1999

Country	Thousand hectares	% of world peatland
Canada	111,328	41.0%
Russian Federation	56,800	20.9%
Indonesia	27,000	9.9%
United States of America	21,400	7.9%
Finland	8,900	3.3%
Sweden	6,400	2.4%
World	271,391	100%

Source: <http://www.worldenergy.org/wec-geis/publications/reports/ser/peat/peat.asp>

At the world level, plants produce about 100 billion tons of biomass, which clearly offers a huge potential for the production of energy and chemicals. However, agriculture and forestry operations do not always make optimal use of these resources. For example, it is estimated that about 50% of the biomass is left on the ground as residue (Jaworski 2003). There are several types of waste. In agriculture and forestry, these are usually called residues. However, what is left on the ground and not necessary for soil regeneration can be considered as waste and produces pollution in the form of GHG, particularly methane, when it decomposes. This small liability can be turned into a valuable asset.

Buckminster Fuller considered pollution, which is often what waste ends up being, "as resources not positioned at their maximally effective location". In fact, according to Sieden (1989),

[Fuller] often illustrated that perspective when he discussed sulfur polluting the atmosphere. Almost everyone has observed huge plumes of sulfur pouring out of industrial smokestacks to dirty the air. Yet, at the same moment one industrial giant is releasing large quantities of sulfur into the air, other production facilities are mining it from the ground to be used in manufacturing processes. Clearly, when examined from a comprehensive perspective, this is a case of resources requiring positive relocation. These polluters need only reclaim the waste sulfur from their processes and relocate it to those industries which require the material. By operating thusly, polluters not only become good citizens, they may also profit from the sale of a substance they once considered waste material.

Agricultural crop residues, such as stalks and stems not normally used for human or animal food, are probably the largest untapped resource. Not all of this particular biomass is fully wasted though; part of it is fed to animals, and some residues are left over in the fields, where this organic matter plays an important role in stabilizing the soil, thus preventing erosion and organic carbon depletion. One of the best examples of dislocation is the methane produced by landfill sites. This is a potent liability since it is a powerful GHG, yet, at the same time, can be transformed into methanol and then used to process waste cooking oil from restaurants into methyl ester, that is, biodiesel. This type of strategy is discussed in Section 3.

This section summarizes the biological feedstocks available in Canada. The three main sources of biological feedstock that will be examined here are:

- Agriculture feedstock and residues
- Forest and peat feedstock and residues
- Human and animal biowastes

2.1 Agriculture feedstock

This section identifies promising crops to scale up the production of biobased products in the near future. This approach is based on leveraging Canada's current natural advantage and is complementary to a longer-term strategy aiming to develop crops whose endpoint is neither food or feed, but rather specific industrial products. The aim of this approach is to identify the feedstock needed to start in earnest large-scale industrial production of biofuels and bioproducts. This does not mean that other factors and approaches should not also be considered. For instance, the cost of feedstock, the cost of harvesting and transforming crops and the value of resulting bioproducts will all need to be considered to implement the strategy. In addition, although this approach focuses on large-scale production, small-scale production based on rare inputs and valuable outputs should not be brushed aside. However, successful strategic planning is all about privileging certain directions against others. The direction of the current strategy aims to create jobs and companies in a biobased economy with a view to creating wealth yet minimizing the ecological footprint of Canadians. This appears to require a large-scale, smart, sensible and sustainable approach.

A sustainable bioeconomic policy based on creating value from crops grown in Canada would likely favour a three-pronged strategy: 1) use crops in which Canada has a comparative advantage, that is, in which Canada has a sizeable production and above average yields; 2) use crops that are generally rare at the world level and more common in Canada and that produce valuable products that cannot be easily produced by other crops or synthetic methods; 3) develop species that are adapted to the Canadian climate and soil condition and that produce useful and high-value feedstocks for products and bioprocesses. This section concentrates on identifying the first type of approach since it is more likely to provide short- to medium-term solutions for creating a robust Canadian bioeconomy. However, the third approach should receive particular attention for investments in R&D since it is the long-term answer to sustainable development and economic competitiveness. This means that a systematic approach to the bioeconomy in the short term should optimize equipment and processes for crops in which Canada is currently competitive and progressively modify them as new, more optimal crops, are harvested in large-enough quantities.

In line with the strategy's stated objectives, that is, identifying resources in which Canada has a comparative advantage, Figure 3 provides a synthetic view of Canada's cereal production compared to that of the world, and Figure 4 provides a view of Canadian oil crop production. The x-axis displays the log of the yield index, where a score above 0 means that Canada has a greater yield than the world average and, conversely, where a score below 0 means that Canada's yield is below world average. The y-axis presents the log of the specialization index. This index is above 0 in instances where Canada produces a larger share of a cereal than the world share of all types of cereal produced by Canada. For instance, it is above 0 for barley, since Canada produces 8.8% of world barley and 2.4% of the world's cereals generally. Another indicator shown in these figures is the relative importance of the production; this is represented by the figure located next to the circle of each crop.

Figure 3 shows that Canada specializes in the production of oat, barley and wheat and in less important crops such as canary seed and mixed grain (log specialization index >0). Canada has greater yields than the world average in maize, oats and barley as well as in canary seed and buckwheat (log yield index >0). Finally, it is important to observe the availability of crops in terms of biomass. Wheat, barley, maize and oat are Canada's most important crops in terms of biomass.

Considering these factors, barley and oat are the crops that should be considered priorities. The possibilities of using wheat, because of its relative importance, and maize, because of Canada's high yields, should also be studied. If one crop should be prioritized, though, it is clearly barley. In fact, considering Canada's clear natural advantage in barley production, there is a clear incentive to investigate which value-added products could be developed from this crop, with a view to transforming this situation into a competitive advantage. Some Canadian companies already use barley as a feedstock for bioproducts. For instance, Canadian Fibretech Inc. manufactures building materials such as fibreboards from compressed straw, using raw materials such as wheat, barley and canola straw. Iogen, located in Ontario, has shown that it is possible to produce ethanol from barley straw.

As mentioned in a CARC (2003) study, "[e]ffort should be made to find places where plant proteins and/or starches can be used as co-products with other end-products. For example, barley protein may find use in specialty adhesives markets while beta-glucan and starch are sold into the food and ethanol markets. Alternatively, other specialty adhesives may be made using the various components of the carbohydrate fractions."

There may be a long-term potential for the use of barley in phytoremediation. In particular, Okumura *et al.* (1991) found that barley possessed metallothioneins, low-molecular weight cysteine-rich metal-binding peptides. Much work has already been done to characterize metallothionein genes. They appear varied in the metals they bind and in the manner in which their expression is

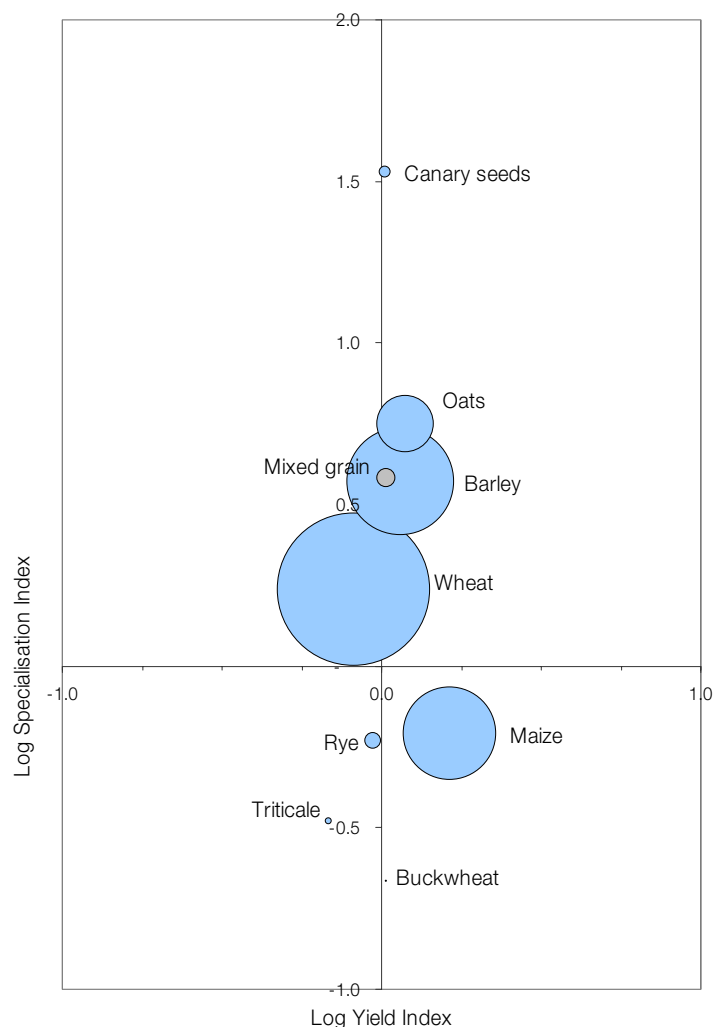


Figure 3 Specialization and yield indexes in Canadian cereal production

Source: Science-Metrix from Faostat data

regulated (Robinson *et al.* 1999). Further research to examine their potential for phytoremediation is required (Britt and Garstang 2002).

Oilseed production in Canada is second to that of cereals and is a very important economic activity. Figure 4 reveals that rapeseed (canola) is the crop to prioritize in Canada, considering the size of the crop, the yields obtained by Canadian farmers and Canada's specialization in this particular oilcrop. Currently, much of the canola crop is exported as raw, unprocessed seed, a situation which is sub-optimal according to a value-added bioeconomic strategy. Moreover, the yields observed in Canada are lower than those obtained on average at the world level. This raises important questions that need to be addressed within the framework of an R&D strategy.

Canola could be used to produce biofuel, since it has important advantages in terms of GHG emissions. Germany, France, Italy and Austria already have significant capabilities for producing rapeseed methyl ester as a substitute for diesel. On an equivalent energy basis, the complete production cycle of canola biodiesel considerably lowers GHG emissions compared to Canadian diesel fuel.

In fact, it is estimated that the production of canola biodiesel creates GHG emissions of 1.25 kg equivalent eCO₂/L, whereas the production of Canadian diesel fuel emits 3.12 kg eCO₂/L (Levelton 2002, cited in CARC 2003). In addition, tests involving the addition of low levels of various biodiesel materials found that canola biodiesel improved lubricity more than biodiesel made from other oils such as linseed and sunflower (Munson *et al.* 1999, cited in CARC 2003). Furthermore, canola biodiesel has important advantages in terms of improved fuel efficiency. Small-scale tests have shown that adding 0.5% canola biodiesel to commercial diesel increased fuel efficiency by 5.8% while simultaneously reducing engine wear by 51% (Hertz *et al.* 2001, cited in CARC 2003).

An important and potentially large-scale use of canola oil is for biobased lubricants. Canola is the dominant North American oilseed crop used for industrial lubricants. About 85% of vegetable oil-based lubricants come from canola. Soy-based lubricants are less expensive than canola but do not

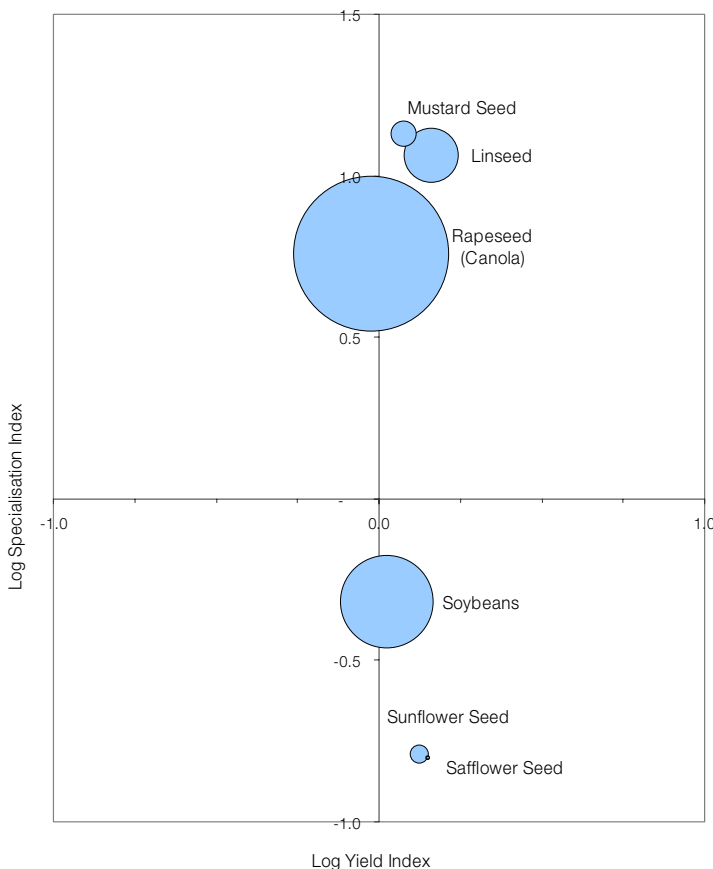


Figure 4 Specialization and yield indexes in Canadian oilseed production
Source: Science-Metrix from Faostat data

perform as well. Hence, transforming canola oil into lubricants is a perfect example of the objective of the Canadian bioeconomic strategy: 1) use a crop in which Canada has a comparative advantage; 2) transform it into a value-added product for a market segment that is growing and where its use provides unique advantages; and 3) lower the environmental impact compared to previously used products and processes (in this case, mineral oil).

Another alternative use of canola is for the production of bioplastics. The life-cycle GHG savings in CO₂ equivalents for oilseed-based plastic alternatives have been estimated to be 1.5 tons per ton of polyol made from rapeseed oil. One of the target molecules is polyhydroxyalkanoates (PHA), which can be used as a replacement for polyethylene and polypropylene. Research conducted by Dr. Suresh Narine at the University of Alberta has so far targeted flax and canola. According to Narine, "[m]any materials derived from agricultural feedstock have advantages of biodegradability. They're more environmentally friendly. They require less expenditure of energy and are completely renewable. Furthermore, there may be direct benefits to farmers if the commercialization of such products is crafted carefully."²

There are many other uses for canola oil including the production of glycerol and glycerine and alkyd resins. However, most of Canada's canola supplies are purchased by Japan, and the remainder of the crop is crushed for domestic consumption or export, primarily to the United States. Hence, biodiesel production in Canada would require displacement from higher-priced food uses. Nevertheless, there is potential for using lower-quality canola oils from overheated or frost-damaged seed without causing any ill effects on the quality of the biodiesel³. Furthermore, there is room to increase yields, and this extra level of production could be used to increase the lubricity of commercial biodiesel, thus reducing engine wear and increasing fuel efficiency.

It is important to balance the need of achieving economies of scale with that of maintaining agricultural biodiversity. As such, in addition to using crops that effectively provide the feedstocks for great quantities of bioproducts, there is also a need to diversify crops with highly efficient species, given the needs of bioproducts. For instance, agroforestry approaches to oilseed production have suggested that chokecherries, a common wild fruit production shrub on the prairies, may produce surprisingly high levels of seed oil and fermentable carbohydrates. Chokecherries have been reported to produce yields of fruit as high as 15 t/ha (fresh fruit). The fruit could be processed to yield 1,800 kg carbohydrates for fermentation to ethanol. The carbohydrates obtained are glucose, fructose and sorbitol. The sorbitol can be converted to glucose by use of a single enzyme. By comparison, a typical wheat crop of 2,800 kg/ha would yield 1,960 kg carbohydrates in the form of starch suitable for fermentation to ethanol. The seed of the chokecherry could also be a source of vegetable oil. The seed yield is 2,250 kg, and based on a 30% oil content, the oil yield would thus be

² University of Alberta. 2003-02-19. Alberta Set to Lead New Bio-Based Economy. *News Details*. http://www.afhe.ualberta.ca/NewsDetails.asp?VAR_News_ID=257

³ Canadian Renewable Fuel Association. <http://www.greenfuels.org/bioworld.html>

675 kg/ha. In contrast, a typical canola crop (1,300 kg/ha) would yield 546 kg oil per hectare. Chokecherries are at a very early stage of their development as an industrial crop, but, clearly, they (and, most likely, other hardy perennial and woody species) should be studied and developed further. Indeed, initial results suggest that hardy northern perennial species have the potential to outperform annual crops currently under cultivation (CARC 2003).

Use of residues from agriculture

According to Kim and Dale 2003, the potential for producing bioethanol from waste crop and lignocellulosic biomass is about 500 billion litres per year at the world level—enough to produce the equivalent of 350 billion litres of gasoline, that is, 32% of global gasoline consumption. If one considers the statistics presented in Kim and Dale, as well as the average percentage of these crops that are cultivated in Canada (calculated from FAOSTAT between 1995 and 2002), then the potential for the production of bioethanol in Canada is 4 billion litres from wheat lignin, 1.9 billion litres from barley, 1.2 billion litres from corn and 440 million litres from oat. Hence, from these crops alone, Canada could produce about 7.6 billion litres of bioethanol, equivalent to 5.3 billion litres of gasoline, which alone is worth about CDN\$3.7 billion. What is important to note here is that most of that matter would otherwise go to waste.

Nevertheless, if a massive programme was put in place to use waste from cereal crops, it would be important to study the effects on the organic composition of soil. Furthermore, operational research would have to be carried out to minimize the natural and human resources required to harvest, transport and process waste.

2.2 Forest and peat feedstocks

Canada has one of the biggest forest-product-driven economies in the world. According to Natural Resources Canada (NRCan) (2003):

- Canada has about 10% of the world's forests and 30% of the world's boreal forests. Canadian forest is mainly composed of softwood (67%), substantially less hardwood (15%) and some mixed wood (18%)
- Canada has 418 million hectares of forestland of which more than one million hectares were harvested in 2000, 183 million hectares are non-commercial forest and largely wilderness, and 235 million hectares are commercial forest. Canada's forests are the engine behind an industry worth about \$74 billion, with exports of \$43 billion and direct employment in excess of 360,000 jobs.
- About two-thirds of Canada's estimated 140,000 plant, animal and microorganism species live in the forest, and there are 180 indigenous tree species in Canada.

The Canadian government invested \$350 millions in R&D in the forest sector in 2000, which is less than half of the R&D investments of the United-States and less than a third of Scandinavia's investments in R&D (Duchesne and Wetzel 2003). The Canadian Forest Service carries out R&D to enhance Canada's capacity to practice sustainable forest management, to help it meet international commitments and to strengthen the country's ability to measure progress toward sustainable forest management. According to Duchesne and Wetzel (2003), the Canadian Forest Service's R&D

program is principally oriented toward diversifying biological products derived from forests, such as producing non-timber forest products and using biotechnology to process biomass.

Several raw biomaterials can be extracted from forest biomass or are by-products of the first transformation of wood. These include gum and wood chemicals such as tall oil, alkyd resins, rosins, pitch, fatty acids and turpentine. The forest biomass can also provide cellulose derivatives, fibres and plastics such as cellulose acetate (cellophane) and triacetate, cellulose nitrate, alkali cellulose and regenerated cellulose (Paster, Pellegrino and Carole 2003).

Producing high grade cellulose could be a promising value-added avenue to give the Canadian forest industry more revenues. Cellulose is already a high-volume renewable feedstock used by the chemical industry to produce chemicals, plastics, food additives, fibres and textiles, and about 700 thousand tons of highly pure cellulose are required each year. The traditional methods of separating cellulose from other wood components (lignin and hemicellulose) include sulphite and prehydrolysis Kraft pulping. The Eastman Chemical Company, the National Renewable Energy Laboratory and a major US producer of chemical-grade cellulose are working on a new technology called clean fractionation that uses an organic solvent and water to make the separation.

Other recent innovations may expand applications of cellulose pulp. For instance, the US Forest Products Laboratory developed “spaceboard”, a lightweight structural composite made by moulding pulp fibre slurries into waffle-shaped forms (Hunt and Scott 1988), now commercialized. Scientists have also developed mouldable plastic materials by combining pulp fibres with thermoplastics. These materials have many potential uses, for example, in car bodies and packaging materials (PRA/CANUC 2002g). Courtaulds, a company from the United Kingdom, and Lenzing, an Austrian firm, each have begun large-scale production of lyocell, a cellulosic fibre made from a solvent-spinning process and sold under the trade name of Tencel. Like rayon, Tencel is wood-pulp-based; however, rayon requires dry cleaning and Tencel is washable. Tencel is the first new textile fibre to be introduced in 30 years and has been described as the “best thing since cotton” (NRC 2000).

Valorization of forest residues and by-products

One of the major concerns of the forest research area is the utilization and upgrading of forest residues that are an obligatory output of lumbering and pulp and paper operations. When solid wood products are made from logs, residues are bark, shavings and sawdust; pulp and paper manufacturers also produce spent pulp liquors such as black liquor, and the production of Kraft paper is accompanied by the production of substantial quantities of black liquor. Since these residues are already collected at the point of processing, they can be conveniently and relatively cheap source of biomass for energy or for processing into other products (BRDB 2001). However, branches and other residues are often left on harvesting sites, and some of this biomass exceeds the level required for soil regeneration.

Traditional approaches toward the management of those residues were mainly, in the case of lumbering residues, letting them decompose in the woods or burning them and, in the case of the pulp and paper industry, burning or burying the solids and dumping the sludge in rivers near the

plants. With increased environmental concern, Canadian paper industries have made huge efforts to lessen their ecological impact. Pulpmill and lumbering residues have found uses such as (H.C. Lavallée Inc 1996):

- In the case of primary residues, being reintroduced into pulp-making processes;
- Being used as liming agents in agricultural and silvicultural practices;
- Being used for construction material. After fuel production, this is the other major avenue of innovation in forest-related bioproducts. Among others, research is conducted on nano-structured biocomposites from cellulose and on the development of bioplastics;
- Being transformed into animal food products (primary residues provide “roughage”, cellulose is high in carbohydrates, and biomass residues can be fermented to produce proteins);
- Being upgraded to fuel, e.g., in the form of pellets or ethanol.

This last point is probably the major avenue for upgrading pulp-making residues. According to H.C. Lavallée (1996), Québec’s paper mills utilize their residues for energetic uses in a proportion of 56%. Incineration is sought after because it can reduce the volume of residues by a 13:1 ratio and produce electricity to power the plant. This figure is identical to that obtained in the US where biomass-process streams and residues provide 56% of the electricity and heat used by the pulp and paper industry and 75% of the electricity and heat used by the solid and engineered wood products industries and composites (BRDB 2001).

A promising avenue is the production of fertilizers from bio-oil produced from the fast pyrolysis of biomass. A Canadian company, Resource Transforms International Ltd, located in Waterloo, has patented a technology for the production of slow-release fertilizers from bio-oil containing about 10% nitrogen from wood production plants (IEA 2000).

The types of residue obtained by the forest industry are substantially different from one part of the country to another. For instance, there are large differences in the bark and whitewood components (i.e. sawdust, shaving, etc.) of surplus residues among the various regions of Canada. Whereas in British Columbia and Alberta whitewood and bark components both account for roughly half of the surplus, in Quebec and some of the Atlantic Provinces most of the residue is bark, and there is very little whitewood residue. Estimates suggest that, in western Canada, approximately 78% of a sawlog is used in the production of various wood products. Close to 40% is utilized in the production of lumber, and 38% is utilized in the production of wood chips for pulp and paper purposes. The remaining 22% of a sawlog is primarily made up of bark, sawdust and shavings and is characterized as wood residues (Hatton 1999).

According to Vourc’h (1994), 40% of the wood used in pulp production ends up consisting of residues. These residues consist of: 38% primary residues (any solid residues); 37% bark residues; 13% de-inking residues; 8% secondary residues (pulp-mill sludge); and 4% ashes. Currently, Canada produces about 17.7 million tons of bone-dried wood residues per year of which 5.4 million tons are surplus to current production needs. British Columbia and Quebec hold the two highest shares of surplus residues by far at 38% and 31%, respectively (Hatton 1999). Bark is currently the residue that eludes the value-adding cycle the most.

Bark residue: Research is being conducted to utilize more bark and other by-products as a fuel in fuel-cell or other energy systems. Technology is also under development to use bark as raw material in a durable panel that has apparent economic potential. However, given the extremely large volumes of bark available throughout Canada, it is thought to be unlikely that these processes will be able to deal with all of it, and there seems to be room for other economic applications for bark as opposed to disposing of it. Breakthroughs are needed to identify and develop value-generating commercial products or processes that would benefit from the unique properties of bark (Levesque 2000).

One way to manage excess bark is the trend toward bringing less roundwood to pulp and paper mills and leaving more bark in the forest to support rejuvenation. Bark is also used for mine reclamation and as mulch for horticultural applications. Agriculture Canada has developed product specifications and procedures for using bark in beef cattle feedlots, and Forintek has investigated the feasibility of producing bark board (Hatton 1999; Neufeld, Burke and Bridges 1999).

Although there is support for value-added bark, it is argued that the commercial impact of these programs is not likely to be significant (Neufeld, Burke and Bridges 1999). On the other hand, gasification processes have the promise of also utilizing bark but are still at an early stage of development (IEA 2000; McCloy and O'Connor 1999). In addition, Vancouver-based DynaMotive has developed a fast pyrolysis method that uses a mix composed of 60% whitewood and 40% bark residues that produces bio-oil with interesting properties as a biofuel and potential feedstock for the chemical industry (see box).

Black liquor: Black liquor is a by-product of pulp and paper production. Canada has a large black liquor resource of about 24 million tons of dry matter. A very rough calculation indicated that about 10 billion litres of methanol or 7.3 billion litres of ethanol might be produced from black liquor gasification and catalytic conversion if the total resource of black liquor solids could be used (CARC 2003). Traditionally, black liquor is a substance whose management was deemed problematic because of its high concentration of acid chemicals. Large efforts have been made in the past decade to reduce the environmental impact of such a solution.

DynaMotive from Vancouver (B.C.) is a world leader in developing technology for the production of BioOil. DynaMotive produces BioOil by converting organic residues such as forest (e.g. sawdust, bark) and agricultural wastes (e.g. bagasse) with a patented fast pyrolysis process called BioTherm™. The process takes less than two seconds to produce BioOil, char and non-condensable gases.

The company claims that zero waste is created since BioOil and char have a significant number of commercial applications and value and non-condensable gases are recycled and produce approximately 75% of the energy required for the pyrolysis process. The company argues that BioOil is an ideal clean fuel because it is greenhouse gas neutral, does not produce sulphur dioxide emissions during combustion and produces approximately half the nitrogen oxide emissions of fossil fuels.

The company has active inventions protected by 18 patents already issued and 20 patents pending on its pyrolysis technology. DynaMotive intends to generate its most of its revenues from license fees and royalties as well as from technical services contracts with licensees.

Nowadays, most pulp industries reuse the solution as a fuel, concentrating it to about 75% of solid matter, burning it in recovery boilers and creating steam-turbine-produced electricity with an estimated overall efficiency of 23% (Nilsson *et al.* 1995). Combustion of those liquors permits a reduction of 95% of the initial volume of the sludge. The only residues left are ashes and chemicals that can be recycled and reintroduced in the pulp-making process. The use of those residues helped produce 513 PJ of thermal energy for Canadian pulp mills in 1999 (Pneumaticos 2002). The same year, pulp and paper industries produced 1500 MW of electricity, and, currently, about half of the energy needs of those paper mills are met by bioenergy. Beyond those major industries, several independent power producers are using sawmill-industry residues. One of those major plants is based in William Lake, B.C., and has a capacity of 66 MW.

Tall oil: Tall oil is a by-product in the production of Kraft paper. Its principal constituents are unsaturated C18 fatty acids, resin acids and unsaponifiable hydrocarbons such as diterpenic alcohols and aldehydes. According to the Canadian Food Inspection Agency, crude tall oil contains a minimum of 95% total fatty acids, a maximum of 1% rosin acids and a maximum of 2% unsaponifiable matter⁴. The range of compounds in tall oil is quite large and unique, including long-chain unsaturated fatty acids. This explains why there are so many possible bioproducts that can be produced from this side-product (Figure 5). World production of tall oil is estimated at about 1.2 million tons a year, with well over 60% of that coming from the US. One of Canada's leading tall oil producers is BC Chemicals.

Tall oil is used in the shape of anionic and non-ionic surfactants in the chemical, textile and soap and detergent industries. According to Pemble Consulting⁵, the recovery, for direct sale or acidulation, of soap is one of the more consistently overlooked profit centers by modern Kraft mills. Not only does its sale as soap or after acidulation as crude tall oil (CTO) add dollars directly to the bottom line of mills, but its removal from the liquor stream prior to evaporation greatly enhances evaporator performance. Tall oil can also be used to produce macromolecules and adhesives. It is also used as a drying agent for inks and coatings.

⁴ <http://www.inspection.gc.ca/english/anima/feebet/sched4/classii4e.shtml>

⁵ <http://pembleconsulting.com/soap.html>

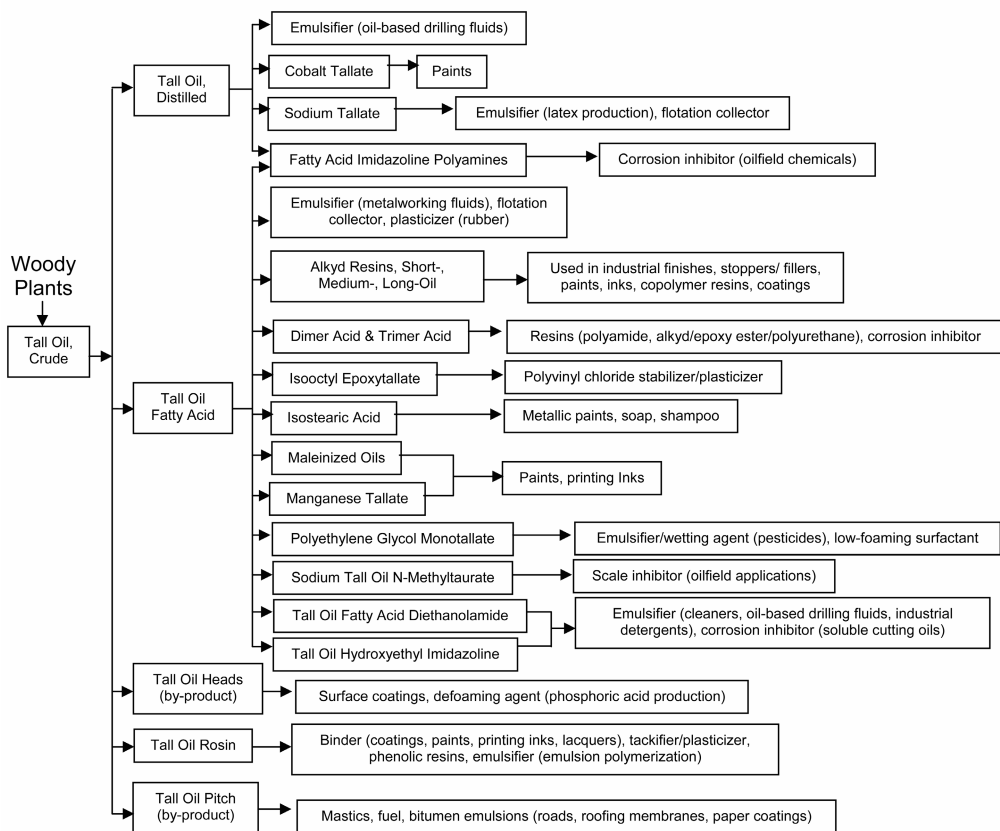


Figure 5 Bioproducts derived from tall oil

Source: Ashford 2001

Peat

Peat, or sphagnum moss, is an accumulation of partially decomposed organic matters. The decomposition is anaerobic, creating acidic compounds such as fulvic and humic acids. Peat bogs are mainly situated in the boreal forests of northern Canada, and their total area is estimated at 111 million hectares, of which only 0.02% is commercially exploited. Annually, it is estimated that 70 millions tons of peat accumulate in the Canadian natural environment (Daigle and Gautreau-Daigle 2001). Of this amount, 1.2 million tons of peat are annually utilized for commercial and industrial purpose, and Canada is a world leader in peat production for horticultural use. Total revenues of peat exploitation in Canada for 1999 were approximately of CDN\$170 million (Daigle and Gautreau-Daigle 2001). Peat is used in four main types of application:

- As fuel, traditionally in Ireland, and increasingly in Finland and Sweden;
- As soil amendments;
- As a biofilter;
- In bioremediation

No peat is used as fuel in Canada for now, unlike in Ireland or Finland. As a fuel resource, peat could be burned to generate steam in turbine generators. Its chemical proprieties could also be leveraged to produce industrial coke, synthetic natural gas and ethanol. The same thermo-chemical conversions

used for pulp and paper residues like pyrolysis, liquefaction and gasification can be used for peat. Sweden ranks high in this field of research. Its peat consumption as fuel has increased considerably: in 1998, Sweden's peat-produced energy reached 3.1 TWh (Hörnell 2001). Peat utilization as fuel could be problematic though. Wetlands, marches and peat bog are important ecosystems as they filter water in the natural environment and host a rich flora and fauna. Thus, exploiting peat for fuel could lead to damaging excesses. One thing is for sure, the environmental organizations that study peat and promote its protection, e.g., the Canadian Sphagnum Peat Moss Association (CSPMA) and the International Peat Association, will be vigilant and might protest vigorously against irrational exploitation of peat bogs. Because Canada has one of the largest amounts of peat accumulation in the world, further research on the innovative utilization of this resource should be carried out within the framework of sustainable use.

Currently, the major utilization of peat in Canada is for horticultural purposes. Although this use is clearly established, it has been losing popularity in the past few years with the advent of new substrate mediums such as rock wool. To keep up with this competitive market, researchers have used the intrinsic qualities of peat to upgrade its utilities. For example, the *Centre québécois de valorisation de la biomasse* (CQVB 1994b) supports research projects on specialized mediums such as biofertilizers, that uses peat as a medium for *mycorrhizae* culture and plant growth promoting rhizobacteria (PGPR) and use of biopesticides added to the peat-based medium.

Because of its high absorbent capacity and ion exchange proprieties, peat can be use as a biofilter for used water. Canadian company PremierTech pioneered the use of peat moss in its Ecoflo® Biofilter, where wastewater from septic tanks is clarified as it percolates down through the peat; the treated effluent is subsequently dispersed for infiltration into the native soil or discharged into a watercourse. Peat is also being developed as an air biofilter, absorbing the odours of such industries as porcine plants, distilleries, etc. Canada seems to be late in performing R&D on this trend compared to the Europeans. Finnish researchers have recently developed an air biofilter that promotes bacterial degradation of styrene in waste gases (Arnold *et al.* 1997). A few European air biofilters are in use in Quebec, and McGill University performed research on those issues (CQVB 1994a). Peat is said to be a potent filter for (K and Yang 2000) and for gases such as H₂S (Wada *et al.* 1986). The efficiency of biofilters has been evaluated at 99.9% for the absorption of heavy metals, phenols and sulphurs, 95% for oils and greases, 85% for the reduction of the chemical demand of oxygen and 65% for nitrate and phosphorus (CQVB 1994a).

Scientists at NRC's Biotechnology Research Institute argue that peat can be used successfully for bioremediation, such as for removing gasoline from contaminated groundwater. Peat has also been used as a sorbent for recovering NH₃ (Togashi *et al.* 1986) and for recovering metals from wastewater, with recovery rates as high as 94 to 98% for Mo, Pb, Ni, Fe, Mn, and Cr and 72% for vanadium (Naumova, Gorlenko and Otmakhova 1995). It is being tested to soak the acid drainage of old mines, absorb oil spills and manage liquid hog manure. Clearly, in the short term, the most promising value-added application of peat is as a biofilter and in bioremediation.

2.3 Biowaste

“so long as there is an abundant surplus of available energy running “to waste” over the sides of the mill wheel, so to speak, so long will a marked advantage be gained by any species that may develop talents to utilize this “lost portion of the stream”

Lotka, 1956

Waste can take several forms, but, conventionally, it is usually divided in solid and liquid waste. Municipal solid waste and municipal waste water are the principal forms of direct waste from humans.

It is important to note that consumers, industry and government all play a role in the development of wasteful habits. In fact, there is clearly a concomitant responsibility to waste: consumers in western countries waste a lot, so does industry, and government is often not pressing individual and corporate citizens hard enough to reduce waste. Consumers are often tempted to pay as little as possible for consumption goods. This puts pressure on industry to lower costs, and the shortest route to this goal has traditionally been to dump one’s waste in the environment. There is often an impression on the part of government and industry that cutting waste will lower the rate of economic growth and, on the part of consumers, that it will lower their living standards.

Wasting is an undignified way to treat resources considered as pure luxury two centuries ago. It probably does not make sense economically, and it certainly does not make sense from a sustainable development perspective. Waste was the forte of the last stretch of the previous millennium; in the third millennium, it should definitely not be seen as acceptable behaviour in Canada to maintain this trend.

Fortunately, there is a growing trend to reduce municipal and industrial waste because of the collective work of conscious citizens, environmentalist groups and responsible governments and companies. Figure 6 illustrates the process of increasing the value of biowaste. It is clear that waste can be fed into a value-adding cycle to serve several useful purposes. This section presents some of the means currently used to transform liabilities into assets.

Municipal liquid waste

Municipal liquid waste takes three principal forms: waste water, sewage sludge, which is also called biosolid, and landfill leachate. Wastewater treatment facilities are used to remove excrement as well as particulate, organic, bacterial, chemical and toxic materials from residential and industrial effluent waters before they are returned to surface waters such as lakes and streams. Secondary treatment of municipal wastewater often uses a biological treatment to remove dissolved organic matter from wastewater. Microorganisms are cultivated and added to the wastewater where they absorb organic matter from sewage as their food supply.

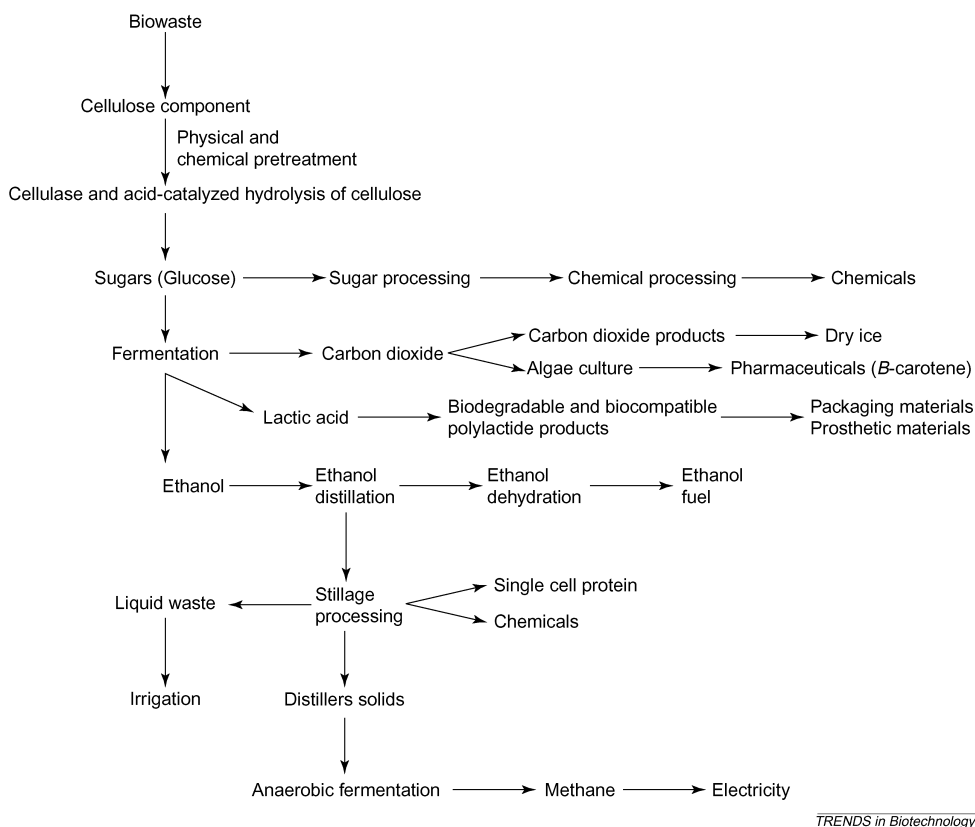


Figure 6 Development of biowaste as a resource for the synthesis of bioproducts

Source: Van Wyk, 2001

Municipal liquids contain components that can be divided into two categories: chemical components, including metals, and pathogens. Chemical components include beneficial nutrients that make sewage sludge a good fertilizer. However, sewage sludge also includes heavy metals and organic pollutants that are well known for their toxicity. Since a sizeable part of municipal liquid waste consists of human excrements, there is a potential for pathogens found in untreated sewage sludge to pose a health risk when distributed on land. Despite this, sewage sludge and municipal waste water is widely used in the US on agricultural lands, in forests and on golf courses because it presents several advantages as a soil fertilizer. For instance, sewage sludge's main advantage is its high organic content since it contains 2.8% nitrogen (N), 1.6% potassium (K), and 0.6% phosphorus (P), respectively five, three and three times those found in manure (Wang 1997)⁶. An advantage of sludge over chemical fertilizers is that sludge adds organic matter to soil thus helping to prevent soil degradation and erosion.

Where disposal by land application has become a problem, disposal of biosolids in landfill is a favoured option. A more promising solution may be to process biosolids through fermentation, thus

⁶ <http://wvlc.uwaterloo.ca/biology447/F03ass3oncamp/group3.htm>

stabilizing the bacterial component, permitting the time needed for precipitation of toxic metals, and producing a high-grade biogas that may be captured and used for co-generation. The resulting low-odour, lower-volume and biologically inert sludge may be used as a soil amendment with fewer complications. This option may be economically beneficial for municipalities, as they currently must pay for the use of land as well as shipment to the site; sale of sludge as fertilizer is currently not permitted in Canada. Furthermore, co-generation may offset the energy cost of treating an increasing volume of sludge to a higher degree.

Because of consumers' right to safe food, it appears that the safest way to dispose of municipal sludge is to use it in silviculture or in forests. Different forms of municipal liquid waste have been used in short-rotation energy forestry, in willow plantations (Hasselgren 1998) for example. They are preferably used after composting or fermentation to reduce the likelihood of pathogens leaching into the groundwater. Ideally, a process should be developed for metal removal, and it is worth exploring the possibility of using peat as a remediating biofilter for this application. Environment Canada and Health Canada could contribute to defining safety norms for the production, sale and use of sludge and its by-products.

Municipal solid waste

Municipal solid waste (MSW) is primarily waste produced by households, but also includes some commercial and industrial waste that is similar in nature to household waste and has been deposited in municipal landfill sites. MSW can be a liability if it requires disposal, but can also represent a considerable resource that can be beneficially recovered (IEA 2003). Currently, this form of biowaste is generally left to decompose in landfill, but it can also be composted; in addition, materials can be recycled and energy can be produced from the biodegradable portion.

Municipal solid waste consists of everyday items such as packaging, grass clippings, furniture, clothing, bottles, food scraps, wastepaper, appliances, paint and batteries. On average 80% of it consists of organic material, which is defined as the biodegradable portion of household refuse, market garbage, yard rubbish and animal and human waste. When the amount of organic agricultural waste, such as corn stalks, leaves and wheat straw from wheat-processing facilities, sawdust and other residues from wood mills, is also considered, this component of solid waste could be a principal resource for biodevelopment. Lignocellulosic biomass represents the primary fraction of municipal solid waste (van Wyk 2001), and this biomass can be reinserted in the value-adding cycle rather than letting it degrade and produce methane, a serious liability since it is such a potent GHG.

Landfill gas, generated at municipal waste landfill sites and containing approximately half methane and half CO₂, accounts for one-fifth of Canada's methane emissions. It has a global warming potential of more than twentyfold that of CO₂. Currently, landfill gas is either flared or used as an energy source. Flaring converts methane into CO₂, thus reducing the impact of global warming gas while simultaneously eliminating odour problems and destroying contaminants. The use of landfill gas to generate energy also presents these advantages and goes one step further by conserving non-renewable sources of energy. In 1999, 290 kilotons of methane were collected and either flared or

used to produce energy in Canada, thus reducing GHG emissions by about six million tons of CO₂ equivalent. In 1999, about 97% of the methane captured for energy purposes was used to generate electricity, with an estimated potential 670 GW/h per year (Pneumaticos 2002).

Animal waste

Animal waste is both a great asset and an enormous liability. In fact, animal waste is one of the best sources of fertilizer. It is certainly not as potent as purpose-designed chemical fertilizers but in addition to providing nutrients, it adds carbon and organic matter to soil, thus stabilizing it and fixing fix nutrients. Animal waste also helps maintain an essential flora of micro-organisms which play a key role in assisting the plant root system to assimilate nutrients. However, animal waste is increasingly considered a liability with the development of industrial-scale farming and the growth of mega-farms. These farms are not only a source of stench, they are also becoming a source of acute pollution. The fertilizers present in animal waste become a huge liability when these "resources [are] not positioned at their maximally effective location". They are also a great source of pollution for rivers and underground water. In addition, animal waste, just like human waste, is a significant source of methane, a highly potent GHG.

Importantly, there are many ways to transform these liabilities into assets. For example, animal waste lagoons can be managed using anaerobic digestion and to recover methane for energy and to produce compost and liquid fertilizers. Direct combustion and gasification of animal wastes can also produce energy while at the same time reducing solid waste (DOE and USDA 2000).

Farming is not the only source of animal waste. In particular, the meat-producing industry is a large producer of animal waste. During the later part of the last century, these wastes were sometimes re-introduced in the animal production chain with detrimental consequences such as the infamous "mad cow disease". Just as human waste should not cycle back into the human food chain, animal waste should not be used as feed for animals. It is possible to use animal fats as raw materials, and, biodiesel produced from animal fats was found to have a lower production cost than that produced from canola or soybean oils (Levelton 2002).

More research is needed to identify the optimal way to manage animal waste in a changing farming context. New models have to be designed to balance the need for organic fertilizers and the increasing dislocation of waste production, which is located in animal large-scale farming area, and for their potential use, which is located in areas with little animal production such as in cereal producing areas.

3 Bioproducts

A vast amount of products are currently produced from biological components, and the potential for new products is huge. Because of this, it is difficult to produce a clear taxonomy of all bioproducts. It is important for a national R&D strategy to set priorities that will help Canada develop a leadership position in specific fields, rather than being a low-value supplier with little or no differentiation.

This section presents bioproducts that meet a specific set of criteria, including the availability or potential availability of competitively priced biomass in Canada, market potential, and versatility. This explains why this section attributes much importance to chemical platforms. These platforms often have a double function: firstly, their base product can often be used in its basic form, e.g.: ethanol can be used directly as both a fuel and a chemical product; secondly, these products are so-called precursors, or intermediates, used in the production of other chemicals, e.g. ethanol is a precursor for ethylene glycol and acetic acid among others.

An effort was made to select chemical platforms that have synergies among themselves. For instance, methanol can be used in the production of methyl ester, another platform that could be developed in priority as part of the Canadian R&D strategy for the bioeconomy. The selected platforms include methyl ester (biodiesel); three types of alcohol (methanol, ethanol, glycol); three types of acid (lactic, levulinic, succinic); and three types of biobased gas (methane, syngas, hydrogen). These precursors provide the basic ingredients for developing not only important products such as bioplastics, but also several forms of bioenergy (biodiesel, methanol, ethanol, syngas, methane and hydrogen).

This section also presents more specific, but still versatile, biomaterials such as adhesives, lubricants, and composites, which are closer to the end-use stage. Again, the emphasis is on the availability of biomass, market potential, and versatility, which explains why they are called versatile biomaterials. These versatile biomaterials include biopesticides, inks, lubricants, paint, and varnish. Many of these products can be built in part from the platforms presented in the first section, but some are produced within specific value-adding cycles.

This section is divided in two parts. Section 3.1 examines ten platform biochemicals that provide great versatility and interconnectedness laying the base of a strong and sustainable carbohydrate economy, while Section 3.2 examines versatile biomaterials.

3.1 Platform bioproducts

Biodiesel and methyl ester – Biodiesel is a replacement for petroleum-based diesel fuel used in cars, trucks, utility vehicles, boats, locomotives, and stationary engines. Biodiesel can be obtained by several routes; one of which is called transesterification that produces methyl ester, a form of biodiesel which is also a platform chemical.

Alcohols - There are several types of alcohols (e.g.: methanol, ethanol, and glycols), which all have a hydroxyl group structure, OH, in common. Alcohols can be used for a variety of applications ranging

from fuel, beverages, and industrial solvents to chemical intermediates used for manufacturing a wide variety of chemicals and materials. Ethanol is used as an oxygenated fuel that helps reduce toxic air pollutants and increase gasoline octane numbers. Glycols are used for making antifreeze, brake fluids, and solvents, whereas sorbitol is used in adhesives (BRDB 2001).

Organic acids - Biomass can be transformed into various types of organic acids. An extremely flexible acid platform is lactic acid, because it can be used as a precursor in the production of a large number of chemicals and biobased products. Other platforms are based on levulinic and succinic acid.

Gases - There is great potential for producing various types of gas from biomass. For instance, methane is naturally produced by decomposition of municipal solid waste in landfills, but not all of it is currently used as biofuel and is therefore a liability because methane is such a potent GHG. Other gases considered here are syngas and hydrogen, two biofuels that also act as chemical platforms.

3.1.1 Biodiesel and methyl ester

Methyl ester, one of the most promising platforms, is currently used as biodiesel. Because there are other ways to produce biodiesel, biodiesel is considered a platform, with methyl ester as the core component. The traditional technology to produce biodiesel is through “transesterification”. This process combines vegetable oils, animal fats and/or microalgal oils with alcohol (ethanol or methanol) in the presence of a catalyst (sodium or potassium hydroxide) to form fatty esters (ethyl or methyl ester). Vegetable oils that can be processed into biodiesel include soybean, canola and industrial rapeseed (Harsch 1992 cited in NRC 2000). Converting triglyceride oils to methyl or ethyl esters through a transesterification process reduces the molecular weight to one-third that of the oil, reduces viscosity by a factor of eight, and increases volatility (Prakash 1998). If the reacted oils have the correct carbon chain length, the fatty acid methyl esters will have chemical characteristics similar to those of conventional diesel fuel when they combust in modern diesel engines. Methanol, for the reaction, is available from biomass, natural gas, or coal (NRC 2000).

Although methyl ester is a chemical intermediate in the production of a wide range of products (fatty alcohols; alkanoamides; alpha - sulfo methyl ester; fatty isopropyl esters; sucrose mono and polyesters; soaps; ink solvent; defoamer; plasticizers; lubricants; detergents; emulsifiers; cosmetics; pharmaceuticals), its principal use takes the form of biodiesel.

Transesterification is not the only process used to produce biodiesel. A competing approach involves simultaneous catalytic hydrogenation and cracking of vegetable and tree oils. This process was developed at the Saskatchewan Research Council, under the sponsorship of the Canada Center for Mineral and Energy Technology (CANMET). The technology has been licensed to Arbokem of Vancouver, Canada, to market the process worldwide. One of the feedstocks successfully used by the Saskatchewan Research Council in the development of a biodiesel called “SuperCetane” is tall oil, a by-product from the Kraft pulping process from pine and Douglas fir. From an economic perspective, the production cost for SuperCetane is estimated at 10 to 12 cents per litre—this

includes the capital and operating costs of a large-scale plant (Monnier 1997, cited in Prakash 1998). The cost of tall oil as raw material could range between 8 and 20 cents per litre of SuperCetane. Thus, the total cost of this product could range between 18 to 32 cents per litre, making it more economically attractive than using vegetable esters currently costing about 66 cents per litre (Prakash 1998).

The cost of biodiesel in the US has fallen from US\$4.50 per gallon in 1997 to US\$1.00 per gallon in 2001. The non-competitive price of biodiesel fuel becomes less of an issue when it is used as a blend of 20% (B20) or less biodiesel with ordinary diesel, and becomes largely irrelevant when used as a fuel additive at 0.5 to 2.0%. Original equipment manufacturers now support the use of biodiesel as a lubricant additive, provided it meets industry standards. Biodiesel fuel can be used without modification in today's diesel engines and in various blends, without adverse effects on engine performance (Hayes 1995).

Research shows that small amounts of canola biodiesel, typically less than 1% (i.e. 0.1 to 0.5%), can be used successfully as a lubricant additive, particularly in winter diesel fuel. Even these small amounts of biodiesel have produced substantial improvements to fuel efficiency (2 to 13%) and reduction in engine wear (9 to 57%). In addition, economic modeling, based on the findings of laboratory studies, has found that a large diesel truck running 250,000 km per year using a 0.5% canola biodiesel lubricant additive would result in almost \$4,000 per year in net economic savings for the owner, based on a 4% improvement in fuel economy and reduced engine wear of 50% (Hertz *et al.* 2001).

Consideration of emissions is particularly important in urban areas suffering from poor air quality. The use of biodiesel provides important environmental benefits, such as the virtual absence of sulphur and aromatic compounds in biodiesel (Abbe 1994). The use of biodiesel in diesel engines (B20 blend) also reduces the emissions of particulate matter (PM), carbon monoxide (CO), and gaseous hydrocarbons (HC), but increases the emissions of nitrogen oxides (NO_x). In the case of particulate emissions, the insoluble fraction decreases while the soluble fraction increases, with a net reduction in total particulate matter (soot). In fact, research has shown that biodegradation of biodiesel in an aqueous solution is much faster than for diesel fuel. Even a B20 blend degrades twice as fast as conventional diesel. This attribute of biodiesel is especially attractive for marine applications in environmentally sensitive waters. Due to its lower particulates and toxic emissions potential, biodiesel is also considered a desirable fuel for diesel engines in underground mines (Prakash 1998).

Canada grows canola in the west (Alberta, Saskatchewan, and Manitoba) and soybeans in the east (Ontario and Quebec). In 2002, canola was planted on 2.8 million hectares and used to produce almost a million tons of oil. Despite the large canola oil output, the use of canola biodiesel as a total fuel replacement is not practical. To satisfy current highway transport diesel fuel requirements, it would require 11 times the acreage of all the canola grown in Canada to replace the diesel fuel used (Hertz *et al.* 2001). According to Prakash (1998), Canada has the potential to produce 385 million litres of biodiesel per year, which amounts to roughly 2% of the current annual diesel consumption of about 19 billion litres. If a biodiesel industry develops in Canada in the short run, it will likely

focus on B100 in eco-sensitive environments such as waterways, on B20 blends in certain niches such as for government fleets, and on fuel additives of less than 2% to prolong engine life.

3.1.2 Methanol

Methanol (CH_3OH) is the simplest of all alcohols. It is used to produce formaldehyde (used in plastics, germicides and fungicides) and other chemicals, including anti-freeze and solvents. It is also used as a high-performance fuel for jets. More than 12 billion pounds of methanol are produced annually in the US, and while some is used as is, most of it is converted into higher value chemicals such as formaldehyde (37%), methyl tertiary butyl ether (28%), and acetic acid (8%) (Paster, Pellegrino and Carole 2003).

Pyrolysis is a well-established thermo-chemical technology that uses “destructive distillation” to convert biomass into useful chemicals and fuels. High temperature and limited air, sometimes in the presence of a catalyst, yield primarily hydrocarbon liquids and a smaller quantity of gases and char. Major product yields following liquid pyrolysis can vary from 25 to 70 percent of inlet raw materials. However, despite earlier optimistic projections, no large-scale methanol manufacturing plant currently relies on destructive distillation, because most methanol production uses the lower-cost method of chemically oxidizing natural gas (NRC 2000). An increase in natural gas prices may encourage the development of alternative processes such as biomass gasification to syngas, and subsequent conversion to methanol (Paster, Pellegrino and Carole 2003).

It is important to note that Swedish researchers have calculated that the black liquor residue from pulp mills could be gasified, then catalytically converted into methanol. Black liquor has the great advantage as a bioenergy raw material, in that it is already partially processed and is in a pumpable, liquid form. The proposed process gasifies concentrated black liquor to produce a synthesis gas. After clean-up, this gas would be reacted in the presence of metallic catalysts to produce methanol (Lindblom and Berglin 2001). A single 1000 ton per day pulp mill could produce approximately 266 million litres of methanol per year. This amount approaches the total amount of ethanol produced in Canada at the present time from all sources. Canada has a very large black liquor solids production—about 24 million tons per year. The potential production of alcohol from this resource could also be very large—on the order of 10 billion litres of methanol per year (CARC 2003).

During the 1980s, Enerkem Inc. developed an interesting gasification process. The process is based on a bubbling fluidized bed gasifier, containing a bed of silica or alumina capable of operating up to 1.6 MPa. From 1984 to 1988, extensive oxygen-blown biomass gasification tests were conducted in a 10 t/hour demonstration plant located at St-Juste de Breteuil in Quebec, to produce synthesis gas for methanol production. Air blown atmospheric gasification tests were also conducted for evaluating cogeneration. The BIOSYN process validated the technical feasibility of gasifying biomass from forest and agricultural residues (IEA 2000).

3.1.3 Ethanol

Ethanol ($\text{CH}_3\text{CH}_2\text{OH}$), also known as grain alcohol, is a colorless liquid that is the product of fermentation used in alcoholic beverages, industrial processes, and as a fuel additive. As an oxygenate, it is an important chemical, because it can serve as a precursor to other organic chemicals required for producing paint, solvents, clothing, synthetic fibres, and plastics. In particular, ethanol can be dehydrated to produce ethylene, the largest petroleum-based commodity chemical (see Figure 7). Ethylene is perhaps the most important petrochemical, because it acts as a precursor to many other industrial chemicals including polyethylene, ethylene dichloride, vinyl chloride, ethylene oxide, styrene, vinyl acetate, and acetaldehyde (Crawford 2000). Ethanol can be made from crude oil and natural gas, as well as from biobased sources, agricultural feedstocks (including cane, beet, maize and cellulose), agricultural residues (such as cereal straws and corn stalks), and forest biomass and wood waste.

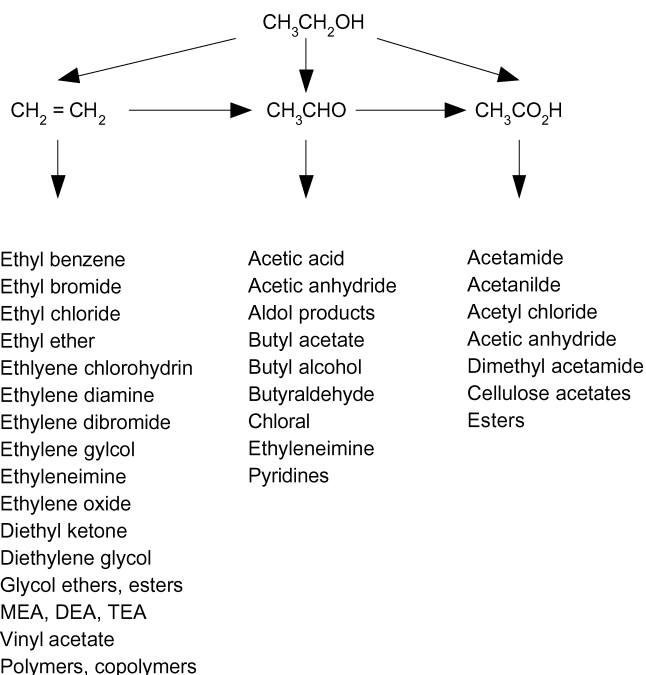


Figure 7 Production of commodity organic chemicals from ethanol

Source: (PRA/CANUC 2002g).

Canada currently produces about 175 million litres of fuel ethanol. Industrial ethanol production is in excess of 60 million litres. Canada's total production capacity is roughly 240 million litres. Actual fuel ethanol consumption is 240 million litres including net imports, or about 7% of the total volume of gasoline sold in Canada. As part of the federal government's Action Plan 2000, the government is committed to increasing ethanol production in Canada by 750 million litres by 2010. That would result in 25% of Canada's gasoline supply containing a 10% ethanol blend (PRA/CANUC 2002d). Without creating a serious conflict with other uses, the total amount of agriculturally produced ethanol in Canada would be about 2.8 billion litres, with a total GHG reduction of 4.24 million tons of carbon dioxide equivalents. By comparison, total Canadian gasoline consumption in 2000 was 38 billion litres.

The retail distribution system for Canadian ethanol is evolving. There are now about 1,000 ethanol refuelling stations in Canada serving the four western provinces, Ontario, and Quebec. All automobiles manufactured since 1970 can use a blend of 10% ethanol and gasoline without requiring engine modifications. This helps to simplify the retailing of ethanol blends (PRA/CANUC 2002d).

Ethanol can be produced both biotechnologically and synthetically. The ultimate process for producing ethanol from plant material must use all of a plant's carbon: polysaccharides, fats, proteins, and lignin. Currently, many producers use concentrated acid or dilute acid hydrolysis technology. A combination of a physical and/or chemical process with a chemical or biological process is needed. An example might be gasification followed by biological/enzymatic or chemical catalytic conversion to ethanol (Hardy 2002). Conversion to hydrogen for fuel cells is another possibility, and a thermo-chemical process is yet another related approach (Kuester 1998).

Currently, most of the ethanol produced in Canada is made from corn grain. The cost of producing ethanol from corn is significantly more expensive than the price of gasoline; however, it is being reduced by the adoption of technology such as very high gravity fermentation. In addition, there are other feedstocks that are potentially cheaper—Tembec, located in Quebec, is currently producing ethanol from pulping liquors. Saskatchewan is planning to open large-scale plants based on the fermentation of wheat. Iogen, located in Ontario, is proposing to produce alcohol from lignocellulosic contents. CARC proposes to explore producing ethanol from black liquor using a gasification process. The potential total production of ethanol from black liquor solids was estimated at 7.3 billion litres per year (CARC 2003).

Some researchers see ethanol being produced more cost-effectively using enzymatic hydrolysis. Currently, the key barrier, and greatest potential for cost reduction, to enzymatic hydrolysis is the high cost of cellulase enzymes. Cellulase enzymes with higher specific activities than currently produced cellulases are required to meet future cost reduction objectives of a biomass-to-ethanol industry⁷. Another ethanol production method developed in the US is based on an advanced bioreactor called simultaneous saccharification and fermentation (SSF) reactor. This reactor can produce ethanol from mixed waste paper, agricultural waste and pulp and paper mill waste. The SSF reactor combines enzymatic and fermentation steps in one process unit using novel recombinant strains of bacteria (NRC 2000).

Stumborg (2002 cited in CARC 2003) estimated that, for every million litres of ethanol produced, the use of cereal residues as the feedstock would reduce GHG emissions by 2.25 million tons of CO₂ equivalents, while the use of cereal grain as the feedstock would reduce GHG emissions by 1.5 million tons of CO₂ equivalents. Additionally, Stumborg calculated that ethanol produced from corn grain reduces GHG emissions by 1.5 kg/l of ethanol, when used in a 10% blend in gasoline. When all the effects on energy and GHG are taken into account, a vehicle using a 10% ethanol blend emits about 3.9% fewer total GHG than a vehicle using gasoline as a fuel. By 2010, it is expected that a vehicle fuelled by a 10% ethanol blend will emit approximately 4.6% less GHG per kilometre driven than a vehicle using gasoline only (Levelton 1999 cited in CARC 2003). There are other benefits. Emissions of volatile organic compounds (VOCs) react with nitrogen oxides in sunlight to form ground level ozone, the cause of smog. Because ethanol contains oxygen, it reduces smog and local

⁷ http://www.ott.doe.gov/biofuels/research_partnerships.html

air pollution. According to the US Environmental Protection Agency (EPA), every 1% increase in oxygenate use decreases toxic emissions by 4.5% (OECD 2001).

Currently, the development of ethanol production is supported by the National Biomass Ethanol Program, a \$140 million program funded by Agriculture and Agri-Food Canada (AAFC) that aims to encourage firms to invest in the Canadian ethanol industry and encourage the production and use of renewable fuels where it is environmentally sound and economically viable. Even though there is already some support for production of ethanol, there is room to carry out R&D to develop more economical production methods, as well as ways to integrate ethanol into the biorefinery concept, thus using this alcohol as a chemical precursor rather than simply as a fuel.

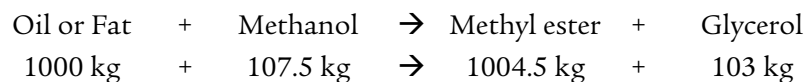
3.1.4 Glycols (polyols)

Glycols comprise a family of widely used chemicals: glycerol, ethylene glycol, polyethylene glycol, propylene glycol, polytetramethylene ether glycol, and 1,4-Butylene glycol (1,4-Butanediol). Glycol derivatives include a number of polyester resins and copolymers, polyethers, and alkyd resins. In 1999, a combined 7 billion pounds of glycols were produced in the US. The antifreeze market is essentially flat, but others, such as the non-ionic detergent and polyester markets are growing rapidly. There is a lack of new capacity for both ethylene and propylene glycol, and it has been estimated that supplies could be short as soon as 2003 or 2004. This could be fortuitous for the entrance into the market of biobased glycol. The Pacific Northwest National Laboratory in the US is developing a cost-competitive biobased route to propylene glycol, which could also be modified for the production of ethylene glycol and glycerol. This process is based on the catalytic hydrogenolysis of sorbitol. Process development is nearing completion and could be used to generate new capacity (Paster, Pellegrino and Carole 2003).

Although glycols are mainly derived from hydrocarbons, they can also be derived from biomass sugar, starch, and acids; for example, from glucose, sorbitol, and lactic acid. For instance, current production of propylene and ethylene glycol is petroleum-based. Propylene glycol is a commodity chemical with a US production of about 1.1 billion pounds per year. It is currently produced by hydrating propylene oxide with small amounts of di- and tripropylene glycols. Although it is possible to convert lactic acid to propylene glycol, it is also possible to thermo-chemically produce it from sugars such as glucose, sorbitol, xylose, and arabinose. The thermo-chemical sugar process is more advanced and is projected to be cost-competitive with the petroleum-based propylene process. Production of propylene glycol from lactic acid may also be a viable route (Paster, Pellegrino and Carole 2003)

Glycerol is the by-product of many processes involving animal or vegetable lipids. It is currently used in cosmetics, toothpastes, pharmaceuticals, food, lacquers, plastics, alkyl resins, tobacco, explosives, and cellulose processing. The reactions used to produce glycerol—hydrolysis, transesterification, dehydration, and hydrogenation—depend on the feedstock. For instance, in the transesterification of vegetable oils, a triglyceride reacts with an alcohol in the presence of a strong acid or base, producing a mixture of fatty acid alkyl esters and glycerol (Schuchardta, Serchelia and Matheus Vargas 1998).

Glycerol is a waste co-product in the production of biodiesel by transesterification. A stoichiometric material balance yields the following simplified equation (Prakash 1998):



According to Crawford (2000), there is currently an oversupply of glycerol. With its price on world markets falling since 1995, there is a need to find new applications. France, the largest biodiesel producer in the world (250,000 tons/year) and generating about 25,000 tons of glycerol annually, is a world leader in glycerol research. Some of the new glycerol applications they have been researching include:

- a substitute for corn gluten in pork and poultry feeding;
- microbial conversion to 1,3-propanediol, which can substitute ethylene glycol in polyesters;
- a polyglycerol or polyglycerol ester with applications to niche markets such as offshore oil drilling, decontamination of polluted soils, agricultural adjuvants, and metal working fluids;
- a substitute for polyurethanes;
- creation of surfactants from press cake;
- a substitute for polyethylene glycol as a wood preservative; and
- creation of new molecules like dihydroxyacetone, which is used in cosmetics, and glycerol carbonate, which could be used as a VOC-free reactive solvent in the paints sector.

An important route to consider is that of seeing the production of biobased chemicals in a system and consequently bringing the concept of co-products to the fore. For instance, a company called Bioriginal Food and Science Corporation is coupling biodiesel manufacture with the synthesis of conjugated linoleic acid (a desirable nutraceutical), using glycerol (a by-product of biodiesel production) as the solvent for the process (Crawford 2000).

3.1.5 Lactic and polylactic acid

Lactic acid ($\text{CH}_3\text{CHOHCOOH}$) is a colorless acid that is prepared by extracting carbohydrates such as starch and glucose from various feedstocks including corn, cane sugar, and whey or from lactose in milk.

Approximately 72 million pounds of lactic acid are used annually in the US, primarily in food and beverages, and about 5 million pounds of lactic acid containing polymers were produced in 1998. Lactic acid has also been used to some degree in biodegradable polymers and as an electroplating bath additive, mordant, and textile and leather auxiliary (Ashford 2001). It is estimated that the lactic acid platform has a potential world market of 3-4 billion pounds. The potential market grows substantially when taking into account intermediate and derivative chemicals. For instance, the estimated world market for polylactic acid exceeds \$10 billion dollars (PRA/CANUC 2002g). Researchers are currently examining the possibility of using lignocellulosic residues, energy crops such as corn stover, wheat straw, alfalfa and switch grass, and other residues such as potato processing waste. Lactic acid can also be synthesized by hydrolysis of lactonitrile (CARC 2003).

Commonly used in the preparation of cheese, sauerkraut, soft drinks, and other food products, in addition to its role as an acidulant in chemicals (salts, plasticizers, adhesives, pharmaceuticals), as a mordant in dyeing wool, as a general-purpose food additive, and as a product in the manufacture of lactates, lactic acid is also a starting compound for polymers and biodegradable plastics. There are many potential derivatives of lactic acid, some of which are new chemical products and others that represent biobased routes to chemicals currently produced from petroleum. These include food additives, amino acids, lactate ester solvents, acrylic acid and polyacrylic acid, propylene glycol, propylene oxide, epoxides, polyurethanes, polycarbonates and polyesters (see Figure 8).

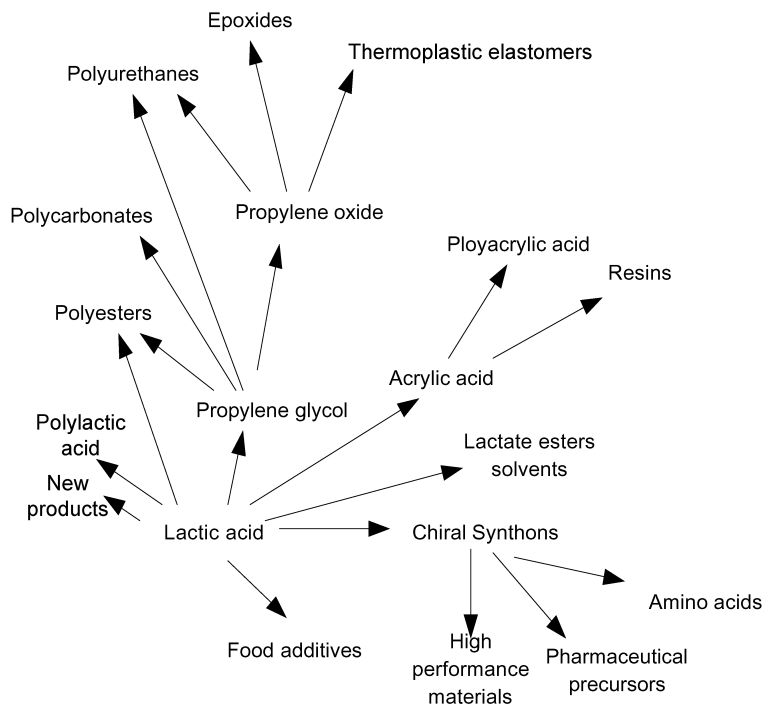


Figure 8 Products of the lactic acid platform
Source: (PRA/CANUC 2002g).

One of the most promising derivatives of lactic acid is polylactide (PLA), a recyclable and biodegradable thermoplastic polymer. In April 2002, Cargill Dow LLC started up their first large-scale PLA plant in Blair, Nebraska. The plant has a 300 million pound capacity and demand for NatureWorks™ PLA has been so strong that Cargill Dow is likely to begin construction of a second plant within a few years. PLA is cost-competitive and offers performance properties equal to or greater than those offered by conventional polymers. It requires 30-50% less fossil fuel to produce than conventional petroleum-based polymers. When it reaches the end of its life, PLA can be melted down and re-used or composted.

3.1.6 Levulinic acid

Levulinic acid is one of the platform chemicals that have developed a special interest in the US. Levulinic acid is produced by acid hydrolysis of waste cellulose. It can then be converted into a

number of products. The most promising is clearly delta-amino levulinic acid (DALA). DALA is a broad-spectrum biodegradable herbicide and pesticide produced from lignocellulosic materials such as waste paper. Another important product is methyltetrahydrofuran (MTHF), which is produced through hydrogenation of levulinic acid and used as a fuel oxygenate and octane enhancer. Uses are not limited to those two products, and they include the production of plasticizers and succinic acid, which is itself another platform chemical that can be converted into a number of products. Levulinic acid can also be converted into diphenolic acid (DPA) and used as a monomer for polycarbonates and epoxy resins, as a component in decorative finishes and as a brominate in fire retardants and environmentally-friendly marine coating (CARC 2003; PRA/CANUC 2002g).

Currently, the major obstacle to the commercialization of levulinic acid is its production cost. The projected production cost is US\$0.20 per pound, with research in the US aiming to lower that cost to between US\$0.04 and 0.10 per pound. After this is achieved, and if the development of DALA and MTHF is successful, the market demand for levulinic acid is expected to move from the current 1 million pounds per year (at US\$4 – 6 per pound) to 200-400 million pounds per year. Including other potential derivatives, some experts say the market could even reach 1 trillion pounds a year (CARC 2003).

R&D activities on levulinic acid are almost exclusively focused on MTHF and DALA. These are done by consortia in the US. For example, Biofine (now BioMetics, Inc.), in partnership with Chemical Industry Services, the National Renewable Energy Laboratory, the Pacific Northwest National Laboratory, and New York State is working on bringing DALA from a pilot plant to a commercial level. The company is also working on producing levulinic acid from paper mill wastes and on setting up demonstration plants. It received the US Presidential Green Chemistry Award in 1999 for a process transforming cellulose into sugars and then into levulinic acid (CARC 2003).

3.1.7 Succinic acid

Succinic acid is an intermediate chemical that could be used in the manufacturing of plastics, clothing fibres, paint, inks, food additives, automobile bumpers, and other products. Additional markets include salts, esters, and succinic acid itself. The US market for these chemicals exceeds US\$1.3 billion per year and is expected to expand by six to ten percent per year (DOE 1999).

Succinic acid and its salts form a platform from which many chemicals can be produced. Industrial succinic acid is currently produced from butane through maleic anhydride, and food-grade succinic acid is produced through older fermentation and separation technology. Both routes are costly, which has limited use of succinic acid in specialized areas. Consequently, the world market is small at 33 million pounds per year. In 1992, fermentation production costs for succinic acid ranged from \$1.50 to \$2.00 per pound. Advances in fermentation, and especially separation technology for the biobased route, have reduced the potential production costs to about \$0.50 per pound (Paster, Pellegrino and Carole 2003). The development of plant-derived succinic acid lags behind lactic acid by about 5-7 years. The economics is still a barrier because it has to compete against maleic

anhydride which can be produced from low-cost butane for \$0.40/kg and then hydrogenated to succinic acid for between \$0.05-\$0.10/kg (CARC 2003).

Ongoing and future advances could significantly reduce the cost of biobased succinic acid. In particular, the US Department of Energy is financing research on the use of a new strain of *E. coli* bacteria (AFP111) to ferment sugars derived from wood wastes and plant crop residues. The microorganism's metabolic pathways were genetically engineered to convert different types of sugars very efficiently to produce succinic acid. The result would be a significant reduction in the use of petroleum resources. In addition to the energy savings that accrue by substituting biomass for imported petroleum, carbon dioxide is "fixed" in the fermentation process, providing the potential to reduce GHG emissions during chemical production (DOE 1999).

Commercialization of these low-cost routes would have a significant impact on the demand for succinic acid, expanding current markets, as well as opening new markets for the acid and its derivatives. It is anticipated that the new low-cost biobased technology will be commercialized within the next one to three years. The real promise of succinic acid lies in its derivatives (see Figure 9).

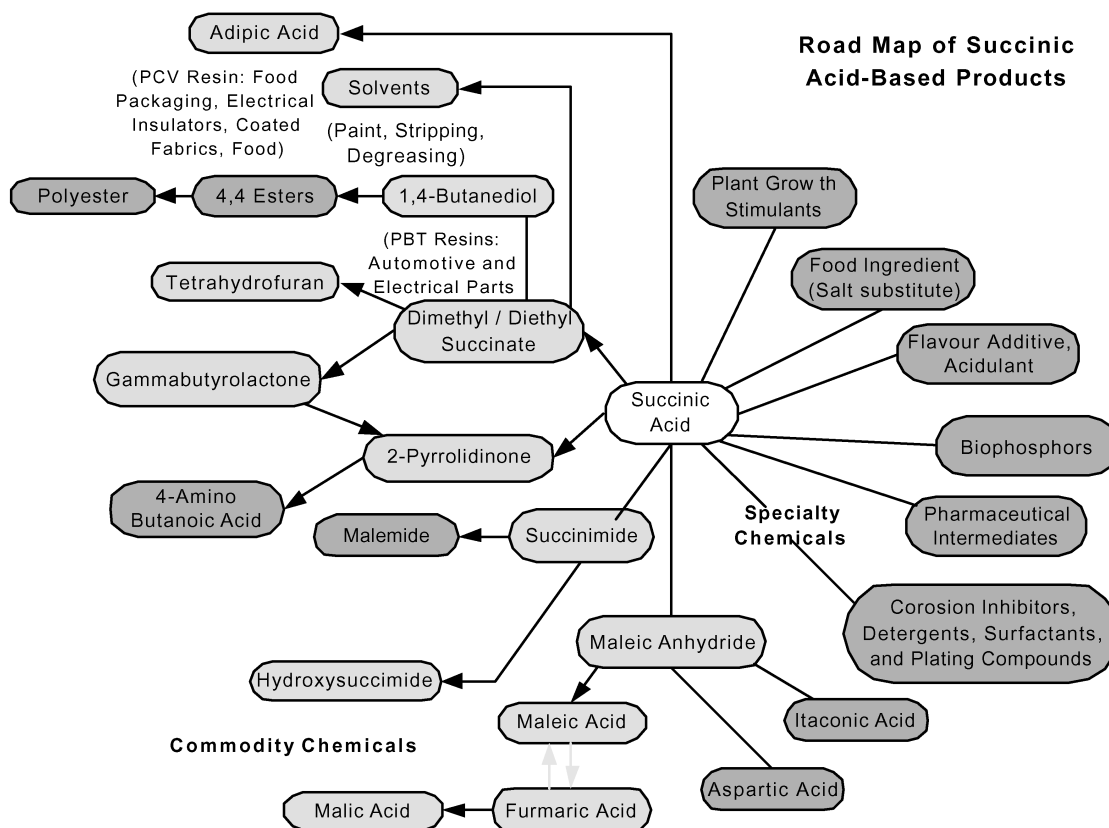


Figure 9 Products of the succinic acid platform
Source: (PRA/CANUC 2002g).

3.1.8 Synthetic gas (syngas)

A very promising avenue for the use of biomass for energy and chemical feedstocks is the production of synthetic gas, commonly called syngas. Gasification uses high temperatures and oxygen to transform solid carbonaceous material into a mixture of mostly gas and a small amount of liquid for use as fuels, chemical feedstocks and power (Paster, Pellegrino and Carole 2003). An advantage of the gasification process is that it can, in principle, convert nearly all the biomass feedstock into syngas, even those components that are difficult to process by chemical or biological means, such as residues. Gasification provides a means to optimize biorefinery operations by utilizing residues or waste streams that might otherwise be land-filled or used for low-value products (DOE 2003a).

Syngas is a mixture of carbon monoxide, carbon dioxide, hydrogen, methane, and water vapour, which can contain unwanted mineral components, particulates and tar. After biosynthesis gas is cleaned of tars and other unwanted materials, syngas can be used to produce (BRDB 2001):

- Electricity: Biosynthesis gas can be used in advanced turbines or fuel cells to produce electricity at more than twice the efficiency of today's combustion systems. By using gasification technology to replace aging power and heat-generating equipment, the US pulp and paper industry could become energy self-sufficient and could even be a net producer of up to 30,000 megawatts of electricity by 2030.
- Alcohols: One such alcohol is methanol, which is used in antifreeze solutions, formaldehyde (used in plastics, germicides and fungicides) and other chemicals and as a high-performance fuel.
- Acids: These include acetic acid, which is used in photographic films, textiles, vinyl plastics and polyesters.
- Clean hydrocarbon fuels: Using the Fischer-Tropsch process, synthesis gas is reacted on a catalyst to make gasoline and diesel fuels. When this process is used with biosynthesis gas, it produces fuels that are sulphur-free.
- Other products: This includes many products currently made with fossil resources, including some plastics.

Syngas can serve as a fuel to produce power, as a source of hydrogen for hydrogen fuel cells, and can also be converted to valuable chemicals and fuel. Fischer-Tropsch chemistry offers flexibility for converting syngas to valuable chemicals and fuels such as paraffin, mono-olefins, aromatics, alcohols, aldehydes, ketones, and fatty acids (see Table III). Other technologies that use syngas include the biological conversion of syngas to acetic acid or methanol. The DOE Industrial Technologies Program is supporting a project to convert reformed natural gas to acetic acid. This route, which requires less energy than the thermo-chemical process, would have to produce acetic acid with a selling price between US\$0.42 and \$0.46 per pound to be cost-competitive with the current petroleum-based route (DOE 2003b).

Table III Potential Fischer-Tropsch products from syngas

Product	Current Applications	Market (M lb)	Price (\$/lb)
Methane (SNG)	Uses: heating fuel, fuel gas (electricity/steam generation) Derivatives: multiple	7 x 10 ¹⁰ (18,986,745 Mcf)	\$0.11-0.19
Propane	Uses: Aerosol propellant, fuel gas, refrigerant, process solvent Derivatives: ethylene, propylene, and others	397 (93.6 M gal)	\$0.06-0.12
Butane	Process solvent Derivatives: 1,4-butanediol, maleic anhydride, acetic acid, acetone, acetylene, n-butyric acid, formic acid, isobutene, methyl formate, propionic acid	15,654 ¹ (3,242 M gal)	\$0.15
Methanol	Uses: solvent Derivatives: formaldehyde, methyl tertiary butyl ether, acetic acid, other chemicals	12,180	\$0.08-0.11
Ethanol	Fuel, solvent	11,682	\$.012-.018
Isobutanol	Use: extraction agent Derivatives: multiple	116r	\$0.30-0.50
Dimethyl ether	Aerosols	10-80	~\$1.00-25.00
Methyl acetate	Derivatives: multiple	645	\$0.60>
Dimethyl carbonate	Methylation/phosgenation reagent, oxygenate	95>	>\$0.74
Gasoline	Fuel	804,043 (127,416 M gal)	\$0.10-0.19 ²
Diesel	Fuel	393,634 (56,638 M gal)	\$0.09-0.14 ²
Paraffin waxes	Barrier/antiblocking/heat sealing agent (hot melt adhesives), casting wax, electrical insulation, floor/shoe/car polish, plastics processing lubricant, rubber compounding	666	\$0.23-0.25

Source: DOE 2003b

Syngas can serve as the basis for production of methane and hydrogen, but it is also worth examining more direct routes to producing these gases from biomass.

3.1.9 Methane

Methane (CH₄) is a large contributor to GHG emissions; it is estimated to have 21 times the warming potential of carbon dioxide. In this context, it is not surprising to find several methods of capturing methane from landfills and from animal manure. This is a clear case of transforming a liability into an asset. Indeed, methane is an important component in natural gas and has an intrinsic value as a fuel, but it can also be used to produce several chemicals including methanol and ethanol. This explains why, in addition to capturing methane from waste, there are also some methods to extract this gas from biomass such as the gasification of straw, wood, and other feedstock.

Landfill sites account for 26% of man-made methane emissions from Canadian sources. Landfill gas contains about half CO₂ and half methane. To obtain methane, it is necessary to separate these two gases, which in turn means two separate sources of revenue: commercial CO₂ and pipeline-quality methane. CO₂ obtained from landfill gas can be processed to high-purity (food grade) liquid CO₂, and can be used for coalbed, oil and gas enhancement; wastewater treatment; dry cleaning; the production of dry ice; or to promote plant growth in greenhouses. Conversely, landfill methane can

be converted to methanol and ethanol for use as a chemical feedstock or to be used in hydrogen production or as a vehicle fuel or fuel additive (DOE 2003b).

Fuel cells can run on hydrogen produced from the methane content in landfill gas and use oxygen from the ambient air. Landfill gas cleanup is an important issue, as fuel cells employ catalysts that could be fouled by trace compounds in landfill gas. Some landfill sites use micro-turbines, a derivative of the much larger combustion turbines employed in the electric power and aviation industries. Both fuel cells and micro-turbines generate a significant amount of thermal energy that can be easily captured for use (i.e.: hot water/steam), thus increasing the total efficiency of these units (DOE 2003b).

A recent study for Environment Canada calculated that the potential for reducing GHG emissions from methane, by capturing and using landfill gas, was about seven million tons of equivalent CO₂ per year over the next 20 years. Suncor, in cooperation with Conestoga-Rovers, has announced a major program to capture landfill methane gas to generate electricity. In addition, biogas is routinely produced at a number of sewage treatment plants across Canada (CARC 2003).

Commercial pilot studies in Manitoba show that using straw as a raw material in a close coupled gasification and combustion system offers cost savings for heating barns and small commercial buildings. Such a system may be of interest to locations where straw and other bioresources are abundant and inexpensive (CARC 2003).

There have been many studies on methods to produce biogas from digestion of animal manures. Capital costs and performance in cold weather are problems currently being investigated. Helwig *et al.* (2002) described a number of anaerobic digestion systems tested in Canada. Masse and Croteau (1998) are studying sequencing batch bioreactor systems, which can operate at lower temperatures than mesophylic or thermophylic systems. Preliminary results indicate that anaerobic digestion of livestock manure in eastern Canada had the potential to reduce GHG emissions by 1.2 million tons of equivalent CO₂ per year (CARC 2003).

3.1.10 Hydrogen

Hydrogen gas has often been cited as the ultimate clean fuel: energy is released by burning it, and the only product of combustion is water—no carbon dioxide is released. In addition, hydrogen is a flexible gas that can be used directly as a fuel. It can also be used to produce electricity with fuel-cell technology and is widely used in the chemical industry. Hydrogen can be generated from agricultural and forest feedstocks as well as from landfill. For instance, as of July 2003, there was a study to investigate the production of hydrogen from a landfill in Florida for NASA's Kennedy Space Flight Center (i.e.: fuel for the Space Shuttle) (DOE 2003b). Advances are required in gasification, pyrolysis, and fermentation technologies to produce hydrogen from biomass crops, plant residues, and animal and human waste (DOE 2002). At least six process families can be used to produce hydrogen from biomass (see Figure 10)

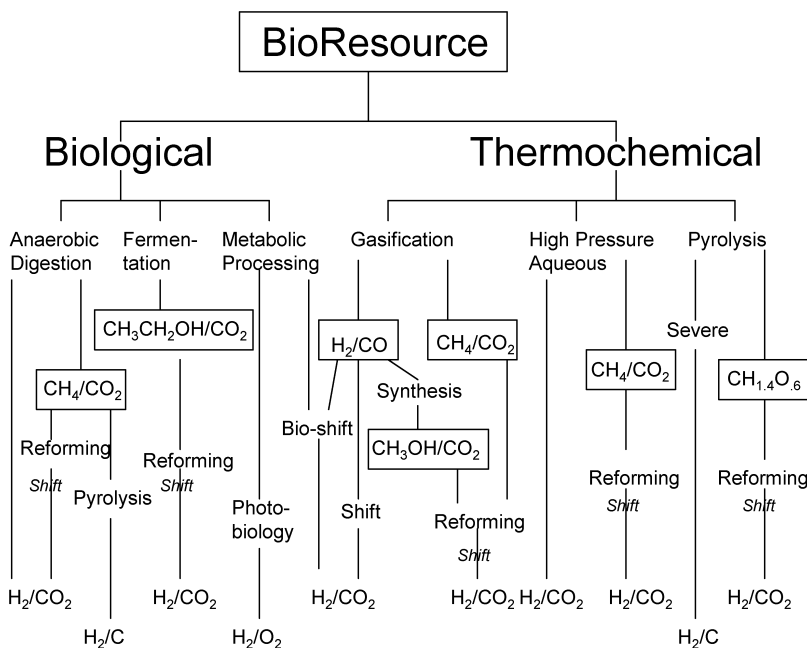


Figure 10 Pathways from biomass to hydrogen.

Source: Milne, Elam and Evans 2001.

Chum and Overend (2001) describe three types of biological process:

- Algal hydrogenases that evolve hydrogen at a rate that is four times that of the wild type and that are three to four times more oxygen tolerant (Ghirardi, Togasaki and Seibert 1997; Seibert *et al.* 1998).
- Photosynthetic organisms with light harvesting, chlorophyll-protein complexes that effectively concentrate light and funnel energy for photosynthesis. These cells showed photosynthetic productivity on a per chlorophyll basis that was six to seven times greater than normally pigmented cells (Melis *et al.* 1998), a phenomenon that could lead to significant improvements in the efficiency of hydrogen production on a surface-area basis. Various reactor designs are under development for photobiological hydrogen production processes single-stage vs. two-stage, single organism vs. dual organism (Szyper *et al.* 1998).
- Systems to convert CO found in synthesis gas to hydrogen via the so-called water-gas shift reaction ($CO + H_2O = CO_2 + H_2$) at ambient temperatures. Microorganisms isolated from nature are used to reduce the level of CO to below detectable levels (Maness and Weaver 1997; Weaver, Maness and Markov 1998). According to Chum and Overend (2001), this process has significant potential to improve the economics of hydrogen production when combined with the thermal processing of biomass or other carbon-containing feeds.

Biomass can be converted into hydrogen through thermal gasification processes, and hydrogen could then be used in a fuel cell. Researchers have calculated that about twice as much transportation energy (GJ/ha/year) could be achieved by gasification of wood to hydrogen compared to enzymatic hydrolysis of wood to ethanol. In addition, twice the transportation services (vehicle kilometres per hectare of biomass raw materials per year) could be obtained by using hydrogen in a fuel cell, as compared to using it as a fuel for an internal combustion engine. These two efficiency

elements combined mean that converting wood to hydrogen provides 4.3 times the transportation services than ethanol produced from wood (Reddy *et al.* 1997 cited in CARC 2003).

Micro-organisms have long been known to be prodigious hydrogen gas producers, and the question has been raised as to whether it makes economic sense to attempt to produce hydrogen gas for fuel via biotechnology. Anaerobic bacteria are the main agents of hydrogen production in nature, and two different sorts of enzyme systems that produce hydrogen gas have been described: hydrogenases and nitrogenases. Under anaerobic conditions, bacteria often get rid of excess electrons by a hydrogenase-catalyzed reduction of protons to hydrogen gas. However, in terms of energy, this process is slightly unfavourable, and, in nature, only relatively small amounts of hydrogen are usually released via this mechanism. Nitrogenases, on the other hand, are responsible for much larger amounts of hydrogen production, even though the primary function of these enzymes is believed to be nitrogen fixation. It appears that one molecule of hydrogen is produced for each molecule of nitrogen that is fixed (OECD 1998).

Of special interest to biotechnologists are the photosynthetic nitrogen-fixing bacteria, which can use solar energy to drive the production of hydrogen. Some of these organisms obtain the electrons required from organic waste, while others are capable of splitting water. Several processes are currently being examined, especially in European and Japanese laboratories, in attempts to combine biotechnology and engineering in ways that will produce useably pure hydrogen at low cost. Each has many challenges to overcome before it can compete with the physical and chemical sources of hydrogen (OECD 1998).

3.2 Versatile biomaterials

The biomaterials and bioproducts identified in this section have an important market and can usually be put to several uses. These are not single products; rather, each represents a family of products that takes a wide variety of forms and uses. These versatile biomaterials are:

- adhesives and resins;
- composites;
- lubricants;
- pesticides;
- fertilizers;
- plastics.

3.2.1 Adhesives and resins

Feedstock for biobased adhesives include starch, protein, fats, lipids, and complex carbohydrates, all of which are found in abundance in Canada. More specifically, wheat, barley, canola, flax, soybeans, corn, field peas, and more are all candidates. As much of the R&D on bio-adhesives has been performed in the US, the raw materials of choice have been corn (as a starch source) and soybean (as a protein source). Equally effective adhesives may also be produced from wheat, field peas, barley starch, other starchy crops, and protein from these and/or other plant or animal sources. In fact, waste streams of plant and animal processing can be used as either a primary source of raw material or, in some cases, a low-cost adjunct in adhesive formulations (PRA/CANUC 2002a). In contrast to previous studies (PRA/CANUC 2002a), Science-Metrix suggests to not invest too many resources on corn- and soy-based adhesives in the Canadian context. There are at least two good reasons to avoid this route: the US has a head start in those fields, and corn and soybeans are not crops where Canada has a clear competitive advantage, relative to our champion crops (wheat, barley, and canola).

The market for adhesives is rather modest when compared to the fuel ethanol industry. However, the use of vegetable fractions or animal by-products as starting materials for adhesives could provide an important end-use that would add to the overall viability of the processing industry and ultimately to the returns for the farming community (PRA/CANUC 2002a). Additionally, the development of biocomposites and the increased use of agricultural and forest residues in engineered lumber will increase the demand for adhesives and resins.

As for resins, they are used in a variety of products and processes. The term itself is rather vague, and refers to various unrelated materials. Resins are used as binders, which is of interest within this section, but also as components to manufacture coatings, plastics, inks and electronics (PRA/CANUC 2002g). In the case of binders, resins are used to glue together components such as wood chips or natural fibres. The resulting material is then used to manufacture products such as fibreboards and other panel boards. Binders are also used by the automotive industry to produce panels. In the other cases, resins are most often an intermediate chemical constituent entering the manufacturing process of the various products mentioned above. Alkyd resins for example are a

major component of oil-based or solvent-borne paint and are produced from agricultural crops (Crawford 2000). Resins can also be used to create coatings that protect wood against termites and rot. Currently, most resins are produced from petroleum. Soy-based resins are however used in some specific areas. There is potential to develop resins from other types of crop, but the focus remains primarily on soy.

3.2.2 Composites

Composites are composed of strong, load-carrying materials with reinforcements embedded in a weaker material referred to as the matrix. The reinforcement provides strength and rigidity and helps to support the structural load. The matrix, or binder, maintains the position and orientation of the reinforcement, balances the load between reinforcements, protects reinforcements from environmental degradation, and gives shape and form to the structure (Paster, Pellegrino and Carole, 2003).

Currently, glass fibres account for almost all of the fibre reinforcements used in Europe (approximately 600,000 tons per annum), but natural fibres show notable progress in becoming a viable replacement in several markets. R&D on natural fibres for biocomposites concentrates on flax, hemp, kenaf, cereal straw, and wood. In addition to kenaf, fibres that could be used include jute, sisal, coir, flax, and straw (wheat, rice). Natural fibre prices range from \$0.03 per pound for jute to \$0.25 per pound for kenaf, compared to glass fibres which cost \$0.50-0.75 per pound (carbon and Kevlar fibres are considerably more expensive). However, when natural fibres are woven into mats or sheets, the price rises to \$1.00-1.50 per pound.

Plant fibres can compete against glass fibres on stiffness, but they lack tensile and compressive strength and especially impact strength when compared to glass fibre composites. Moisture can also be a problem when using natural fibres as reinforcements in polymer composites. Moisture causes the fibres to swell, and after prolonged exposure, they can be subject to rotting from fungi attacks. As a result, this compromises the durability and mechanical properties of the composite. In the case of automotive parts made from natural fibre composites, this has restricted products to interior components of cars not subject to moisture effects (CARC 2003). Additionally, most matrices are synthetic polymers, but it is anticipated that with the development of bio-resins and plastics true biocomposite materials will soon be a reality (CARM 2002). With the rapid advancements in biotechnology, materials science, and related fields, the potential for biocomposites is large (Paster, Pellegrino and Carole 2003).

Research is being conducted at all stages of the supply chain, but most of the R&D in the biocomposites area has focused on improving the production and performance of natural fibre composites (CARC 2003). Importantly though, biobased materials have the potential to replace one or both parts of a composite system while maintaining or improving performance. One simple example of a biobased composite is a board material being developed by the USDA Forest Service Laboratory. The material consists of as much as 70-80% wood flour and the rest is a conventional plastic. Plant fibres are very ductile and do not splinter, producing panels that are more shatter-

resistant than traditional composites made with wood flour or saw dust. They also weigh considerably less than traditional composites.

Almost 100,000 tons of natural fibres were produced in the European Union (EU) in 1999, with flax accounting for roughly two-thirds, and hemp the other third. There has been a significant uptake of natural fibres within the composites sector, which uses flax and hemp, for example, as reinforcements in polymeric matrices. It has been estimated that in 1999, in excess of 21,000 tons of fibre were used in the automotive sector in the EU, the main components produced in this way being door panels, passenger rear decks, pillars, and boot linings. At present, around 5-10 kg of natural fibres may be used per automobile. Demand is expected to rise to 40,000- 70,000 tons in the near future (Kaup and Lohmeyer 2000 cited in CARM 2002).

Canada has developed considerable skills and knowledge in the area of natural fibre composites, using flax fibres residues and industrial hemp fibres (CARC 2003). There are three main regional centres of excellence working on biocomposites in Canada.

- Biocomposites are being studied within the Automobile of the 21st Century (AUTO21) program in Windsor and Montreal. The project investigates polymer composites with natural fibre matrixes. This research program will conduct manufacturing trials, perform computer simulations, evaluate test specimens, optimize processes and formulations, and conduct material characterizations and test specimen production using hemp, flax, kenaf, and wood.
- Alberta is rapidly developing an expertise in biocomposites made with hemp, flax, and cereal straw. Hemp agronomic studies and prototyping of hemp panels and non-woven products are receiving particular attention. Hemp is a potential candidate to increase the biodiversity of Canada.
- Saskatchewan represents a third potential regional centre for biocomposite production. A flax straw processing plant (Durafibre) developed an animal bedding (Flaxsorb) and a natural fibre reinforcement (NatureGlass) to replace glass fibres in the automotive composites market. The University of Saskatchewan is also applying for a National Centre of Excellence for natural fibres.

3.2.3 Lubricants

Lubricants are no small affair. US consumption of lubricants in 1997 was 2.7 billion gallons, whereas about one billion litres of lubricants were sold in Canada in 1994. In the US, automotive lubricants accounted for 54% of sales, industrial oils 44%, and greases 2%. Sales of vegetable oil based lubricants and hydraulic fluids in the US in 2000 were estimated to be less than 1% (that is about 100 million litres based on 1997 consumption), whereas in Canada only about 200,000 litres of biolubricants were produced from vegetable oils. Typical customers included logging companies, municipalities, parks, and golf courses. The markets for vegetable oil based lubricants were expected to increase to 1 million litres by 2000. The potential European market for vegetable oil based lubricants in 2010 is projected to be 1.7 million tons, worth close to CDN\$10 billion. If North America reached the same market potential (35%) as Europe in 2010, Canadian sales would be about \$350 million (PRA/CANUC 2002e).

Petroleum-based lubricants generally cost less and perform better than vegetable-based lubricants. The performance limitations of the latter include thermal, hydrolytic, and oxidative stability. On the plus side, vegetable oils offer high lubricity (the ability to reduce friction and wear), less viscosity change with temperature, low evaporation loss, rapid biodegradability, and negligible environmental toxicity (Crawford 2000).

There are several advantages to using carbohydrate-based as opposed to hydrocarbon-based oil. For instance, in places where gear oil and hydraulic fluids could come in contact with food, there is a clear safety advantage to using food-grade oil. Farm tractor oil can sometimes spill and contaminate agricultural land, so there is a clear benefit to using biodegradable oil. Because up to 30% of the oil mixed in fuel in two-stroke engines is not burned, these engines would clearly benefit from the use of biodegradable oil, this is particularly the case for marine engines which currently exhaust burnt fume in water. Chain bar lubricants such as the ones used for chainsaw use total loss lubricants. There are great benefits to using vegetal-based oil since lost oil is dispersed on the ground, on plants, and in water. One can also mention metal-cutting oil, which is used to keep tools sharp in industry—use of vegetal-based oil could improve the level of workplace safety in addition to lowering the environmental impact.

Rapeseed oil is widely used because of its relatively good oxidative stability in comparison to other vegetable oils, its reasonable cost compared to alternative fluids, and its wide availability in both Europe and North America. Other oilseed crops like crambe and lumaria are being studied, but their oil yield is much lower than rapeseed, and there is also a consistent message from industry that it is not interested in specialty crops, because it has already all the “molecules” it needs to meet market needs and because it is more cost effective to use existing seed oil crops (PRA/CANUC 2002e).

Canada is one of the leaders in the development of high oleic canola and high erucic rapeseed oils, which are used to make industrial lubricants and other products in the plastics and cosmetics industries. Nevertheless, there may be additional research required in Canada to improve the economics of lubricant production using new advances in chemical processing and reactor design (CARC 2003).

3.2.4 Pesticides

This report looks at three types of pesticide: herbicides, fungicides, and insecticides. A very large proportion of pesticides, particularly insecticides, are from the organochlorine family, and most are made from petroleum feedstocks. They constitute a substantial part of the energy spent on growing crops and have a long list of adverse environmental effects, such as non-specificity, in addition to producing substantial amounts of VOCs. Chemical pesticides are an important cause of air, soil and water pollution.

Biopesticides are certain types of pesticide derived from natural materials such as animals, plants, bacteria, and certain minerals. For example, canola oil and baking soda have pesticidal applications

and are considered biopesticides. At the end of 2001, there were approximately 195 registered active biopesticide ingredients and 780 biopesticide products⁸. Biopesticides are very old, for instance, the insecticide powder *chrysanthemums* was developed nearly 2000 years ago in China. Closer to home, a small-scale test of formulated *Bacillus thuringiensis* (B.t.) for corn borer control was started in Europe in 1928, while commercial production began in France in 1938. Although they are not pesticides per se, there are also some biological repellents that protect plants without killing pests.

According to the EPA, there are three principal families of biopesticides. The first type, microbial pesticides, consists of a certain microorganism (e.g.: a bacterium, fungus, virus, or protozoan) as the active ingredient. Microbial pesticides can control many different kinds of pests, although each separate active ingredient is relatively specific to its target pest[s]. For example, there are fungi that control certain weeds and other fungi that kill specific insects.

A second type, plant-incorporated-protectants (PIPs), are pesticidal substances that plants produce from genetic material that has been added to the plant. For example, scientists can take the gene for the B.t. pesticidal protein and introduce the gene into the plant's own genetic material. Then the plant, manufactures the substance that destroys the pest, instead of the B.t. bacterium.

The third type is composed of biochemical pesticides, naturally occurring substances that control pests by non-toxic mechanisms. Conventional pesticides, by contrast, are generally synthetic materials that directly kill or inactivate the pest. Biochemical pesticides include substances such as insect sex pheromones that interfere with mating or various scented plant extracts that attract insect pests to traps.

Pesticides are widely used to control forest defoliation. The Canadian Forest Service developed several microbial pesticides including ones 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 its estimated annual market in North America is \$48 million (Ah-You, Suleiman and Jaworski 2000). Traditionally, organochlorine insecticides were the main products used, but B.t. is increasingly being used. B.t. is also used as a plant-incorporated-protectant. In particular, it has been used in transgenic corn currently grown in Eastern Canada.

Most of the development of new biopesticides centers on biochemical solutions. For instance, DALA (delta-amino levulinic acid) is being developed as a broad-spectrum biodegradable herbicide that shows high activity toward dicotyledonous weeds, while showing little activity toward monocotyledonous crops such as corn, wheat, and barley. It may also have potential as an insecticide. Researchers in the US have found a simple way to synthesize DALA from levulinic acid, and a new method has been found to produce levulinic acid inexpensively from low cost lignocellulosic materials such as waste paper (PRA/CANUC 2002n).

⁸ <http://www.epa.gov/pesticides/biopesticides/whatarebiopesticides.htm>

An interesting development is an herbicide developed by the US Department of Agriculture, which isolated a protein (Nep1) from the micro-organism *Fusarium oxysporum*. The protein triggers a hypersensitivity reaction in certain weeds. Dicotyledon plants are sensitive to the protein, but it has little effect on monocotyledon crops such as wheat. The protein is active at very low concentrations; about six grams per hectare are necessary. Because the protein is a natural product, it would probably be acceptable to the organic market (PRA/CANUC 2002n).

A natural pesticide has been discovered in Saskatchewan. It is a simple peptide in the protein fraction of the pea flower. It can be extracted from the pea flower, while the rest can be feed to animals. The patented extract, when applied at 0.1% to cereal grain, kills 90% of rice weevils and 50 to 70% of rusty grain beetles. Although this pesticide is clearly effective, it still has to receive regulatory approval from Health Canada and demonstrate economic viability (PRA/CANUC 2002n).

Probably one of the most interesting solutions to explore in Canada is the co-production of biodiesel and biopesticides from mustard seed crops. Chapter 2 has shown that although mustard seeds do not represent a large crop, it is nonetheless one that Canada produces more than its usual share of world production, and has yields comparable to that of other countries. In the US, the National Renewable Energy Laboratory (NREL) and the Department of Energy have a joint initiative to produce biodiesel and biopesticides from mustard seeds, which are perceived as a promising feedstock for producing low-cost oils for biodiesel production. The process generates a co-product from mustard-seed meal that can serve as an effective pesticide, insecticide, herbicide, and even nemacide. The R&D project has already shown results, suggesting that research should also be carried out in Canada (PRA/CANUC 2002b). Results include:

- the defatted meal (after the oil is removed) can be used as a pesticide without further processing;
- specific varieties can be bred to act as fungicides, insecticides, herbicides, or nemacides;
- application trials have shown mustard meal to be highly effective against fungi, nematodes, cut worms, wire worms, crab grass, and other agricultural pests;
- oil content varies between 25 and 40%. Depending on the variety, the oil is 90% monosaturated, or even more in some cases;
- crop yields of two tons per acre of seed appear to be achievable in rotation with dry land wheat production without irrigation;
- wheat yields have increased as much as 20% when grown in rotation with industrial mustard;
- the mustard crop can be planted and harvested with existing wheat equipment;
- the mustard crop appears to be resistant to many of the pests common to canola.

The NREL is selecting lines of mustard crops that have high concentrations of glucosinolates and oil. Mustard breeding is proceeding in the opposite direction in Canada: varieties are being developed that are low in glucosinolates and have an oil composition similar to that of canola (PRA/CANUC 2002n). Research could be undertaken to develop species adapted to the co-production of biodiesel and biopesticides in Canada.

Sales of crop protection products in Canada amounted to \$1.31 billion in 2000. Herbicides constituted 81% of sales, fungicides 9%, insecticides 5%, and specialty products 5% (PRA/CANUC

2002n). In the US, the cost to purchase and apply pesticides, herbicides, and fungicides on domestic farms totalled about \$8.5 billion in 2000, or about 5-7% of farm expenditures and annual use of pesticides on crop farms, which was over 800 million pounds (Paster, Pellegrino and Carole 2003). Biotechnology products are expected to account for 10% (about US\$4 billion) of the world pesticide market in 2005. In 1996, ten Canadian establishments, mostly subsidiaries of multinational companies, were identified as producers of pesticide chemicals. Most of the activity in Canada is in formulating and not in developing and producing active ingredients. Uniroyal is the only multinational producing active ingredients (an antifungal seed treatment chemical) in Canada (PRA/CANUC 2002n).

3.2.5 Fertilizers

Bio-fertilizers are fertilizers or fertilization processes that derive from organic materials or organisms, as opposed to chemicals fertilizers. For example, some companies will use the natural capacity of rhizobial bacteria, found in the roots of legumes, to fix nitrogen from the air to develop organic alternatives to existing chemical nitrogen fertilizers. Other biological fertilizers will act as catalysts, improving the capacity of plants to absorb nutrients already present in the soil (Ah-You, Suleiman and Jaworski 2000). Bio-fertilizers are either used exclusively or, as is most often the case, along with chemicals fertilizers.

Currently, bio-fertilizers are most often viewed as a sellable by-product in the production of other bioproducts. Many biorefineries producing biofuels, biopower, and other bulk chemicals can reuse organic production waste as fertilizer and compost. Development of co-products, including fertilizers, in ethanol plants is a major area of biorefinery R&D (PRA/CANUC 2002f). Other sources include manure treatment with aerobic or anaerobic digestion systems, which produce biogas as well as a rich fertilizer (Wood and Layzell 2003). Municipal biowaste can also be decomposed by bacteria and fungi to create an efficient fertilizer (van Wyk 2001).

R&D avenues in the field include the possibility of creating non-leguminous crops that possess the root nodules containing the rhizobial bacteria found in legumes, therefore eliminating the need for nitrogen fertilizers. This could not be seen as a fertilizer *per se*, but rather as a fertilization bioprocess. Another such process being developed is the fostering of microbial consortia which are naturally present in soils, but have been disrupted by intensive agriculture. The restoration of such microbial consortia would greatly increase soil richness and thus, productivity (Ah-You, Suleiman and Jaworski 2000).

As with other bioproducts and bioprocesses, biological fertilizers offer a clear environmental advantage over their chemical counterparts. Bio-fertilizers reduce the use for other chemical fertilizers, consequently reducing the potential for fertilizer runoff into lakes and streams, which cause algal bloom and eutrophication. This also contributes to the reduction of GHG emissions associated with chemical fertilizer production and transport (Ah-You, Suleiman and Jaworski 2000). The environmentally sound aspect of bio-fertilizers is of particular importance to maintain coherence in the global production of bioproducts. These products derived from crops are

considered environmentally clean and the production processes should be too. In order to achieve the high quantity of feedstocks from crops needed to produce bioproducts, large quantities of fertilizers are and will be needed. Developing and using bio-fertilizers will bring bioproducts and bioprocesses one step closer to being fully environmentally sound.

3.2.6 Plastics

It is important to distinguish two types of plastics made from biomass. A first type of plastics is based on organic chemistry and uses existing production methods but, in contrast to chemical-based plastics, the plastics are made from carbohydrate-based precursors rather than hydrocarbons—these can be considered as biobased plastics. Renewable resources such as industrial starches, fatty acids, and vegetable oils can serve as sources for bioplastics. A second type is made of polymers that are more directly derived from natural organisms; these can be considered as bioplastics. It is also important to note that biodegradable plastics can stem from hydrocarbons—only that products are added in the mix to ease biodegradability. These are neither bioplastics nor biobased plastics.

In general, there are two main sources of commercially available bioplastics: starch-based materials (either unmodified, or modified and complexed with other polymers) and polylactic acid, where starch is first fermented to lactic acid and then polymerized into polylactic acid. PHA, proteins, and cellulose derivatives represent only a minor proportion of the current market (CARC 2003).

Biodegradable thermoplastics such as starch esters, cellulose acetate blends, polylactide, thermoplastic proteins (e.g.: zein) and poly hydroxybutyric acid (PHB) show great promise for replacing the plastics derived from petrochemicals that are generally not biodegradable. Graft plastic polymers (plastics based on plant materials and petrochemicals) are less biodegradable than plant-based bioplastics.

Bioplastics account for about five percent of the total polymer, plastics and resin market (NRC 2000). Table IV shows that there are still relatively few bioplastics on the market. In fact, most of the literature on bioplastics refers to the promises of Cargill Dow polymer derived from polylactic acid (NatureWorks™). European consumption of bioplastics was estimated to be 10,000 tons in 2000 and could reach about 60,000 tons per annum by 2005 and 300,000 tons per year by 2010. Common uses include food packaging, compost bags, paper coatings, and dishes and cutlery, accounting for over 10,000 tons each. Starch-based biodegradable plastics have been gaining market momentum in Europe as a result of government regulations promoting the composting of biodegradable materials.

US markets are also expanding, but they are led by more traditional economic drivers like price and performance (CARC 2003). According to PRA/CANUC (2002c), unlike other biobased products such as ethanol and biodiesel, bioplastics (like NatureWorks™) do not rely on government regulations and tax incentives to spur market development. US chemical companies like Dow and DuPont focus on creating new products that offer their customers superior price and performance advantages. Their R&D emphasizes new bioprocessing manufacturing technologies that have the potential to dramatically lower capital and operating expenses. These new products and bioprocesses are

designed to contribute to product portfolio mixes that result in higher corporate profits and greater shareholder value.

Table IV Expected short term growth in bioplastic sales (as of 2000)

Type of biopolymer	Company/product	Expected growth in sales (as of 2000)
Synthetic biopolymers	Eastman Chemicals - Eastar Bio	<ul style="list-style-type: none"> • expect sales volume to double in 2-3 years • may expand production facilities in either the UK or US
	BASF - Ecoflex	<ul style="list-style-type: none"> • significant increase in sales • developing plans for a world-scale plant • expect production will be sold out by the time the plant is constructed
	Bayer - BAK biodegradable polyester amide	<ul style="list-style-type: none"> • too early to tell if it will expand production
	DuPont - 3GT	<ul style="list-style-type: none"> • constructing a 12,000 tonnes/year plant that will be expandable to 50,000 tonnes/year
Starch polymers	Novamont S.p.A. - Mater-Bi	<ul style="list-style-type: none"> • sales growth about 40%/year • plans to double capacity
	National Starch and Chemical Company - ECO-FOAM, etc.	<ul style="list-style-type: none"> • expects more than 20%/year compound growth over the next 5 years
Polyactic acid (PLA)	Cargill Dow Polymers - NatureWorks™	<ul style="list-style-type: none"> • 140,000 tonne/year plant in Blair, Nebraska, scheduled for 2002 • planned expansion in Europe, mid-2003 • future plant in Japan is also being planned

Source: (PRA/CANUC 2002c)

Cargill Dow Polymers has built a 140,000-ton-per-year polylactic acid plant, whereas DuPont has built a new factory that will produce Sorona, a copolymer made from 1,3 propanediol (produced from corn starch) and terephthalic acid (made from petrochemicals). Sorona is also targeted at fibre applications. Other US companies include Genencor International, Eastman Chemicals, MetaboliX, Proctor & Gamble, DuPont Soy Polymers, and ECM BioFilms, the latter having developed an additive that renders conventional plastics like polyethylene and polypropylene biodegradable. EU manufacturers of bioplastics include Novamont (Italy), Natura Verpackung (Germany), Rodenburg Biopolymers (Netherlands), ICI/National Starch and Chemical Company (UK), AVEBE (The Netherlands), and BASF (Germany).

Canada has a few small start-up companies producing biofilms and biofibres from animal proteins, and there are efforts in both Quebec and Alberta aimed at producing PHA in plants. For instance, BioMatera specializes in the development of PHA-type biopolymers, using bacteria to ferment agricultural residues. Current biomaterials being developed include gels and creams for injectable drug delivery systems, cosmetics, and tissue regeneration matrices. Other potential applications include food packaging, plastic bottles, suture threads, biodegradable inks and paints, fibres, films, resins and nanobiomaterials (CARC 2003).

4 Bioprocesses

Bioprocessing uses living cells or the molecular components of their manufacturing machinery to produce desired products. Three major types of effect are obtained in bioprocessing: reduction, conversion, and synthesis. Reduction reduces complex structures to simpler forms, whereas synthesis does the opposite; that is, it starts from simple materials and combines them to create a more complex structure. Conversion changes the structure of materials without necessarily involving reduction or synthesis; instead, it "shuffles" matter around in such a way that the final product is different from the original.

According to the OECD, there are eight principal types of process biotechnologies: bioreactors, fermentation, bioprocessing, bioleaching, biopulping, biobleaching, biodesulfurization, bioremediation, and biofiltration (Devlin 2003).

The most commonly used living cells are single-celled microorganisms, such as yeast and bacteria, whereas the biomolecular components most commonly used are enzymes, which are proteins that catalyze biochemical reactions (Bio 2003). Additionally, using genetically-engineered plants to produce specific chemicals is another type of bioprocess, and there are also promising avenues such as molecular farming.

Whereas chemical processing often uses pressure and heat, bioprocessing usually operates on mostly solid feedstocks, more or less at atmospheric pressure and room temperature and mostly in an aqueous medium. This is an important factor to consider when it comes to process economics: the fact that bioprocessing does not require heat or pressure means that equipment is often cheaper to build and operate. Because process heat often uses hydrocarbon-based energy, directly or indirectly, chemical processing is usually more likely to produce GHG.

Bioprocesses are beginning to compete with conventional chemical processes, but industry experts believe that further improvements in enzymatic catalysis and fermentation engineering may be required before many companies develop world-scale bioprocessing plants. The competitive edge may ultimately come from developing bioprocesses that use cheap biomass feedstocks such as agricultural and forest residues rather than dextrose, which is currently the preferred renewable raw material (OECD 2001).

The chemical, textile, pharmaceutical, pulp and paper, food and feed, and energy industries are all benefiting from cleaner, more energy-efficient production, made possible by incorporating biocatalysts into their production processes. Biotechnology holds some promises for the mining sector, where it helps replace high-temperature processes such as roasting and smelting with more economical processes such as bioleaching and biooxidation. These bioprocesses occur at ambient temperatures and prevent some of the pollution associated with conventional processes. Similarly, enzymes are used in the pulp and paper sector in bioprocesses that help reduce the energy and chemicals used in treating and bleaching pulp and in paper recycling. Another interesting use of biocatalysis is for producing adhesives, whereby the use of peroxidase enzymes replaces

formaldehyde, a toxic chemical, in the production of phenolic resins (Ah-You, Suleiman and Jaworski 2000).

This section presents only the most common families of bioprocesses. Section 4.1 describes fermentation technology, while Section 4.2 analyses biocatalysis. These are often used separately or in a conjugated manner in bioreactors (Section 4.3), while biorefineries (Section 4.4) combine several bioprocesses to produce a variety of biomaterials and bioproducts. Importantly though, as noted in Section 4.5, chemical and physical processes are not going to disappear overnight and many of them will need to be optimized to be able to transform biomass or intermediate biobased material into final products.

4.1 Fermentation

Fermentation is defined as: “the decomposition of organic material to alcohol, methane, etc., by organisms, such as yeast or bacteria, usually in the absence of oxygen” (BRDB 2001). The organic material used in this decomposition is most often sugar, which is either produced as is or derived from cellulose, starch or other polysaccharides (NRC 2000). This sugar most often takes the form of glucose in current processes. In applications where research efforts are currently concentrated, the glucose used is provided by agricultural or forestry crops and waste. The products created by fermentation consequently offer the benefit of coming from a renewable source. Feedstocks used for biomass fermentation include corn, wheat, sorghum, potato, sugar beet, and sugarcane (NRC 2000).

Fermentation processes are widely used to create traditional products, but new uses are also being developed. Ethanol, a prime example of new crops usage, is produced by fermenting sugars. It is already being used to a certain extent for transportation, and a great deal of bioenergy research deals with making ethanol an efficient biofuel.

Although much of the work and research on fermentation processes focuses on producing ethanol, fermentation has many other applications. One such application is the production of plastics with properties resembling those of polypropylene or polyethylene. These plastics, made from industrial starches, are biodegradable and, as such, hold great potential. They have already been adopted by Cargill Dow for the production of disposable plastic items (NRC 2000).

Bioplastics are considered to be speciality chemicals. Fermentation is one of many routes available to produce speciality chemicals, a high-value branch of chemical production. Speciality chemicals include industrial biopolymers, bioherbicides, and enzymes. In 1994, the market for specialty biochemicals was worth over US\$3 billion (NRC 2000). The processing of starch or cellulose in biomass through fermentation can, with some additional physical steps, also lead to products such as ethylene glycol, adipic acid, acetic acid, isopropanol, acetone, butanol, citric acid, 1,4-butanediol, methyl ethyl ketone, N-butanol, succinic acid, itaconic acid, lactic acid, fumaric acid, and propionic acid. These intermediate chemicals have uses in the manufacture of such polymers as nylon polyesters and urethanes, various plastics and high-strength composites, and products as varied as solvents, coatings and antifreeze (NRC 2000).

Some organizations and researchers are optimistic enough about the fermentation process as to affirm that “[g]enetic engineering has now made possible microbial fermentations that can convert glucose into many products and can yield an essentially unlimited diversity of new biochemicals.” (Zeikus 1990 cited in NRC 2000)

However, a number of issues are slowing the widespread commercialization of products derived from fermentation (NRC 2000):

- Existing sources of glucose are insufficient to sustain planned levels of use for fermentation. New sources or processes will thus have to be found or developed.
- The use of cellulose to produce glucose has limited yields, due to a loss of much of the glucose during the transformation process. The alternative provided by xylose is also problematic since fermentation can only be done by a few micro organisms.
- In some cases, the products resulting from fermentation are highly diluted in large amounts of aqueous streams. The methods used for separation of the products are derived from traditional petroleum processes. This situation illustrates a perceived inadequacy of existing processes and the need for new methods, specific to fermentation.

Technical solutions to these problems are expected to reduce the production cost of fermentation products, therefore making them an attractive option for industries. This will be attained after glucose can be efficiently produced from cellulose (coming from growing trees or grasses) and xylose can be easily fermented. Such a breakthrough would give access to lignocellulosic materials as biomass feedstocks for fermentation, providing a much larger and cost efficient source than starches which are currently used (NRC 2000).

4.2 Biocatalysis

There are many definitions of biocatalysis, but the difference is usually a matter of scope. For instance, the OECD (1998) defines a biocatalyst as an “enzyme, used to catalyze a chemical reaction.” This contrasts with a US definition that has a much wider scope: a biocatalyst usually “refers to enzymes and microbes, but it can include other catalysts that are living or that were extracted from living organisms, such as plant or animal tissue cultures, algae, fungi, or other whole organisms” (DOE 2002). The first definition seems restrictive since unicellular organisms are sometimes used in biocatalytic processes. The second definition, on the other hand, is so far-ranging that nearly all bioprocesses could be considered as biocatalytic processes. A compromise could be to say that biocatalysis is the replacement of chemical catalysts by biological catalysts in industrial production.

Biocatalysis mainly uses enzymes as catalysts. Natural and genetically-engineered microbes can also act as “biocatalysts” to increase product concentrations, production rates, and yields or selectivity (NRC 2000). Enzymes are proteins produced by all living organisms. In humans, enzymes help digest food, turn the information in DNA into proteins and perform other complex functions. Enzymes are characterized according to the compounds they act upon.

Some of the most common enzymes are (Bio 2003):

- *Proteases*, which break down protein;
- *cellulases*, which break down cellulose;
- *lipases*, which act on fatty acids and oils;
- *amylases*, which break starch down into simple sugars.

Enzymes are considered to be environmentally superior to many catalysts used in industrial manufacturing. This is due to their capacity to dissolve in water and the fact that they work best at neutral pH and comparatively low temperatures. They are also more specific than chemical catalysts and produce fewer unwanted by-products. However, the characteristics that make biocatalysts environmentally advantageous may limit their usefulness in certain industrial processes. For example, most enzymes fall apart at temperatures above 100°F. Scientists are circumventing these limitations by using protein engineering to increase enzyme stability under harsh manufacturing conditions (Bio 2003). Additionally, most enzymes currently used are hydrophilic and do not resist very well to the harsh solvents that are often used in the chemical industry. Here again, research is helping and several strains of enzymes are being developed for use in the chemical industry. In fact, the development of recombinant biocatalysts and the isolation of effective enzymes from natural sources are crucial to removing obstacles from the wider industrial penetration of clean biotechnological processes.

Genomics and proteomics may provide robust tools to rapidly design new enzymes. At this stage, genomics plays an important role in characterizing enzymes with industrial significance. For instance, Adrian Tsang of Concordia University is currently funded by Genome Canada and Genome Quebec to sequence between 70,000 and 100,000 genes in 14 species of fungi, all of which occur naturally in Canada. Tsang is aiming to discover which genes are activated when exposed to various chemical substances, to analyze the enzymes produced by these genes and to test their effectiveness in industrial processes. The application of this genome-based approach to industries, such as the pulp and paper industry, should help decrease the environmental impact of the processes used and to increase the competitiveness of Canadian industries at a time when the demand for environmentally-friendly products is increasing. Tsang argues: “Using enzymes, we can potentially make industry greener, less pollutant. In addition, in some cases, the same enzymes can be used in environmental remediation. Genomics helps us understand the enzymes better”⁹.

The enzyme market alone is a \$1 billion global business. Microbial and enzymatic processing has been used for a long time to convert biologically-derived feedstocks. Importantly though, this is changing as biocatalysis is increasingly used in fossil fuels. Uses are as different as chiral enzymatic transformations within an organic synthesis for a drug or the microbial desulphurization of diesel fuels (CCR 2000). In addition, using cellulosic biomass, which represents approximately 80 percent of all plant material and is plentiful everywhere in the world, biocatalysts may hold the possibility of

⁹ <http://www.genomecanada.ca/projects/projectDetail.asp?id=c2p56&l=e>

producing ethanol at a cost that is roughly competitive with that of refining gasoline from oil at current world oil prices (Woolsey 2000).

Although biocatalysis has helped the commodity chemicals industry reduce its level of waste, it is in the fine chemicals industry where the impact of biocatalysis has been felt most strongly (Bruggink 1996; Sheldon 1997 cited in OECD 1998), owing to the:

- need to replace traditional stoichiometric processes to improve the product/waste ratio;
- failure to translate chemocatalytic processes from petrochemicals to fine chemicals;
- ready acceptance of enzymes by organic chemists;
- low entry barrier, i.e.: low investment, for new technologies in this small-scale industry;
- high specificity (including chiral specificity) and selectivity of biocatalysts.

The number of biocatalysts currently being employed, or in later stages of development, is unknown. Many commercial applications are trade secrets. However, the perception is that the toolbox is very sparse. There are several challenges that R&D should address so that biocatalysts become more widely used. A US industry/government workshop identified four priority areas (CCR 2000):

- Conventional processes (aqueous processing on small- to medium-sized scales) for typical industries such as specialty and fine chemicals (pharmaceuticals) and in unconventional arenas such as commodity chemicals and petrochemical processing (organic media, gas phase, etc.). Organic media should not be specific to commodity and petrochemical processing; rather, it should be examined in all potential arenas.
- Biocatalyst discovery and the need for additional resources for the design of new biocatalysts with optimized/tailored properties.
- New avenues of biocatalyst use for processing renewable biomass resources, renewable gas conversion (carbon dioxide, nitrogen oxides, etc.), and other unconventional resources, e.g.: inorganics. Included in this component will be the development of biocatalysts in unconventional hosts, such as plants and animals.
- Tool development and fundamental understanding of the biocatalyst structure and function. This will provide the critical technology to allow biocatalyst developers to make significant advances in the other two strategies.

Bioleaching and minerals biooxidation

Bioleaching and minerals biooxidation are process technologies that are commercially employed by the mining industry world-wide for the extraction of base and precious metals. Bioleaching is the use of bacteria, principally *Thiobacillus ferrooxidans*, *Leptospirillum ferrooxidans*, and certain thermophilic (high-temperature) bacteria, to leach metals of value, such as copper, zinc, and cobalt, from a sulphide mineral. During oxidation, bioleaching places the values of interest in the solution phase, the oxidation residues are handled for maximum recovery of the solution (within the volume and solution grade constraints of downstream processes), and the solid residue is discarded.

For copper recovery companies, there are reported advantages in using bioleaching relative to conventional roasters, smelters, and pressure autoclaves. These include the elimination of noxious gases (roasters produce As_2O_3 and SO_2 , which must be contained), shorter construction time, more rapid acquisition of environmental permits and cheaper environmental reporting, the elimination of

toxic effluents, the fact that iron arsenate residues are environmentally stable, an increased metal recovery rate, simpler and safer operation due to ambient temperature and pressure processing, and smaller, more economical projects with a higher net present value (OECD 1999).

4.3 Bioreactors

Bacteria are often used in bioreactors. Particularly encouraging is the application of partitioning bioreactors for synthesizing and recovering high-value products, including proteins. Many new bioreactor designs are now available, which may accommodate novel biocatalytic reactions.

An advanced bioreactor concept is the simultaneous saccharification and fermentation (SSF) reactor. This reactor can produce ethanol from mixed waste papers, agricultural waste and pulp-and-paper-mill waste by combining enzymatic and fermentation steps in one process, using novel recombinant strains of bacteria (NRC 2000).

Advanced bioreactor concepts, especially for high-volume products, might allow significant increases in productivity, therefore reducing capital and operating costs. The goals for future research on fermentation operations should include (NRC 2000):

- Combining the biological and physical operations of sugar production, fermentation and product recovery in fewer vessels and fewer microorganisms to reduce capital costs and inhibition by microbial products, thereby increasing rates, yields and selectivity;
- Improving bioreactors for heat, momentum and mass transfer for viscous, non-Newtonian fermentation broths and solid-liquid broths;
- Developing new methods for monitoring biological processes, such as discrete sensors using microfabrication, real-time monitoring, and digital imaging of bioreactors;
- Developing new concepts in process control, such as the application of expert systems, artificial intelligence, neural networks and principal component analysis.

Use of animals and plants as bioreactors

There are important uses of plants aiming to reduce pollutants through bioremediation and phytoremediation. Phytoremediation uses plants to remove pollutants from the environment or to render them harmless (Salt, Smith and Raskin cited in Gleba *et al.* 1999). According to Gleba *et al.* (1999), the process of phytoremediation works as follows:

Giant underground networks formed by the roots of living plants function as solar-driven pumps that extract and concentrate essential elements and compounds from soil and water. Absorbed substances are used to support reproductive function and carbon fixation within shoots. Metal phytoextraction relies on metal-accumulating plants to transport and concentrate polluting metals, such as lead, uranium, and cadmium, from the soil into the harvestable aboveground shoots. Hydroponically grown plant roots can also directly absorb, precipitate, and concentrate toxic metals from polluted effluents in a process termed rhizofiltration.

Although the central role of plant molecular farming to date has been to produce pharmaceuticals¹⁰, there are other uses. These involve leveraging the biomass, such as for the production of¹¹:

- biofuels and hydraulic oil;
- biodegradable plastics and biopolymers;
- industrial enzymes.

Specific examples include genetically-engineered canola and soybeans, which are used to produce lubricants. Similarly, genetically-modified canola is used to produce detergents, and tobacco has been used to manufacture novel polymers. Plants are not the only vehicle for novel forms of farming. For instance, Canadian company Nexia's Biosteel® is derived from spider silk produced from the milk of genetically-modified goats.

One example of a bioplastic is that produced by Cargill Dow Polymers, which harvests the carbon that living plants remove from the air through photosynthesis and that is stored in plant starches. The company produces "proprietary" polylactide polymers for fibres, plastic packaging, and other products. The company claims that future applications of this technology could include injection-blow-moulded bottles, foams, utensils, fibres for cloth and carpeting, emulsions, and chemical intermediaries¹².

The production of industrial enzymes from plants could produce substantial cost savings: whereas it typically costs US\$50 to US\$250 per gram to produce industrial enzymes in fermenters, using plants as bioreactors to grow the enzymes could reduce the cost to less than one cent per gram¹³.

4.4 Biorefinery

The biorefinery concept derives from the traditional petroleum industry refinery, which produces a variety of products from one or multiple feedstocks. In the case of the biorefinery, raw biomass materials, such as corn grain, agricultural residues, and energy crops, are processed and then transformed (or could potentially be transformed) into various products such as electricity and heat,

¹⁰ van Brunt (2002) defines molecular farming as "using plants as living bioreactors to produce recombinant proteins and monoclonal antibodies". Similarly, Michael Quinion, who has a website dedicated to explaining neologisms, argues that molecular farming: "describes growing and harvesting genetically modified crops, with the object of producing not foodstuffs but pharmaceuticals. The idea is to use such crops as biological factories to generate drugs difficult or expensive to produce in any other way" (see <http://www.quinion.com/words/turnsofphrase/tp-mol2.htm>). Of course, not everyone restricts molecular farming to pharmaceuticals. The following definition, for instance, is more encompassing: "molecular farming involves growing crops to produce proteins, bioplastics and other products rather than traditional food or fibre [...] Instead of producing a food product, the end result could be a plastic, medicine or even an additive for the paper manufacturing process" (see <http://www.farmacule.com/what.htm>).

¹¹ See <http://www.molecularfarming.com/about.html>

¹² <http://www.wired.com/news/print/0,1294,33598,00.html>

¹³ White, D. (1999, July 12) Two-for-one Special: Industrial Enzymes and Food Grown in One Plant. *News*. US Department of Energy. Pacific Northwest National Laboratory (<http://www.pnl.gov/news/1999/99-30.htm>).

ethanol and other fuels, solvents, organic chemicals, biochemicals, fibres, plastics, adhesives, food/feed and pharmaceutical products. Biorefineries use a number of mechanical, thermal, chemical, and biological processes to achieve these transformations. These processes include hydrolysis, gasification, catalysis, and fermentation (Crawford 2000; DOE 2003a; NRC 2000; Paster, Pellegrino and Carole 2003). The clear advantage of a biorefinery over a petroleum refinery is that it is able to produce similar products, using domestic, renewable, and environmentally sound feedstocks.

Biorefineries are still in their early stages of development, and we are still waiting for many of the anticipated results. As of now, examples of functional biorefineries include Cargill Dow's PLA plant, ethanol plants, wet and dry corn milling plants, which produce fuel ethanol, enzymes, lactic and citric acids, amino acids, and other chemicals from corn grains, and pulp and paper biorefineries, which use papermaking by-products to produce chemicals, fibres and plastics (DOE 2003a).

Before biorefineries are able to produce the variety of products mentioned above, many technical barriers will have to be overcome. Bioconversion, which transforms sugars to value-added products such as polyols, needs to be invented. The hydrolysis of cellulose and processing into sugars by enzymes has to be improved by pre-treating biomass. More efficient enzymes also need to be developed to cut production costs. Finally, enzymes that can break down lignocellulose and microbes and then convert the resulting component into the desired constituent will be a major step forward (DOE 2003a). Another barrier is the uncertainty surrounding feedstocks. Biomass from agricultural residues can vary greatly in physical and chemical composition, and characteristics and the supply system need to be stabilized (DOE 2003a). In order to be economically viable, biorefineries will have to be developed in a flexible manner. Paster, Pellegrino and Carole (2003) argue that:

Ideally, the biorefinery would have the capability to vary feedstock inputs and process streams to create on-demand product slates, much like petroleum refineries do today. High-value products may represent only 20% of production, for example, yet account for 80% of profits. By operating with a highly flexible and profitable product output, the biorefinery will be able to get the most value from a bushel of biomass, while optimizing overall profitability.

This requirement of flexibility is also very important considering our experience with petroleum refineries, which teaches that the processing technologies used improve incrementally over time, allowing for new uses to be developed (Crawford 2000; NRC 2000). To realize the vision of an efficient and viable biorefinery producing a variety of products, research is being performed on several fronts. Some of these are (DOE 2002; DOE 2003a; NRC 2000):

- utilization of existing biomass processing and conversion facilities in the development of biorefineries;
- development of new cost-competitive biomass technology platforms for additional biorefinery concepts;
- bioconversion of sugars to products such as polyols or other products that can be used to produce chemicals, materials or other biobased products;

- development and commercialization of the conversion of vegetable oils to hydraulic fluids, lubricants and monomers for a wide variety of uses in plastics, coatings, fibres and foams to enable a biodiesel/bioproducts biorefinery;
- development of syngas systems that can use any biomass residues for chemical, power or fuel production;
- further processing of ethanol into intermediate and derivative chemicals like ethylene;
- co-processing ethanol and succinic acid;
- linking ethanol and beef feedlots/meat packing into a broader value-added chain that includes the production of biodiesel, biogas, and/or fertilizers from waste meat processing streams.

4.5 Chemical and physical processes

Although bioprocesses will likely play an increasingly important role, one should not dismiss physical and chemical (mechanical) processes. For instance, mechanical processes are very useful in reducing the size of raw materials. Mechanical processes are also widely used to separate objects. Fast pyrolysis is very useful when it comes to transforming biomass into various products including bio-oil. Fast pyrolysis is a process in which materials are rapidly heated to high temperatures in the absence of oxygen and decomposed into a combination of solid, gas, vapours, and aerosols (Johnson, Yavari and Radlein 2003). Gasification is used to convert biomass, such as black liquor, into useful products and to produce energy in combined-cycle power plants. Section 3 mentioned that Fischer-Tropsch chemistry was instrumental in transforming syngas into a wide array of products. Several chemical and physical processes can not readily be replaced economically by bioprocesses. R&D on these should definitely be part of a Canadian strategy for the bioeconomy.

5 Demand-Side Analysis

This section focuses on the actual and potential markets for bioproducts and bioprocesses. It is structured by industrial sectors rather than by specific bioproducts or raw materials. The analysis focuses on the existence or absence of market opportunities for Canadian bioproducts, with a specific emphasis on the Canadian market.

It is important to note that the same bioproducts or bioprocesses can be used in several markets, in the same way that petroleum-based products can be used in fine chemicals, which are themselves used not only in paints but also in packaging, etc. Therefore, they are the basis of plenty of end-use products. One should also note that the line between industrial sectors is often quite thin. Industrial sectors are more often than not linked to each other, making it difficult to establish a clear delineation between them.

Also noteworthy is the fact that this section is not an exhaustive review of all market possibilities for bioproducts and bioprocesses. Such a review would take hundreds of pages and require an inordinate amount of resources. Its objective is, nevertheless, to give a broad overview of market applications and possibilities.

5.1 Automobiles, transportation and stationary engines

Everything pertaining to an automobile has its origin in the earth. There is no need to exhaust the mines and forests if the material required can be grown on the farm; and in addition the growing of the material on the farm will give to the farmer, when markets are developed, another source of cash. When the industrial market for farm products has been developed, it will not be long before there appears the farm-factory. In this farm-factory much of the processing by which the product is advanced into better condition for the raw material will be done in or near the fields where the raw material is harvested.

RH McCarroll, Ford Motor Company, 1936. cited in Young 2003.

The automotive industry is one of the largest in the world. In North America, almost seven million jobs are directly related to automobile manufacturing and allied automotive industries (ILSR 1997a). In Canada, some regions are heavily dependent on this industry: for example, in central Ontario, it is directly responsible for one job out of six¹⁴. Figure 11 shows that since 1994, Canada has produced more than one million trucks and vans and more than one million passenger cars per year. The industry is clearly a large user of natural resources, mostly metals and fossil-based products but also some biobased products.

¹⁴ <http://www.greater.toronto.on.ca/ataglance/gta-facts.html>

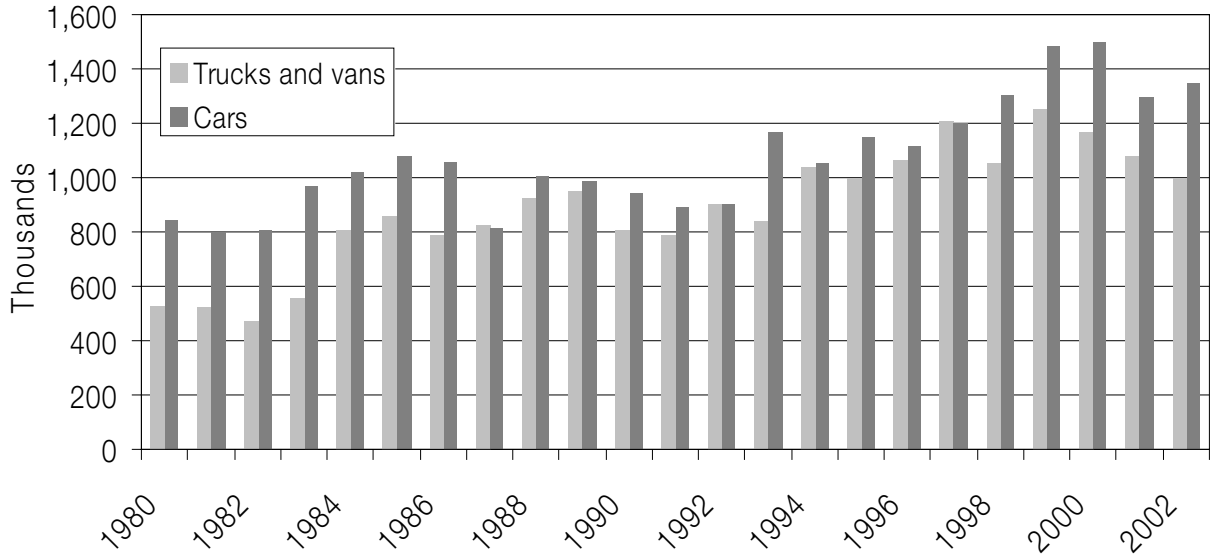


Figure 11 Production of new motor vehicles in Canada, 1980-2002

Source: Statistics Canada, Cansim Table 303-0018

Figure 12 shows that transportation equipment manufacturing is a huge industry with annual revenues in excess of CDN\$100 billion and over CDN\$80 billion spending on materials and supplies. The automobile industry is a large consumer of petroleum-based products and raw materials of all sorts. In the US, the automobile industry consumes over 60% of the oil, 50% of the rubber, 65% of the iron and 20% of the iron (ILSR 1997a).

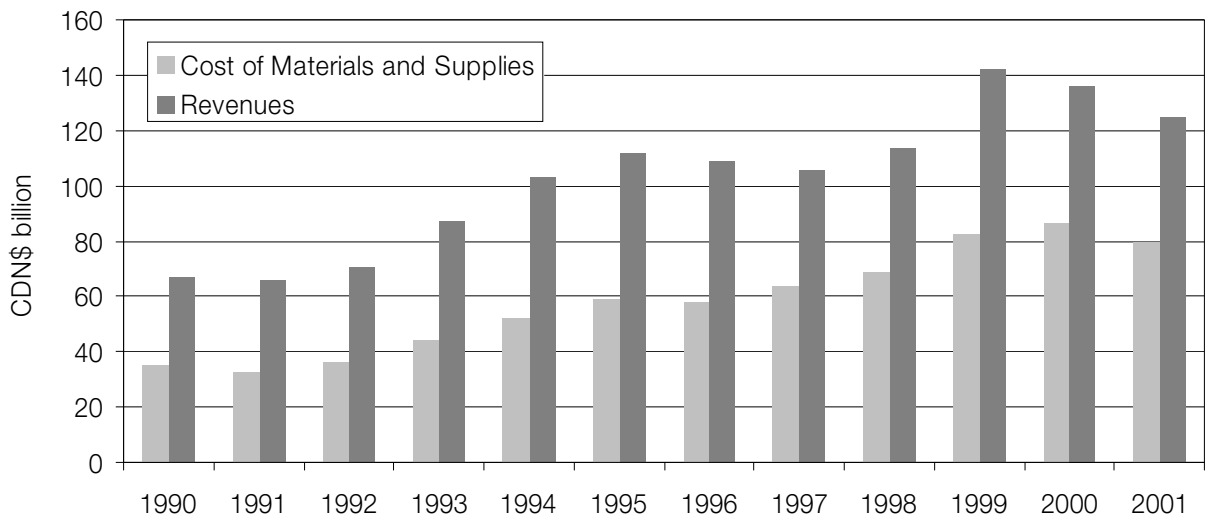


Figure 12 Cost of manufacturing goods and supplies and revenues in the Canadian transportation equipment manufacturing industry

Source: Statistics Canada. Annual Survey of Manufactures (ASM) for principal establishments in Canada's transportation equipment manufacturing industry (NAICS 336), 1990 to 2001.

5.1.1 Textiles and non-wovens

Textiles and non-woven natural fibres can find multiple applications in motor vehicle components (Table V). Currently, about 5 to 10 kg of natural fibres are used per vehicle (PRA/CANUC 2002j). Most car manufacturers use natural fibres and non-woven materials, but European car companies are well ahead of their American counterparts in doing so. This is particularly the case in Germany, where, in 1999, the automotive sector used 70% of the 22,400 tons of fibre used in Europe (CARC 2003). Many applications, including seat backings, sunroof sliders, headliners, and floorpans are currently the object of feasibility studies and experiments.

Table V Natural fibres used in the automotive industry

Natural Fiber	Leading Producing Countries	Applications
Banana	Philippines, Uganda, India, Brazil, Ecuador	Reinforcement of polyester resins
Cotton	China, U.S., India, Pakistan, Brazil, Uzbekistan, Turkey, Australia, Turkmenistan, Egypt, Mexico	Manufacture of interior trims, supports and sound insulation mats
Flax	Canada, China, Argentina, India, Poland, Romania	Manufacture of interior supports; reinforcements of plastics
Hemp	India, Romania, Thailand, China, Hungary, Poland, Turkey, France	Backing for carpets
Jute	India, China, Bangladesh, Brazil	Reinforcement fibers and filling for automotive plastics
Coir	Philippines, Indonesia, India, Mexico, Vietnam	Rubber/hair mating for seats and head-rests; reinforcements fibers for plastics
Ramie	China, Japan, Brazil, India, Taiwan, Philippines	Reinforcements for composite materials; creation of blended fabrics for car textiles
Sisal	Brazil, Tanzania, Angola, Kenya, Madagascar, Mexico	Manufacture of supports for interior; reinforcement for plastics

Source: Institute for Local Self-Reliance. 1997

Recent research suggests that hemp and flax fibres could replace glass fibres in injection moulding for both interior and exterior parts, although production costs are presently higher because of the infrastructure having been designed to use glass fibres. It is expected that, when the cost-issue is solved, the potential market for natural fibres will rise to 10-20 kg per car. Despite the fact that the Canadian automotive sector is a big employer, no major car company belongs to Canadian interests. However, Magna International, a leading supplier of automotive components, does belong to Canadian interests. With sales of CDN\$9.2 billion, Magna is a major actor in the industry. However, its current biobased production is oriented toward woodstocks rather than fibre-based substrates (PRA/CANUC 2002j).

Taking into account the fact that Canadian companies are, generally speaking, dependent on major US car companies, and that those US companies are lagging behind European firms in this area, Canadian firms are therefore not part of the automobile natural-fibre supply chain. They have the resources, but there are no car companies to buy them. Despite the fact that there is clearly a market for natural fibre-based components, this market is, for now, mainly overseas. Europe has passed a mandatory law that requires car companies to use at least 25% of natural fibres for interior car components (AAFC 2000). A similar regulation in North America could perhaps foster the

development of a market; but given Canada's dependent status in the industry, it is rather unlikely that the initiative will come from this side of the border.

5.1.2 Lubricants and hydraulic fluids

Transmission fluids and motor oils are generally mineral based. However, there is an important potential for vegetable-based fluids, particularly because of their biodegradable properties. These biolubricants—mostly made from soybeans, high oleic canola oil, and erucic rapeseed oil—could be used in several vehicle types, ranging from boats to cars and trucks. Canada is already a leader in the production of these raw materials (CARC 2003). With the EU preparing to make mandatory the use of biodegradable oils in all environmentally-sensitive areas, the market could rise drastically in the next few years (PRA/CANUC 2002e), and it is expected that North American countries will adopt similar legislations within that timeframe (USB 2000).

5.1.3 Ethanol

As a transportation fuel, ethanol is mainly used as an additive in conventional gasoline. It is generally used as a 5% to 10% blend. A blend of up to 10% of ethanol can be used in cars made since 1970 without any engine modifications. However, ethanol's cost is higher than that of gasoline and diesel; the wholesale price for ethanol is 62.5 cents per litre, whereas that of gasoline and diesel is 35.4 cents per litre (PRA/CANUC 2002d). Therefore, tax incentives are essential in promoting the use of ethanol as an additive—one cannot expect consumers to buy ethanol for their cars and trucks if it costs twice as much as conventional fuels. Canadian provinces have created tax incentives for the ethanol portion of gasoline, although those exemptions are not equally distributed among provinces. Ethanol can also be used as an additive in diesel. As argued by the Canadian Renewable Fuels Association, extending the same tax reduction as that for gasoline to the use of ethanol as a diesel additive could double the ethanol market in Canada, assuming it is used as a 5% to 10% blend.

Ethanol is not the only fuel additive available. It has some competitors, among others methyl tertiary butyl ether (MTBE). However, this additive is known to be a ground water contaminant. Environmental regulations in 11 US states have banned the use of MTBE within their borders, and an additional 14 are planning to do so. The replacement of this fuel additive by ethanol would increase the US demand for ethanol to 3.2 billion gallons by 2004. With new plants under construction—added to those already existing—supplies could equalize demand if MTBE was banished (PRA/CANUC 2002d).

Antifreeze and windshield washer liquids made from ethanol have already been commercialized in North America. 300,000 and 50,000 gallons respectively were sold in 1996 (ILSR 1997a). Antifreeze made from propylene glycol is also on the market, but this market segment is essentially considered flat (Paster, Pellegrino and Carole 2003).

5.1.4 Biodiesel

As with ethanol, tax incentives and regulations are an important issue when it comes to using biodiesel as a transportation fuel. Furthermore, while the cost of biodiesel was an issue at the end of the nineties (Prakash 1998), it is becoming less and less problematic. As stated in PRA Inc. and CANUC's report on biodiesel (2002):

The cost of pure biodiesel (B100) in the US has fallen from US\$4.50 per gallon in 1997 to US\$1.00 per gallon in 2001. The noncompetitive price of biodiesel fuel becomes even less of an issue when it is used as a blend of 20% (B20) or less and becomes largely irrelevant when used as a fuel additive at 0.5 to 2.0%.

The size of the biodiesel market in Canada will depend largely on the new sulphur reduction standards and whether Canada chooses to implement a renewable fuel standard. Extending an excise tax exemption to biodiesel, similar to the approach to ethanol, would also be a key factor. Assuming a renewable fuel standard starting at 0.8% and rising to 2.0% in 2010, the market demand for biodiesel in Canada could start at 170 million litres and rise to 424 million litres by 2010. Using canola as an example, canola seed sales would increase by 879,800 tons by 2010 or by 10.2% of the 8,798,000 tons produced in 1999 (PRA/CANUC 2002b).

If the renewable fuel standard is set at 5% (the level being proposed in both Europe and the US), the market demand would be 1,060,000 litres of biodiesel or 2,199,500 tons of canola seed, which represents 25.5% of the 1999 canola crop production. The huge projected demand for biodiesel opens up tremendous market opportunities for oil seed crops like soybean and canola. In fact, the demand is so great that the domestication of other specialty oil seed crops, like industrial mustard, should be examined closely. Research on edible mustard is well developed in western Canada and could form an important research base for investigating industrial varieties (PRA/CANUC 2002b).

Acceptance of biodiesel fuel by the automotive industry is also critical for future market expansion. John Deere, Caterpillar, Cummins, Detroit Diesel, and International have approved biodiesel for use in their engines (PRA/CANUC 2002b). In Europe, many engine and vehicle manufacturers, including Volkswagen and Mercedes Benz, have approved the use of biodiesel in their diesel engines (Prakash 1998).

5.2 Power Generation

Canada is the world's sixth-largest producer of electricity, with annual production in excess of 585,000 GW/h in 2001 (Statistics Canada 2002). Production of electricity represents 2.4% of its GDP, or about CDN\$22 billion in 2001. After France and Paraguay, Canada is third in the world in the export of electricity, exporting 38,400 GW/h in 2001¹⁵, which represented a trade balance of CDN\$2.2 billion.

¹⁵ www.cia.gov/cia/publications/factbook/ (CIA, The World Factbook)

With growing concerns about global warming and potential shortages caused by decreasing accessibility and political instability, many countries want to lessen their dependence on fossil fuels and focus on renewable and sustainable sources of energy for the generation of electricity.

Although Canada has a strong hydroelectric capability, about 25% of its electric use is provided by fossil fuels (Statistics Canada 2002), and, surprisingly, this last source of electricity is on the rise, while hydro is slowly losing ground. In order to maintain access to electricity at a reasonable price, despite evolving demand and environmental concerns, Canada should diversify its energy sources of electricity, paying special attention to sustainable sources.

Developments in biotechnology have led to new perspectives in the energy sector. Biomass is increasingly considered as a potential source of energy. Canada has a large territory with well-developed agricultural and forest industries.

In Canada, the energy contained in yearly harvested timbers could replace 62% of the energy derived from fossil fuels while agriculture can replace nearly 25% (Wood and Layzell 2003). Therefore, Canada could reduce its use of fossil fuels by 87% if it dedicated all its land production to energy. More realistically, forests are already harnessed, and the possibility of lowering the need for feed and food is not as great. However, there is a considerable amount of residual biomass that could be recuperated from those industries. Residues from domestic, industrial and agricultural activities represent non-negligible resources that could be turned into energy.

Research is currently being conducted in Canada on the use of raw materials, including agricultural residues, whole forest biomass and forest harvest residues, for energy production, (Kumar, Cameron and Flynn 2003). For example, biosynthesis gas can be used in advanced turbines or fuel cells to produce electricity at more than twice the efficiency of today's combustion systems.

The combined energy potential of forest residues (1.54 EJ), agricultural residues (0.38 EJ), and municipal waste (0.29 EJ) is 2.2 EJ and represents 17.5% of the actual annual Canadian energy use (12.60 EJ). This supplementary energy could be used to boost Canadian electricity exports by as much as 400%, thus helping the balance of trade to reach CDN\$10 billion.

However, those numbers are ideal figures, and the energy content of residual biomass has to be concentrated and transported before it can be converted to electricity. That could be a substantial challenge, as biomass residues are scattered and conversion to electricity is done more easily in large-scale installations.

For a long time, residual biomass has been burned directly on site, but new physicochemical (pyrolysis, gasification) and biological methods (fermentation, composting) can turn low-grade combustibles into high-value fuels or fertilizers. This can rule out certain hurdles associated with transportation, but the costs associated with conversion are still prohibitive, especially at a small scale.

Many factors have to be considered: collection method, cost of the biomass, cost and externalities of transport, transformation, etc. A life-cycle assessment (LCA) would surely demonstrate many

features regarding the real costs and benefits of producing energy this way, particularly with a growing competition for biomass for other bioproducts.

Investments in R&D on bioconversion and LCA models could assuredly set an example for future development, but no projects appear to be economically viable in the short term. However, outcomes from Kyoto debates, such as CO₂ credits, could be very important incentives. In fact, the 2.2 EJ potentially produced from residual biomass could replace about 27% of our annual use of fossil fuels and produce up to 50% of our electricity needs.

In the short term, research should probably focus on local, small-scale uses. Certain industry types, such as wood transformation and wastewater treatment, produce a large amount of waste that could be transformed into power for in-house uses. Research has shown that, using gasification technology to replace aging power- and heat-generating equipment, the US pulp and paper industry could become energy self-sufficient and could even become a net producer of up to 30,000 megawatts of electricity by 2030.

5.3 Construction industry

Figures recently released by the Canadian Construction Association reveal that the gross output of construction activity in 2000 is expected to total \$119.2 billion. This is a 9.5 percent jump from 1999's gross output of \$108.8 billion. Furthermore, the total number of Canadians employed in construction both full- and part-time in 2000 is estimated at 815,600 workers, up 1.2 percent from 1999.

Projections for 2001 indicate that growth in the construction industry will continue at a healthy pace. It is expected that gross output will increase by 4.2 percent to \$124.3 billion in 2001, and that employment levels will increase by over 7 percent to 879,700 workers. Employment growth is expected to be recorded in every province (*Aggregates and Roadbuilding Magazine* 2001).

5.3.1 Adhesives

Revenues from the production of adhesives in Canada reached more than CDN\$700 million in 2001 (Figure 13). Considering that, in 2001, Canada had a trade deficit in adhesives worth CDN\$324 million, the Canadian market is worth in excess of CDN\$1 billion. The cost of materials and supplies going into the manufacture of adhesives was CDN\$360 million in 2001. In and of itself, this is not a huge market. However, current adhesives used in the construction industry often emit a substantial amount of volatile organic compounds (VOC). VOC air emissions have been under attack for contributing to a variety of modern illnesses, including smog- and ozone-depletion-related illnesses and the "sick house syndrome." Formaldehyde, a major constituent of many of the wood adhesives used today, has been especially targeted, as have the phenoxy compounds found in phenol resins (CARC 2003). There is some concern about the effect of these emissions on the health of inhabitants of new homes.

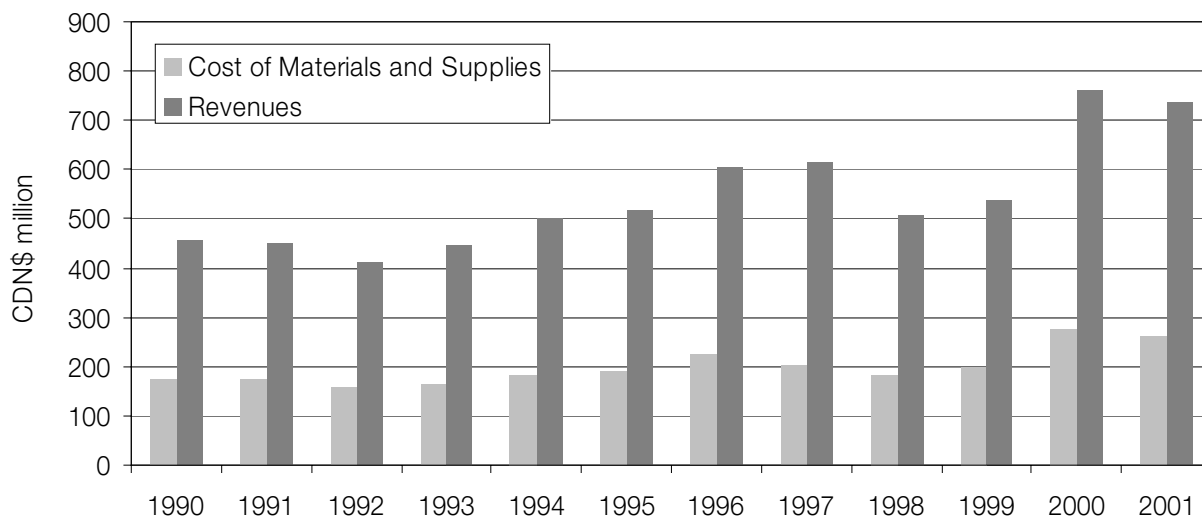


Figure 13 Cost of manufacturing goods and supplies and revenues in the Canadian adhesive manufacturing industry

Source: Statistics Canada. Annual Survey of Manufactures (ASM) of principal establishments in Canada's adhesive manufacturing industry (NAICS 3252), 1990 to 2001.

Therefore, even though it is a niche product, compared to platform chemicals such as ethanol, there is probably some room to develop safer adhesives for use in the construction industry. It is argued that markets are being driven by the industry's need for (PRA/CANUC 2002a):

- low VOC content;
- use of annually renewable resources (natural materials);
- biodegradability;
- repulpability;
- recyclability;
- compatibility with waste management infrastructures.

The potential to use locally produced adhesives in composite boards and construction materials using Canadian straw and forest resources could be an attractive business opportunity if the quality and price of local biobased adhesives was competitive with petrochemical-based products. The fact that vegetable-protein-based adhesives were used as standard practice in this industry in the first part of the twentieth century bodes well for their reintroduction in the 21st century as environmental concerns about current products escalate (PRA/CANUC 2002a). There is potential for a major research program concentrating on the use of biobased adhesives to supplement and/or replace both formaldehyde- and isocyanate-based resins in panel board manufacturing (CARC 2003).

Canada has a significant furniture manufacturing industry in which adhesives play an important role. Locally produced adhesives have the potential to make this industry more competitive by generating additional revenues for the local economy and creating greater markets for agricultural raw materials. Canada's strengths in medical research should also provide opportunities for more biocompatible adhesives (PRA/CANUC 2002a).

The adhesives industry has undergone considerable changes in recent years due to increasing legislative control of the emission of volatile organic compounds. This driving force, coupled with an ever expanding array of new uses for adhesives, and the desire to replace petrochemicals with renewable materials, has led to a mounting research interest in biobased adhesives. The vast majority of this research is being performed in the US and the EU. A significant adhesives industry currently operates in Canada, but imports from the US are approximately three times greater than Canadian exports. Of greater concern is the low level of investment in adhesives research in Canada in both the public and private sectors, with virtually no efforts being directed toward biobased adhesives. Much of current US research in this area is focussed on biobased adhesives using corn and soy as the starting material, with funding coming from the respective grower associations (CARC 2003).

Although research opportunities relating to VOC elimination still exist, opportunities for GHG reduction are limited due to the relatively small tonnage of material when compared to other biomaterials and to biofuels. The major hurdle facing the Canadian research community is the dearth of corporate head offices in Canada and, therefore, research budgets. The answer to this problem may lie in collaborating with researchers in the US and the EU (CARC 2003).

5.3.2 Engineered lumber, boards and panels

The engineered lumber and particle, sawdust, and woodchip board industries grew substantially in the 1990s. Whereas revenues of Canadian establishments were below \$1 billion in 1990, they increased more than fourfold by 1999, rising to CDN\$4.6 billion. Although revenues fell slightly in 2000 and 2001, this remains an important sector (Figure 14). The sector is important in the bioeconomy because it lowers residue waste by using small-size materials that would otherwise be burnt or simply put in landfills. There is a need to develop techniques whereby this material could be reused and recycled after its useful life. There is also a challenge to develop safe products that do not emit VOCs and that are safe to burn. This will ease heat recovery when burning waste products and will make products safer in case of fire.

Construction materials, such as fibreboards and panels, have traditionally been produced from wood residues. In the last few years, however, the possibility to produce such materials from crop fibres has emerged. Various crops can be used, the most common being waste hemp, flax, wheat, or soy straw. The types of construction sheets produced with wood are glue-laminated beams, plywood veneers, oriented strandboards, flakeboards, chipboards, particleboards, and medium-density fibreboards. Use of crop residues has concentrated mostly on particleboards and medium-density fibreboards.

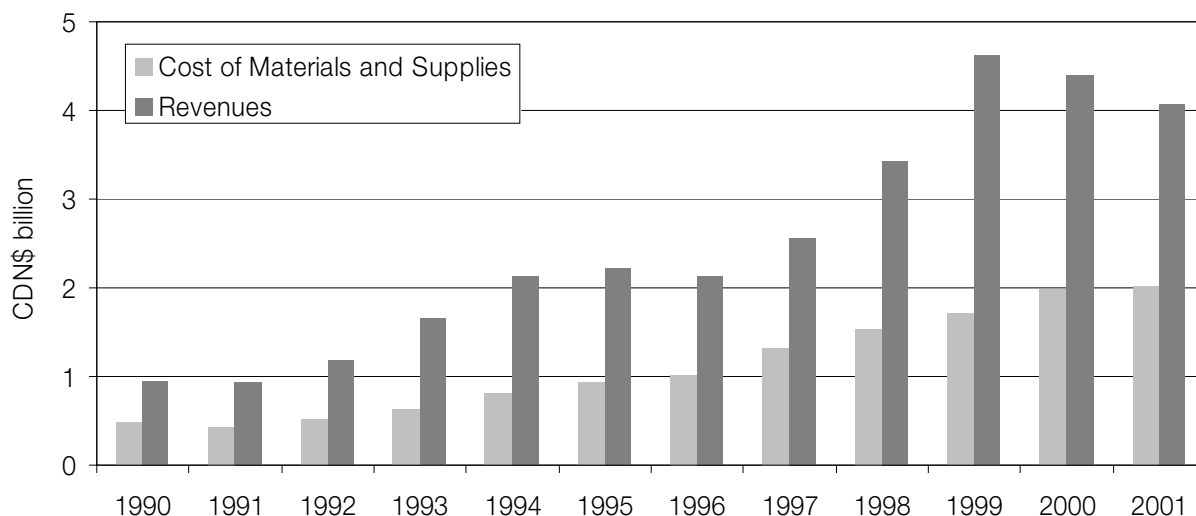


Figure 14 Cost of manufacturing goods and supplies and revenues in the Canadian engineered lumber and particle board industry

Source: Statistics Canada. Annual Survey of Manufactures (ASM) for principal establishments in Canada's structural wood product manufacturing industry (NAICS 321215), particle board and fibreboard mills (NAICS 321216) and waferboard mills (NAICS 321217), 1990 to 2001.

Before achieving commercial success of construction boards and panels made from agricultural residues, serious obstacles must be overcome. Wood residues are available all year long and are easily stored. Agricultural fibres, on the other hand, are harvested once or twice a year and must then be stored on a long-term basis. Storage is problematic, as straw is affected by weather, fire and vermin. Covered storage in a facility is too expensive to be considered. Appropriate baling methods, which can resist high winds, have to be developed. Crop residues are thus more expensive than wood residues; this, together with the fact that the adhesives used for crop residues are also more expensive than those used for wood, increases production costs. Finally, the market for fibreboard is very competitive. Most plants involved in this production operate on a large-scale basis. Thus, agricultural fibreboard plants, which, so far, are small installations, are in a difficult position to compete. Furthermore, the January 2002 RISI North American Wood Panels Forecast reported a 7% decrease in particleboard consumption and that the decrease would continue in the following years (PRA/CANUC 2002f).

These factors have led the last decade's initial enthusiasm for agriculture-based fibreboards in the US and Canada to meet with market failure, as indicated by recent PRA/CANUC findings in a study for AAFC. Of the 18 agricultural fibreboard mills instigated to investigate the viability of straw fibreboards, only 6 were still open in 2002 (PRA/CANUC 2002f). Comparatively, the 1995 Ashmead report provided a positive portrayal of non-wood fibre panels and boards. Agricultural fibreboard plants were said to be less costly than wood-based plants, the properties of waste fibreboards to be as good as or better than those of wood panels, and agricultural fibreboards to have an environmental edge over wooden ones, in that their source was renewable annually, whereas forests took much more time to renew (PRA/CANUC 2002k).

Uses for bioproducts and bioprocesses in this field are not limited to the direct production of panels and boards. One source mentions possible market opportunities for fibre-based insulation and fibre-reinforced cement and ceramic tiles (CARC 2003). New processes such as entanglement, non-woven needling, and thermoplastic methods could lead to glass fibres being replaced by plant fibres (PRA/CANUC 2002f). Biotechnology could also lead to the development of wood preservation bioproducts, which would serve as pest repellents (termites is a problem that Canadian wood exporters need to deal with) or prevent decay (Ah-You, Suleiman and Jaworski 2000).

Bioproducts could also be used for the adhesives needed to produce boards and panels, whether they are made from wood or agricultural crops. Soybeans can be used to produce the adhesives necessary in the production of these construction materials. Although soybean adhesives meet with strong competition from their chemical counterparts, recent concerns about the environment and renewable resources have increased research in this area. Research goals, notably, for the US's United Soybean Board, are to develop binders that combine soybean and chemical components (Crawford 2000, PRA/CANUC 2002a).

5.3.3 Paints and Coatings

The paint and coating industry is also an important supplier of material to the construction industry. In Canada, the paint and coating industry is a \$2.5 billion enterprise that employs 11,000 people, 7,500 of whom are directly associated with the manufacture of products. Paint shipments in 1997 are reported at 62% in Ontario, 22% in Quebec, 11% in British Columbia, and 3% in Manitoba. Although this is a significant industry in Canada, it is dominated by branch plants of multinational enterprises (MNEs) with head offices in the US or the EU (PRA/CANUC 2002m). Materials and supplies entering this industry cost more than CDN\$1 billion in 2001 (Figure 15).

Paints using vegetable-oil-based binders are estimated to represent less than 25% of the current paint market, and this share is declining. Paints and coatings are formulated products. The base material, known as the binder or vehicle, is the film-forming ingredient that largely determines the performance of coatings. In the past, binders were largely based on natural products such as linseed oil and natural resins. Today, to achieve better performance, almost all binders are based on synthetic polymers (PRA/CANUC 2002m).

The Canadian paint industry is mature, and growth will, in general, match the pace of the economy, but industry shifts and environmental regulations may potentially have an impact. For example, environmental health and safety considerations are driving the product development efforts of paint industry members, and costs associated with environmental permitting and hazardous waste handling or disposal will continue to increase. Although progress in the reduction of VOCs from paints has been made, increases in VOC-generated smog will force additional reductions of allowable paint solvent emissions over the next decade. Paint industry R&D labs continue to search for cost-effective routes to lower VOCs from paints and coatings (PRA/CANUC 2002m).

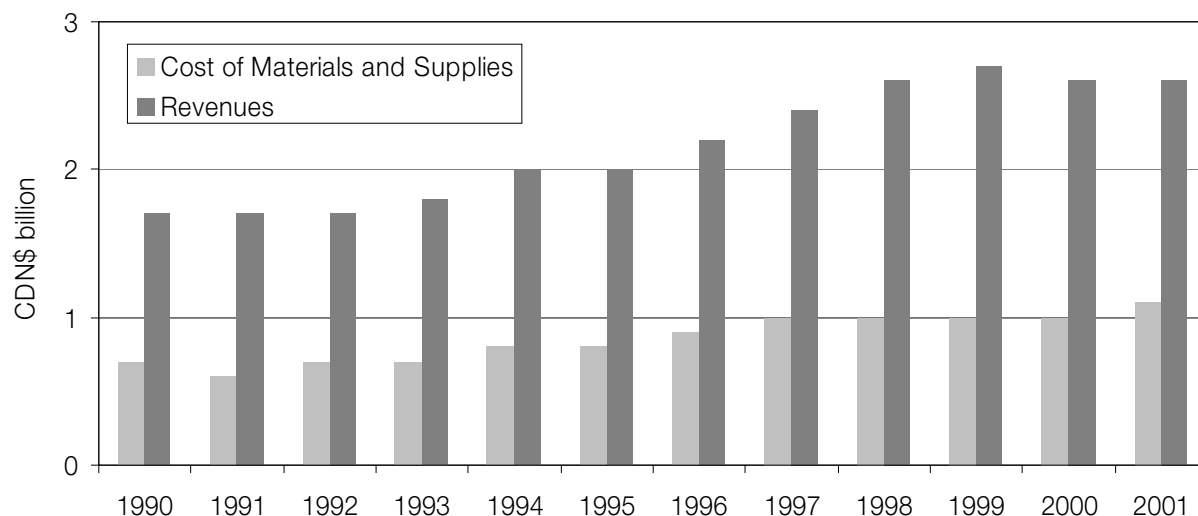


Figure 15 Cost of manufacturing goods and supplies and revenues in the Canadian paint and coating manufacturing industry

Source: Statistics Canada. Annual Survey of Manufactures (ASM) for principal establishments in Canada's paint and coating manufacturing industry (NAICS 32551, 1990 to 2001).

5.4 Pulp and Paper

Pulp and paper is one of the most important industries in Canada: more than 25 million tons of pulp was produced in 2002. The revenues are substantial, and so are the costs of materials and supplies used in manufacturing: in 2001, inputs cost close to CDN\$18 billion while revenues were in excess of CDN\$37 billion (Figure 16).

New sources of raw materials can be classified according to two broad categories: non-wood plant fibres and fast-growth wood plantations. The market for non-wood papers represents around 50,000 tons annually, notably because of the cost of non-wood fibres, which is five to eight times higher than that of wood fibres (PRA/CANUC 2002f). Short-term developments are limited, mainly because of the high cost of financing this sector and the even higher cost of paper (PRA/CANUC 2002h).

However, as stated in a PRA/CANUC (2002f) report on the pulp and paper industry:

- Given current paper recovery rates, it is unlikely that recovered fibre will be able to meet all of the projected demand for fibre, so the question is: where will we find the additional 100-125 million tons of fibre needed by 2010?
- The likely answer is that much additional fibre resources will be required to meet future demand including fast growth wood plantations, increased paper recovery, and non-wood plant fibres from crop residues and fibre crops.

Therefore, even though the market for these additional fibre sources remains limited for now, the anticipated shortage will create a heavy demand in a few years' time. Three types of non-wood fibres are to be used in pulp and paper production (PRA/CANUC 2002h):

- Agricultural residues such as cereal straws, corn stalks, sugarcane bagasse, and oilseed flax straw;
- Fibre crops such as textile flax straw, kenaf, sisal, abaca, hemp, bamboo, and switch grass;
- Natural strands such as reeds, grasses, and bamboo.

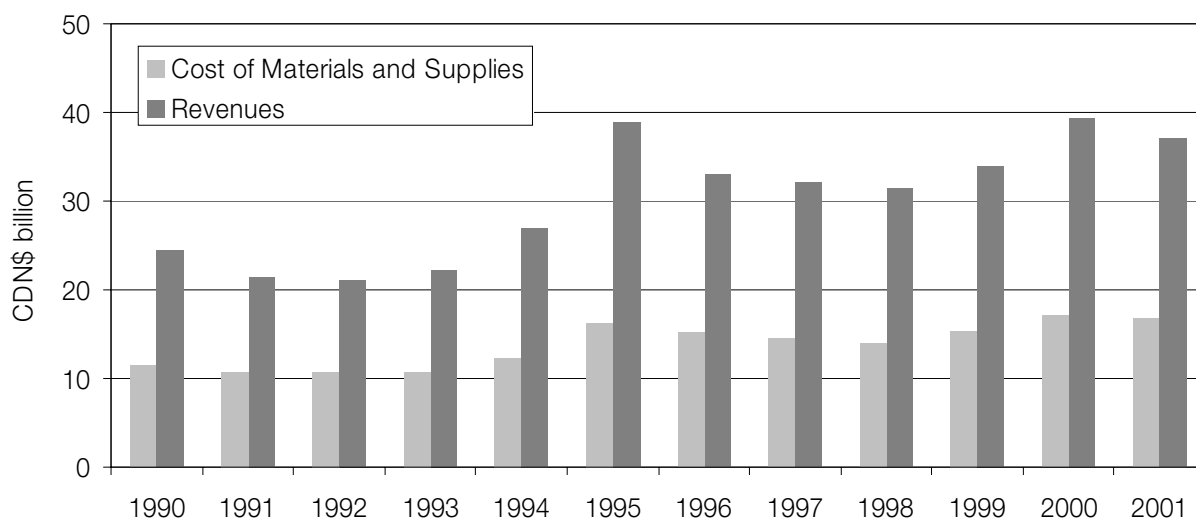


Figure 16 Cost of manufacturing goods and supplies and revenues in the Canadian pulp and paper industry

Source: Statistics Canada. Annual Survey of Manufactures (ASM) of principal establishments in Canada's paper manufacturing subsector (NAICS 322), 1990 to 2001.

In the Canadian context, agricultural residues are the most available raw material. For example, if all wheat straw available was used in pulp production, it would annually produce about 11 million bone-dry metric tons of bleached chemical straw pulp suitable for papermaking (PRA/CANUC 2002h).

There are bioprocesses that could be used to improve the pulp and paper industry's efficiency and product quality. Table VI shows the different bioprocesses that could be used depending on the paper process stage. Fungi and enzymes are likely to be used increasingly. Biopulping pre-treatments using fungi and dewatering using enzymes could save energy, whereas the pre-treatment of Kraft pulps with enzymes such as xylanases and hemicellulases could increase the effectiveness of subsequent chemical bleaching and lower the quantity of chemical bleaching agents required. In addition, the genetic engineering of trees may facilitate cleaner manufacturing processes and increase energy efficiency by allowing the feedstock to be tailored to the transformation process (Ah-You, Suleiman and Jaworski 2000).

Table VI Potential biocatalyst applications, pulp and paper

Process stage	Biocatalysts	Benefits
<u>Raw material pre-treatment:</u> Debarking Wood preservation	Pectinases Micro-organisms (fungi)	Energy and raw material savings Environmentally benign methods
<u>Mechanical pulping:</u> Pre-treatment Refining	Micro-organisms (fungi) Cellulases, Lipases	Pitch removal, energy savings Energy savings, improved product quality
<u>Chemical pulping:</u> Bleaching	Hemicellulases (xylanase), Laccases	Improved brightness, chemical savings, increased capacity, reduced AOX-formation
<u>Paper manufacturing:</u> Drainage Deinking Wet end chemistry management	Cellulases, Hemicellulases Various enzymes	Chemical savings, improved product quality Chemical savings Improved runnability, slime control, improved product quality, reduced chemical need

Source: IPTS (2002)

5.5 Printing industry

Despite the paperless office promises of the 1980s, growth of the printing industry has not stopped. For instance, revenues from the printing industry in Canada rose by 50% during the last 12 years, that is, from CDN\$8 billion to CDN\$12 billion between 1990 and 2001 (Figure 17). This industry spends more than CDN\$4 billion on supplies, many of which could be biobased.

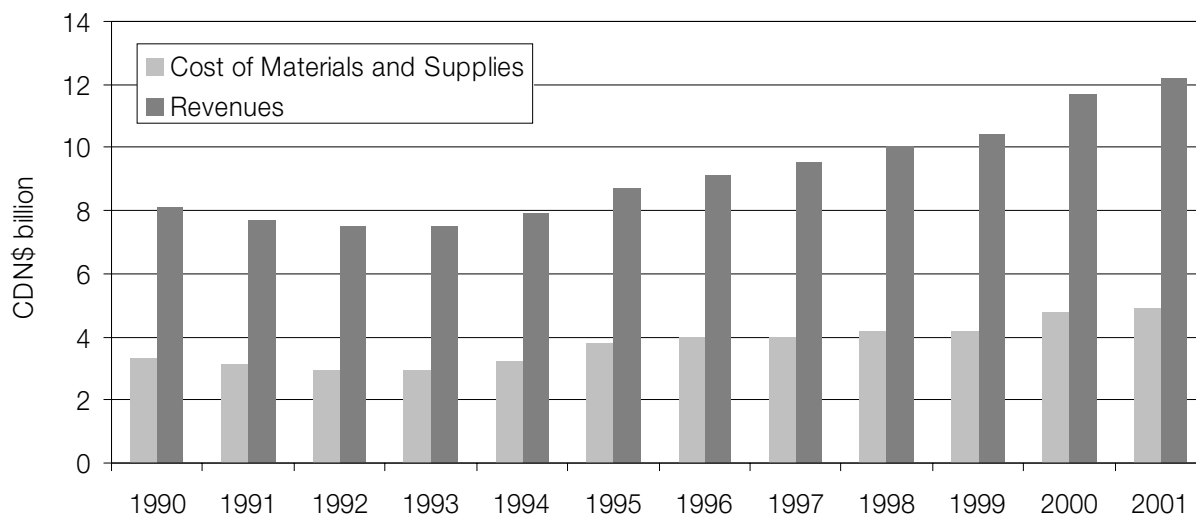


Figure 17 Cost of manufacturing goods and supplies and revenues in the Canadian printing industry

Source: Statistics Canada. Annual Survey of Manufactures (ASM) of principal establishments in Canada's printing and related support activities subsector (NAICS 323), 1990 to 2001.

Vegetable-based inks now account for approximately 25% of the printing inks market. New advances in technology offer the potential to further increase this market share. The vegetable ink market is dominated by soybean ink, which accounts for 9% of the inks used in the US (PRA/CANUC 2002l). It already occupies a specific niche, as 90% to 95% of daily newspapers in the US use coloured soy ink (ILSR 1997b). The ink is considered to be of higher quality than petroleum-based ink, giving brighter colours. It also offers environmental advantages, such as making printed paper easier to recycle. Black soy ink is more expensive than petroleum black ink (US\$0.80/lb compared to US\$0.60/lb in 1997—see ILSR 1997b), but the cost is offset by an easier printing process. As for coloured inks, the cost of soy ink is competitive with that of petroleum-based inks.

The United Soybean Board and the Soy Ink Information Center are a strong marketing force in the US. There is no comparable marketing organization in Canada. However, opportunities to promote the production of vegetable-based inks in Canada do exist. Sun Chemicals has a production plant in Weston (Toronto), Ontario, that uses both linseed and soy oil in its formulations. Linseed oil has the advantage of faster drying. Canola oil can also be substituted for soy oil. The different performance characteristics of vegetable oils are matched to meet specific customer needs. In some applications, a variety of vegetable oils may be used. Linseed, canola, and soy are all grown in Canada. Further follow-up in this growing market sector is recommended (PRA/CANUC 2002l).

Bioproducts in the printing industry have two main uses: they can be used as alternatives to traditional petroleum-based press cleaners and as ink components. Biological cleaning solvents offer a clear environmental advantage, being biodegradable and much less toxic than petroleum products. This also has impacts on the safety of workers. The basic selling price of biological solvents for press cleaning is higher than that of petroleum products, but the overall cost, when considering environmental and safety issues, is very competitive (ILSR 1997b).

5.6 Packaging

Packaging is an important market. It is not an industry per se, but comprises suppliers from a considerable number of different industries. In fact, packaging uses nearly every type of material: glass, metal, paper, plastic, textiles and wood. As such, it is difficult to estimate the economic importance of this field but Canadian revenues were worth in excess of CDN\$16 billion in 2001, according to data compiled by Science-Metrix (Figure 18). In fact, the actual value is probably closer to CDN\$20 billion. Half the revenues of the industry are spent on materials and supplies. Importantly, a substantial part of these materials are used only once, thus becoming a liability because these materials represent a substantial, and rising, proportion of municipal solid waste disposed in landfill sites. A great portion of these materials, such as bottles used for soft drinks, can be reused; another portion, such as metal cans, can be recycled; and the rest should, as much as possible, be biodegradable. A policy to produce biodegradable packaging should go hand in hand with a policy to manage municipal urban waste so that these liabilities can easily be converted into assets.

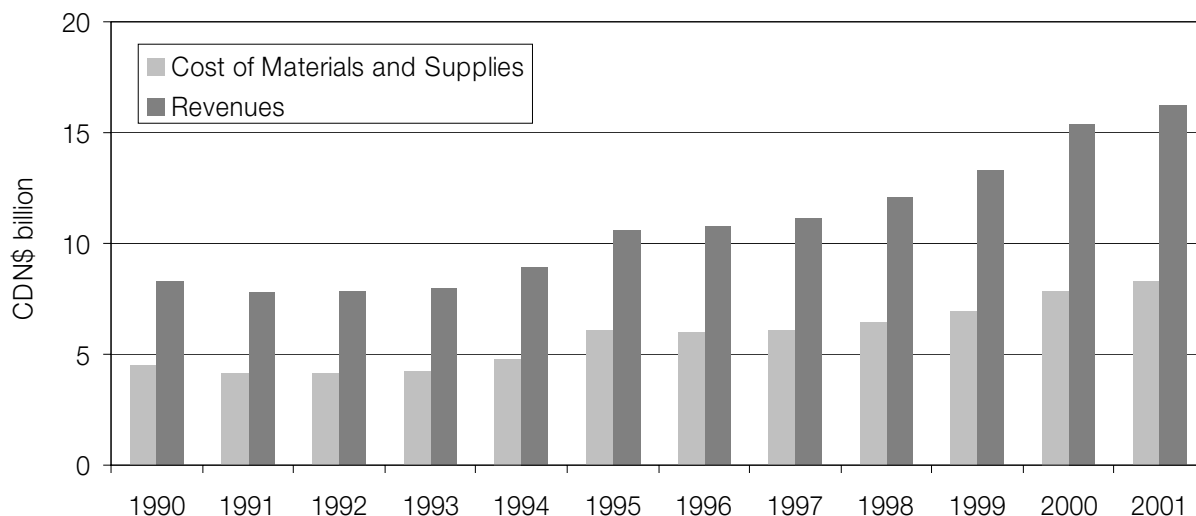


Figure 18 Cost of manufacturing goods and supplies and revenues in the Canadian packaging market

Source: Statistics Canada. Annual Survey of Manufactures (ASM) Annual Survey of Manufactures (ASM) of principal establishments in Canada's packaging (NAICS 33243, 32221, 32222, 32611, 32616, 31491, 32192) market, 1990 to 2001¹⁶.

The packaging industry is an important sector of application for bioplastics. Companies have been working on this for a long time now, but until recently, few results were noteworthy. As mentioned earlier in the report, Cargill Dow recently manufactured a bioplastics production plant that employs corn sugars to produce polylactic acid that is used in plastic packaging and loose-fill biodegradable packaging. The \$300 million plant, located next to Cargill's wet corn mill, was designed to produce 140,000 tons of PLA-plastic from corn starch, creating a new market corn starch. The plant will use 14 million bushels of corn per year and add about 25 cents to the price of a bushel of corn (Crawford 2000). The resulting polymer plastics are price-competitive with fossil-fuel-based plastics *and* offer superior performance characteristics. Moreover, it is expected that PLA polymers will account for 50% of the near-term market for biopolymers (PRA/CANUC 2002c). Currently, they are used in utensils, plates and cups (NRC 2000).

Plastic packaging is the largest single market for polymer resins. For instance, over 21 billion pounds of thermoplastics were used in packaging in 2000. With its physical properties, which are equal to or superior to those of conventional polymers, PLA has the potential to break through the market polymer market. PLA polymer demonstrates a higher degree of stiffness, clarity, gloss, dead-fold, and grease resistance, as well as having unique flavour and aroma barrier properties (Cargill Dow 2001).

¹⁶ Part of NAICS 31491 comprises items that are not packaging. There are also some types of packaging that are buried inside generic categories such as glass bottles (part of NAICS 327214), foil containers (part of 332999), aluminium foil (part of 331317) and plastic containers (part of 326198).

North American and European approaches toward regulations differ. While the EU is fostering the development of biodegradable plastics with regulatory controls and government-designed market incentives, there are no such incentives in North America. Conversely:

Just recently, the US Federal Trade Commission voted to designate PLA a generic fibre category like cotton, wool, silk, nylon, and polyester. As a result, the market opportunities and potential for growth are very significant (PRA/CANUC 2002c).

There is no doubt that there is a market for bioplastics in the packaging industry. This market is not a homogenous one. First, biodegradable plastics for loose-fill packaging offer tremendous potential, despite concerns about increased methane emissions (CARC 2003). However, consumers will prefer the use of biodegradable packaging as long as prices do not increase. The market for packaging enhanced with new fibres is still limited to certain sectors, like blocked packaging for electronics, injection moulding, films and fillers, and children's toys (CARC 2003).

The importance of Canada in this market is not clear. Even though Canada has a strong science base in biotechnology, grows considerable starch and protein crops, and is home to Cascades, one of the world's leading packaging companies, it is not a strong player in new types of packaging. The world's major chemical companies are taking part in the race for bioproducts. Perhaps the lack of a Canadian-owned chemical company is to be held responsible for the situation (PRA/CANUC 2002c).

5.7 The environment industry

The environment industry mainly uses bioprocessing-based biotechnologies for biofiltration, biotreatment and bioremediation, including phytoremediation. Biobased products are also developed and used for environmental monitoring and biodiagnostics.

In Statistics Canada's 2001 Biotechnology Use and Development Survey, nearly 25% of firms that use biotechnologies to develop bioproducts or bioprocesses belong to the environment industry. With 32 firms, this sector is second in terms of the number of firms. In 2002, a PRA/CANUC study reported the environmental products cluster as a very promising sector for the development of the biobased economy (PRA/CANUC 2002n). The study cited the Ashmead-Serecon report (1997), which had estimated the Canadian market to be worth CDN\$150 million with 15% annual growth over five years.

However, a more recent CANUC estimate of five industrial biobased market clusters for 2005 is more moderate. In fact, CANUC estimates the potential market size for the environment sector (bioremediation, phytoremediation, and biocontrols) in 2005 to be worth CDN\$50 million. This estimate makes the environment sector the smallest one after the biochemical (CDN\$1,690 million), biomass fibres (CDN\$570 million), health (CDN\$260 million), and energy (CDN\$110 million) sectors (Crawford 2000).

Table VII Environmental goods and services market by industry segment and by region, US\$ billion, 2000

	USA	Western Europe	Japan	Asia	Canada	Latin America	Eastern Europe	Australia & New Zealand	Middle East	Africa	Total \$	Total %
Equipment	46.03	31.65	17.55	8.19	2.90	2.66	2.20	1.66	1.34	0.76	114.95	24.2%
Water Equipment & Chemicals	16.70	11.42	5.17	3.22	1.23	1.03	1.01	0.77	0.55	0.47	41.57	8.8%
Air Pollution Control	16.10	7.99	3.05	2.97	0.62	0.43	0.55	0.31	0.44	0.06	32.52	6.9%
Instruments & Information Systems	2.46	1.71	0.93	0.61	0.12	0.24	0.09	0.08	0.11	0.03	6.38	1.3%
Waste Mgmt Equipment	9.52	9.93	7.88	1.13	0.86	0.84	0.55	0.46	0.22	0.19	31.58	6.7%
Process & Prevention Technology	1.25	0.59	0.52	0.27	0.06	0.12	0.00	0.05	0.03	0.00	2.89	0.6%
Services	103.49	82.32	49.60	9.58	7.01	5.35	3.77	4.56	3.71	1.09	270.50	57.1%
Solid Waste Management	39.80	33.42	30.22	3.70	2.34	1.55	1.47	1.54	0.99	0.44	115.47	24.4%
Haz. Waste Management	5.23	5.95	3.91	0.56	0.43	0.24	0.37	0.27	0.27	0.03	17.26	3.6%
Consulting & Engineering	15.94	9.13	1.13	0.93	0.99	0.36	0.37	0.61	0.27	0.16	29.90	6.3%
Remediation/Industrial Services	11.09	7.89	3.98	0.43	1.03	0.96	0.66	0.76	1.71	0.18	28.67	6.0%
Analytical Services	1.24	1.19	0.52	0.32	0.12	0.10	0.09	0.08	0.05	0.03	3.74	0.8%
Water Treatment Works	30.19	24.74	9.85	3.64	2.10	2.15	0.82	1.31	0.41	0.25	75.45	15.9%
Resources	54.24	43.82	26.60	6.23	3.16	3.35	3.67	2.18	1.79	1.50	146.54	30.9%
Water Utilities	32.21	22.36	12.44	5.24	2.10	2.51	3.02	1.46	1.48	1.11	83.93	17.7%
Resource Recovery	12.69	15.46	9.71	0.24	0.74	0.48	0.46	0.38	0.16	0.19	40.51	8.5%
Clean Energy Systems & Power	9.35	6.00	4.45	0.76	0.32	0.36	0.19	0.34	0.14	0.20	22.10	4.7%
Total \$	203.76	157.80	93.75	24.00	13.06	11.36	9.65	8.41	6.84	3.35	531.99	
Total %	38.3%	29.7%	17.6%	4.5%	2.5%	2.1%	1.8%	1.6%	1.3%	0.6%	100.0%	

Source: Environmental Business International

5.7.1 Solid waste and water biotreatment

Biotreatment broadly refers to all processes, including bioremediation and phytoremediation, that use biological agents to detoxify waste. In the case of solid waste and water biotreatment, these processes are used to detoxify process waste streams directly at the source, as opposed to bioremediation, which is often used after a site has been contaminated. Biotreatment involves selecting the right microorganisms (such as bacteria or fungi) and enzymes to act as biocatalysts to accelerate the naturally occurring degradation process of hazardous or toxic substances. Other methods include accumulation, biologically-induced precipitation, bio-enhanced filtration, formation of biological barriers, and bioregeneration of granular activated carbon¹⁷.

According to Business Communications Company's 2002 Waste Treatment Technology Industry Review, the world market for waste treatment is worth approximately US\$400 billion. The annual growth rate is expected to be 2.2% over the next five years, bringing the figure to US\$445.6 billion in 2007¹⁸. These figures are aggregate and include recycling, water treatment, remediation, air pollution and solid and hazardous waste treatment. Solid waste management, hazardous waste management and water treatment works are all dynamic areas, each respectively accounting for markets worth

¹⁷ <http://www.buscom.com/archive/C110R.html>

¹⁸ http://www.the-infoshop.com/study/bc15910_waste_treatment.html

US\$2.34 billion, US\$0.43 billion, and US\$2.10 billion (see Table VII above) in Canada. However, biological treatment within these fields, at the moment, most probably represents a very low percentage of this market. Nevertheless, the future holds some interesting promises, as biological treatments are predicted to perform very well in the years to come. A study published in 2002 by Frost and Sullivan concluded that waste management sales in Europe would rise from US\$32 billion around 2000 to US\$38 billion in 2009. The largest growth area is expected to be biological treatment, resulting from a shift in focus from landfill disposal to waste pre-treatment and investments in new technology¹⁹.

In the water and wastewater field, the federal government estimates that Canada has a leading position in the global market, owing to cutting-edge technologies and a good pool of skilled workers. Canada notably has an expertise in the area of biological sludge treatment. According to this source, the water and wastewater field is the largest component of the environment industry in Canada, with an estimated market value of US\$5.5 billion²⁰. The interest in this area is not limited to Canada. The world market for wastewater treatment experienced a growth rate of 16% in 2000, and it should be more than 8% through 2010²¹. Given the information provided above, one can assume that biotreatments will occupy an increasingly important position in this growing market.

5.7.2 Bioremediation and phytoremediation

Bioremediation technologies increased their importance as competitive on-site remediation strategies ever since microbes started being used in oil-spill cleanups in the 1980s. More recent developments in genomics, such as the use of DNA microarrays to improve microbe screening, generate the know-how to leverage companies' in-house expertise in identifying more effective microorganisms in soil, air, and water bioremediation processes and developing environmentally sound bioreactors. A recent review of clean technologies recognizes that linking bioremediation companies' expertise and complementary expertise in organisms screening and testing is a challenge. This link could lead to the development of new, cleaner industrial bioprocesses (Ah-You, Suleiman and Jaworski 2000).

In 2000, the market of the remediation services industry was evaluated to be worth US\$1 billion in Canada and US\$28.7 billion in the US, 30% of the environmental services market (EBI 2002). In Canada, this industry segment is the third most important, after solid waste management and water treatment works services. The market is likely to be receptive to biotechnology-based remediation services, as there are already more than 40 bioproducts-firms that specialize in decontamination using biofiltration, bioremediation, and phytoremediation.

¹⁹ http://www.edie.net/gf.cfm?L=left_frame.html&R=http://www.edie.net/news/Archive/5850.cfm

²⁰ <http://www.dfait-maeci.gc.ca/beirut/water-en.asp>

²¹ <http://pqasb.pqarchiver.com/jgpress/access/92601320.html?FMT=FT&FMTS=FT:PAGE&date=Nov+2001&desc=Estimating+growth+rates+for+wastewater+markets>

The world market for bioremediation products is estimated at €1.62 billion or approximately US\$2 billion (Table VIII). Based on the 2000 market value provided by EBI, the market share of bioremediation products is likely to be 7% of the total remediation services market. From this, we can assume that the bioremediation market in Canada was worth around US\$74 million in 2000. In terms of growth, a market increase of 18% was estimated for the 1997-2001 period. Based on this trend, it is reasonable to expect the Canadian bioremediation market to be worth more than US\$85 million in 2005.

Table VIII World market for bioremediation products, € billion, 1997 & 2001

Sub-sector	1997	2001
Hazardous waste bioremediation	0,80	0,98
Waste water bioremediation	0,31	0,34
Municipal solid waste	0,20	0,24
Waste to energy applications	0,06	0,06
Total	1,37	1,62

Source: Yorkshire Bioscience, 2003

Phytoremediation is not as largely diffused as other bioremediation 30 times more developed in the US than in the rest of the world (Table IX). In 1999, Glass Associates estimated the Canadian phytoremediation markets to be worth between US\$1 and US\$2 million. In Canada, a considerable number of laboratory and field tests took place in 1999 for the remediation of heavy metals and petroleum hydrocarbons, but commercial markets are still weak.

Table IX Estimated world phytoremediation markets in US\$, 1999

United States	\$ 30-49 million
Europe	\$ 2-5 million
Canada	\$ 1-2 million
Other	\$ 1-2 million
World	\$ 34-58 million

Source: D. Glass Associates

Information gathered confirms that the markets for bioremediation are therefore healthy and expanding. As with many other sectors of the environment industry, remediation is highly competitive. The development of new biotechnology-based platforms and services offers a bright potential for the creation of new market opportunities in this sector of the environmental industry. The Canadian remediation market is worth more than US\$1 billion, and offers good opportunities for growth. Also, the strong and growing demand for bioremediation in the US offers excellent opportunities for Canadian businesses offering new technologies and specialized services.

6 Benchmarking of Canadian bioproduct and bioprocess research

This section provides a quantitative analysis of inputs (research grants) in scientific research on bioproducts and bioprocesses in Canada (Section 6.1) and measures Canada's scientific (scientific papers, see Section 6.2) and technological outputs (patents, see Section 6.3). The aim of this section is to quantify the scientific and technological capacity of the country to appropriate and interpret knowledge on bioproducts and bioprocesses. The aim is also to benchmark the contribution of Canada to bioproduct science and technology against the world science and technology frontier, therefore assessing Canada's readiness to become a world leader in the bioeconomy. This also provides information on the Canada's capacity to develop certain sectors faster than others, to evaluate Canadian strengths and weaknesses, and to determine where its receptor's capability is strongest.

6.1 NSERC Awards

This section examines the rate of funding by NSERC and, more briefly, by the Canadian Foundation for Innovation (CFI) for university-led research on bioproducts and bioprocesses in Canada.

NSERC awards for bioproducts and bioprocesses rose from CDN\$5 million in 1991 to more than CDN\$8 million in 2002 (Figure 19). Although this represents a rise of 62% over a 12-year period, bioproducts and bioprocesses are still relatively marginal in NSERC expenditures. In fact, in 1991, only about 1.1% of NSERC awards were granted in these fields and less than 1.5% in 2002. However, it is noteworthy that NSERC grants in this field increased regularly after 1998.

A compilation of data from the CFI reveals that about CDN\$17 million has been invested in bioproducts and bioprocesses R&D infrastructures between 1998 and 2003. When this is added to grants from NSERC, one can see that approximately CDN\$50 million has gone into supporting research on the bioeconomy in universities—that is about \$10 million per year. During the same period, the US government spent more than US\$1 billion.

Table X shows that British Columbia, Quebec, and Alberta are the most specialized provinces in terms of obtaining awards from NSERC for bioproducts and bioprocesses. Ontario obtains the largest financial support from NSERC, but it does not obtain as much NSERC support in bioproducts as it does generally. This is indicated by the specialization index (SI). The specialization index is above 1 when a province receives more funding in bioproducts than it does in every field considered. Conversely, it is below 1 when a province does not receive as much financing in bioproducts as it does in aggregate terms. The Atlantic Provinces, Saskatchewan, and Manitoba are not present whether in absolute or relative terms.

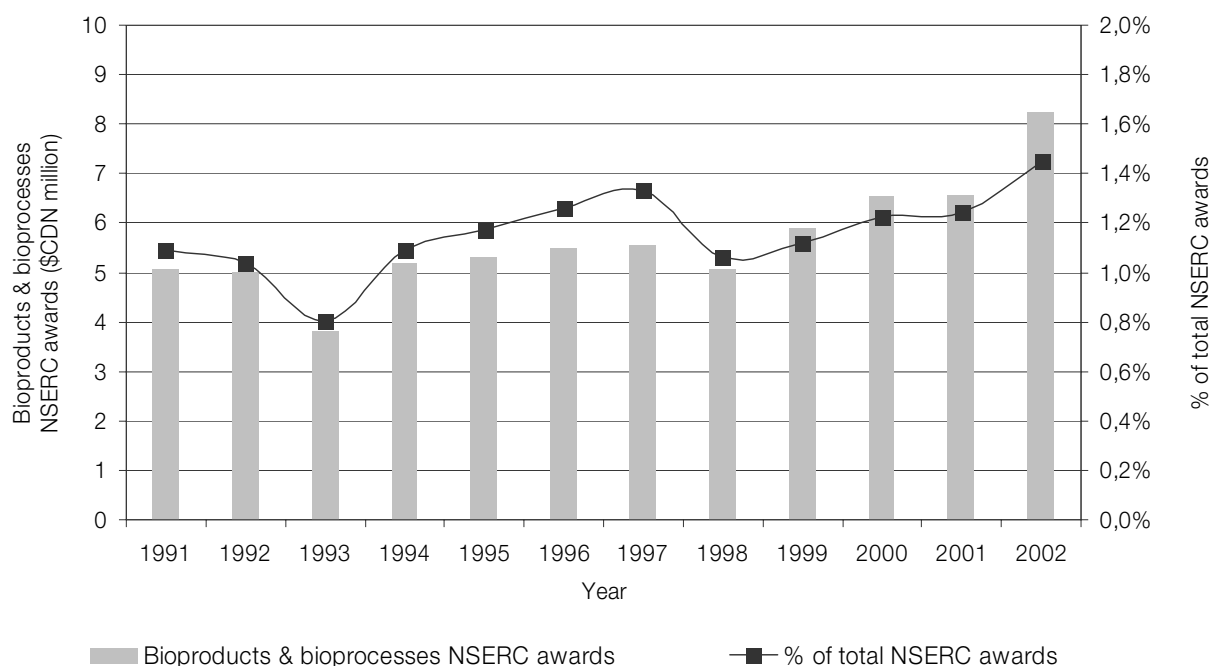


Figure 19 NSERC awards for bioproducts and bioprocesses, 1991-2002

Source: Compiled by Science-Metrix from the NSERC awards database.

Table X NSERC awards and specialization index in bioproducts and bioprocesses by province, CDN\$ thousand, 1991-2002

Province	1991-1993	1994-1996	1997-1999	2000-2002	1991-2002	S.I.
Ontario	4,445	5,809	6,159	7,709	24,122	0.9
Quebec	3,757	4,390	4,817	6,308	19,272	1.2
British Columbia	2,701	3,021	2,802	3,737	12,262	1.3
Alberta	2,282	1,386	1,388	2,230	7,287	1.1
Saskatchewan	270	435	501	397	1,604	0.8
Manitoba	156	392	269	283	1,099	0.6
New Brunswick	175	277	180	176	808	0.8
Nova Scotia	44	132	139	257	572	0.2
Newfoundland	67	118	83	205	475	0.5
Prince Edward Island	0	0	0	0	0	0.0
Outside Canada	0	0	189	38	227	0.2
Total	13,898	15,961	16,528	21,340	67,727	1.0

Source: Compiled by Science-Metrix from the NSERC awards database.

Table XI shows that the University of British Columbia clearly exerts leadership in the field of bioproducts and bioprocesses, receiving 16% of NSERC awards in the field. University of Waterloo is no slouch either, having received more than \$5 million received during the last 12 years. McGill is also an important player, although it does not specialize in this field of research nearly as much as

UBC or Waterloo do, or, even, the École Polytechnique de Montréal, which receives 2.7 times more funding from NSERC for bioproducts than it does for every other field considered. The University of Western Ontario also specializes in this field, whereas the University of Toronto, despite being awarded CDN\$3.8 million, receives 40% fewer awards in bioproducts than its usual share of NSERC funding. Other universities that stand out in bioproducts and bioprocesses by their specialization index are Guelph, Calgary, the Institut national de la recherche scientifique, Sherbrooke, Brock, and Ryerson Polytechnic.

Table XI NSERC awards and specialization in bioproducts and bioprocesses by institution, CDN\$ thousand, 1991-2002

Institution	1991-2002	S.I.
University of British Columbia	10,785	1.9
University of Waterloo	5,814	1.8
McGill University	4,694	1.3
École Polytechnique de Montréal	4,365	2.7
University of Western Ontario	4,082	2.2
Université Laval	3,965	1.2
University of Toronto	3,790	0.6
University of Alberta	3,685	0.9
University of Guelph	3,646	1.7
University of Calgary	3,391	1.5
Institut national de la recherche scientifique	2,685	3.7
Université de Sherbrooke	1,678	1.5
University of Saskatchewan	1,321	0.8
Queen's University	1,294	0.5
University of Ottawa	1,057	0.7
University of Manitoba	1,037	0.6
Brock University	826	3.9
Ryerson Polytechnic University	804	6.3
Simon Fraser University	795	0.5
Carleton University	754	0.6
Université de Montréal	713	0.3
University of New Brunswick	604	0.8
University of Windsor	532	0.7
Concordia University	519	0.6
McMaster University	512	0.2
Total	67,727	1.0

Source: Compiled by Science-Metrix from the NSERC awards database.

Table XII shows that environmental engineering, chemical engineering, and microbiology are the subjects that receive the largest share of NSERC awards in bioproducts and bioprocesses. In fact, research projects undertaken in these fields receive two-thirds of NSERC awards. Organic chemistry, biochemistry and polymer chemistry are also important, as are different fields of biology, most notably molecular biology, plant and tree biology, and evolution and ecology.

These findings suggest that research on biochemical platforms may be well under way in Canada. This means that the R&D community in Canada would be ready to undertake the challenges presented by the development of the chemical platforms described in Section 3. However, there may be some weaknesses in terms of improving Canadian feedstocks. Plant and tree biology and evolution and ecology are not as important as one might expect, and neither is genetics. Considering the importance of understanding the genomic structure of plants to increase yield and hardiness, there may be a need to invest more on improving knowledge on feedstocks. For example, plant and tree biology receives about 10% less financing in bioproducts than it does for any other type of research, and genetics receives only 30% of its baseline amount of funding.

Table XII NSERC awards and specialization index in bioproducts and bioprocesses by subject, thousand CDN\$, 1991-2002

Subject	1991-2002	S.I.
Environmental engineering	18,471	18.9
Chemical engineering	16,546	9.6
Microbiology	10,654	10.2
Organic chemistry	3,084	1.5
Biochemistry	2,290	2.0
Molecular biology	1,749	2.4
Plant and tree biology	1,232	0.9
Evolution and ecology	1,187	0.4
Polymer chemistry	1,103	3.1
Genetics	1,011	0.7
Physical chemistry	877	0.5
Cell biology	641	0.6
Other studies in natural science and engineering	604	0.8
Earth science	543	0.3
Material science and technology	515	0.2
Food science and technology	422	0.8
Soil science	406	1.5
Fuel and energy technology	365	1.4
Agricultural engineering	363	2.3
Forest engineering	294	2.6
Life science research related to human health and disease	208	0.3
Mining and mineral processing	199	0.7
Industrial engineering	198	0.2
Animal biology	158	0.1
Hydrology	147	0.3
Mechanical engineering	102	0.1
Others	352	0.0
Unavailable	4,006	0.3
Total	67,727	1.0

Source: Compiled by Science-Metrix from the NSERC awards database.

Table XIII shows that the largest sector of application of R&D on bioproducts and bioprocesses is the environment, which received close to one-third of NSERC funding during the last 12 years. Manufacturing processes and products as well as commercial services received about one-third of the awards, which shows that R&D is in large part applied in nature, something that could be expected. Energy resources are important, but natural resources and agriculture are not as present as one could have expected.

Table XIII NSERC awards and specialization index in bioproducts and bioprocesses by sector of application, CDN\$ thousand, 1991-2002

Sector of application	1991-2002	S.I.
Environment	20,495	3.7
Manufacturing processes and products	10,381	3.1
Commercial services	9,241	2.5
Advancement of knowledge	8,048	5.0
Energy resource	7,245	3.9
Natural resources	4,594	0.7
Agriculture and primary food production	1,875	0.5
Health education and social services	471	0.2
Northern development	158	0.1
Construction, urban and rural planning	57	0.1
Transportation systems and services	55	0.1
Not available	5,107	1.6
Total	67,727	1.0

Source: Compiled by Science-Metrix from the NSERC awards database.

6.2 Scientific publications in bioproducts and bioprocesses

This section presents data on the global rate of growth of scientific papers in the field of bioproducts and bioprocesses at the world level (Section 6.2.1). It subsequently benchmarks Canadian scientific output against that of other leading countries in terms of impact factor (Section 6.2.2) and by specialties (Section 6.2.3).

6.2.1 Growth of scientific output in bioproducts and bioprocesses at the international level

Figure 20 shows that the number of scientific papers in bioproducts and bioprocesses grew steadily from 1998 to 2002, growing from more than 3,000 papers in 1998 to more than 4,000 in 2002, an increase of nearly 33% over the five-year period. In terms of the percentage of total papers in the SCI Expanded database, this field is still relatively small, and its growth has been somewhat slow, that is, increasing from 0.4% in 1998 to 0.5% in 2002 (close to 28% growth).

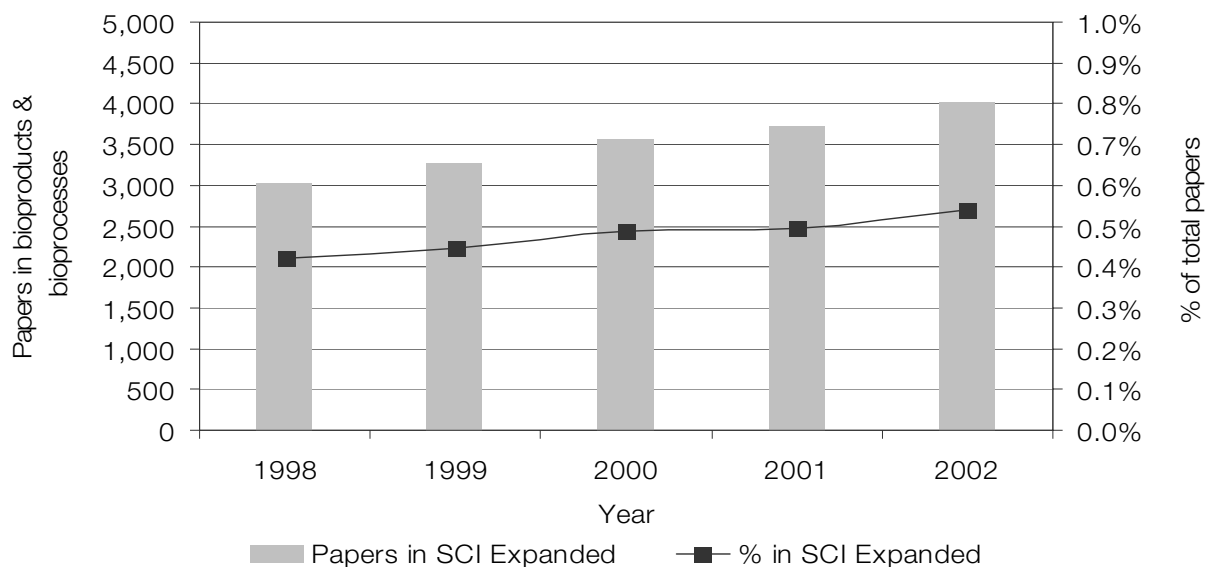


Figure 20 Papers in bioproducts and bioprocesses in SCI Expanded, 1998-2002

Source: Compiled by Science-Metrix from data prepared by ISI Thomson.

Canada's output of papers in this field during the last five years is consistent with the place Canada occupies among the G8 countries. Data presented in Figure 21 show that Canada ranked 7th among 25 leading countries. With an average yearly growth in papers of 3.8% over the five-year period, we can assume that Canada is not keeping pace with the international community in terms of scientific growth (World=7.3%). Among the leaders, Japan is one of the most prolific and active countries when looking at total output and average yearly growth (3rd and 12.8%). It will certainly be the world's leading country after the US in the near future, as Germany and the UK are not growing nearly as rapidly. Also noteworthy, the G8 economic countries are not the G8 leading countries in bioproduct and bioprocess biotechnology. Surprisingly, India ranked 5th in the field. In fact, the total Indian scientific output between 1990 and 2001 indexed in the SCI database places India in 14th place at the world level (Parent *et al.* 2003). Scientific outputs of the Republic of Korea and China are also remarkable, both displaying more than 20% of average annual growth.

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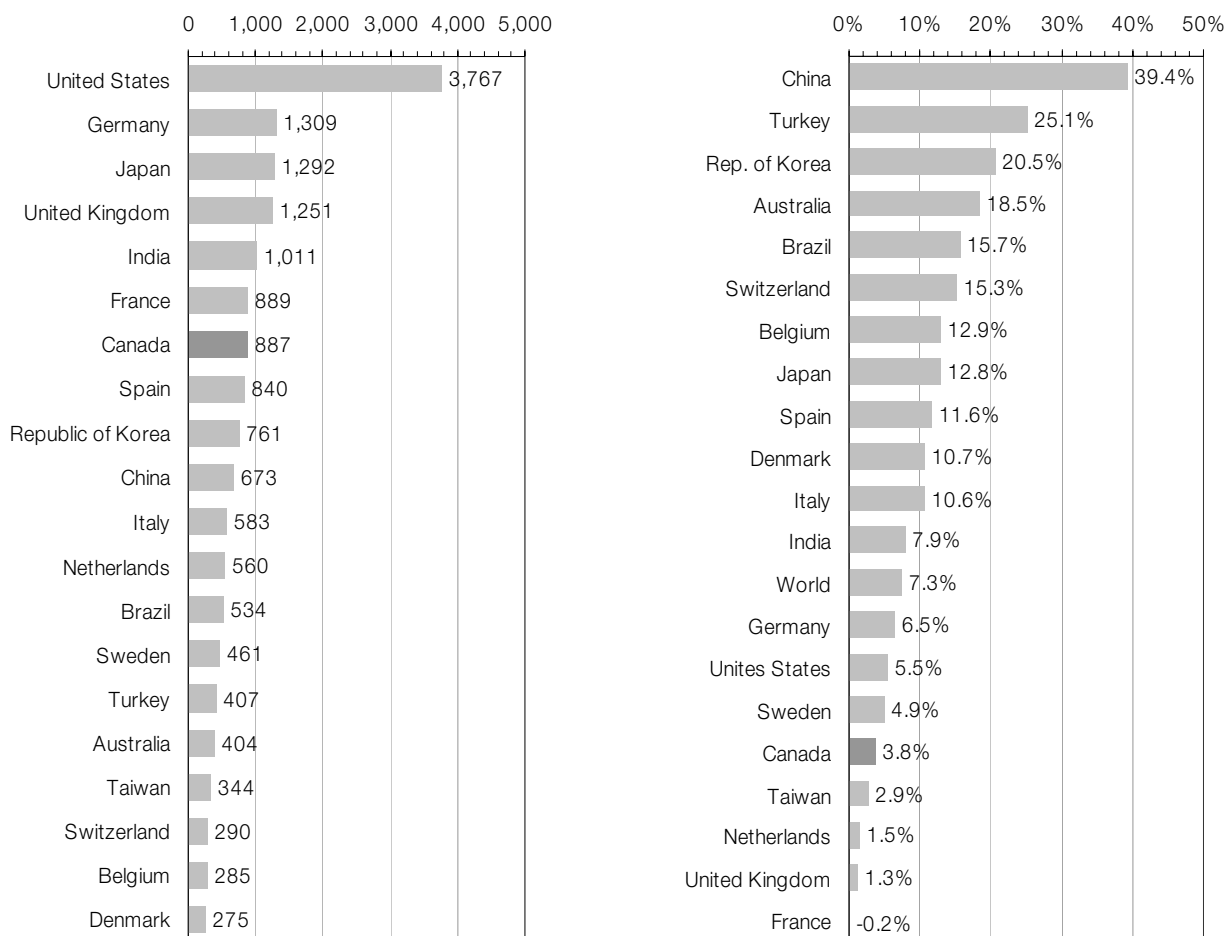


Figure 21 Number and average yearly growth of papers in bioproducts and bioprocesses by leading countries, 1998-2002

Note: Countries with more than 250 papers over the five-year period measured.
 Source: Compiled by Science-Metrix from data prepared by ISI Thomson.

Table XIV shows that between 1998 and 2001 the number of papers at the world level grew slowly and steadily. Over the same period, the output of many leading countries stayed at more or less the same level as that observed in 1998. Data presented in Table XIV indicates that Canada was overtaken by Spain, the Republic of Korea, and China in 2002. This suggests that, with everything being equal, Canada will certainly no longer be in the top-ten leading countries by 2005. Like Germany, the United States, Sweden, the Netherlands, and the United Kingdom, Canada experienced slower growth than the average observed at the world level. Canada's scientific output remained stable from 1999 to 2002, and kept up with that of Spain, the Republic of Korea, and China in 2002. In fact, Canada's position shifted downward in 2002, dropping from 7th to 10th position. The Republic of Korea and China showed the highest growth in output, and they have jumped from the 11th and 15th to the 6th and 7th ranks respectively. In 2002, Japan overtook Germany by 50 papers and will likely remain 2nd behind the US in the future.

Table XIV Papers by leading countries in bioproducts and bioprocesses, 1998-2002

Country	1998	1999	2000	2001	2002	1998-2002
United States	689	730	747	751	850	3,767
Germany	229	261	238	293	287	1,309
Japan	209	221	246	279	337	1,292
United Kingdom	251	224	278	245	254	1,251
India	165	199	212	213	222	1,011
France	192	160	187	165	183	889
Canada	157	182	179	189	180	887
Spain	127	150	164	208	191	840
Rep. of Korea	96	114	172	184	195	761
China	60	85	139	168	221	673
Italy	96	103	132	114	138	583
Netherlands	109	118	103	118	113	560
Brazil	76	95	118	113	132	534
Sweden	95	82	90	85	109	461
Turkey	54	67	67	91	128	407
Australia	55	73	91	81	104	404
Taiwan	68	51	70	92	62	344
Switzerland	46	69	50	54	71	290
Belgium	44	48	68	58	67	285
Denmark	48	39	55	68	65	275
World	3,036	3,278	3,564	3,724	4,029	17,633

Source: Compiled by Science-Metrix from data prepared by ISI Thomson.

6.2.2 Benchmarking Canada's scientific impact at the international level

The impact factor (IF) is used to evaluate the expected impact of papers from each country, which can then be compared to other papers in bioproducts and bioprocesses at the world level. This indicator provides a proxy for the quality of the journals in which papers are published: the higher the value of the factor, the higher the average quality of a journal is.

For instance, for the whole five-year period measured, Switzerland published papers whose expected impact was considerably higher (by 81%) than that of other countries (Table XV). Switzerland is followed by the United States, Denmark, the Netherlands and Germany, all of which published papers on bioproducts and bioprocesses in journals that were cited 30% to 39% more often than the field's world average.

On average, Canada published papers in journals that were cited 20% more than the world average. In 2002, the impact factor of Canadian papers increased to 47% more than the world average. The IF of the United Kingdom, Denmark, and the Netherlands grew more slowly, which explains why Canada jumped from 8th rank in 2001 to 4th in 2002 in terms of its IF. Even if Canadian scientific output in bioproducts and bioprocesses is not growing quickly enough to keep up with the rest of the world, Canadian authors are increasingly publishing.

Table XV Impact factor of leading countries in bioproducts and bioprocesses, 1998-2002

Country	1998	1999	2000	2001	2002	1998-2002
Switzerland	1.99	2.02	2.67	1.82	1.79	2.03
United States	1.39	1.60	1.47	1.56	1.77	1.57
Denmark	1.34	2.09	1.35	1.55	1.46	1.53
Netherlands	1.38	1.75	1.34	1.58	1.50	1.52
Germany	1.26	1.67	1.40	1.51	1.68	1.52
United Kingdom	1.26	1.42	1.28	1.32	1.50	1.35
Canada	1.08	1.35	1.16	1.44	1.65	1.35
Sweden	1.02	1.36	1.08	1.83	1.40	1.33
Belgium	1.26	1.41	1.33	1.19	1.38	1.31
Australia	1.07	1.34	1.17	1.41	1.35	1.29
France	1.11	1.22	1.13	1.44	1.29	1.23
Japan	1.15	1.21	1.01	1.21	1.42	1.22
Italy	1.08	1.26	1.17	1.16	1.24	1.19
Spain	1.10	1.15	1.21	1.16	1.24	1.18
China	0.89	1.06	0.89	1.14	1.13	1.05
Rep. of Korea	0.95	1.03	0.97	1.09	1.08	1.04
Taiwan	0.99	1.04	0.94	0.96	1.23	1.02
Brazil	0.73	0.86	0.91	0.99	1.06	0.93
India	0.77	0.83	0.82	1.00	1.08	0.91
Turkey	0.92	0.84	0.79	0.77	0.94	0.86
World	1.12	1.26	1.15	1.22	1.36	1.23

Source: Compiled by Science-Metrix from data prepared by ISI Thomson.

6.2.3 Benchmarking Canada's scientific specialization at the international level

The index of specialization provides an appreciation of the intensity of a country's scientific output in a given field, relative to its overall scientific output. Turkey, India, and the Republic of Korea have become the clear leaders in terms of specialization in bioproduct and bioprocess biotechnology (Table XVI). Brazil is a strong contender for the 4th place, probably due to its long-time efforts in the production of bioethanol. China has made a marked improvement on its initial position: it ranked 18th in 1998 and was 8th in 2002.

Since 1998, Canada has not produced as much in this field as one might have expected, given its share of the world scientific output in general. In fact, during the 1998-2001 period, Canada was the only G8 country with an index of specialization above 1. In order to put into perspective the Canadian performance in terms of the absolute number of papers, this section benchmarks Canada's concentration of efforts by speciality. Bioproduct and bioprocess papers were assigned to fields and subfields based on journal field classifications developed by CHI Research Inc. Starting from a list of more than 100 fields and subfields, only those fields with 100 articles or more at the world level were considered. Overall, six fields and 16 subfields are presented in the next two sections to characterize the output in bioproducts and bioprocesses science during the five-year period of the study. The fields of research are Biology, Biomedical Research, Chemistry, Earth & Space, Engineering & Technology, and Clinical Medicine & Health. Even if the focus of the study excludes

health and medical subjects, the CHI classification fields Biomedical Research, and Clinical Medicine & Health are presented here because they include journals pertinent to bioproduct and bioprocess biotechnology²².

Table XVI Index of specialization of leading countries in bioproducts and bioprocesses, 1998-2002

Country	1998	1999	2000	2001	2002	1998-2002
Turkey	3.17	3.16	2.76	3.05	3.06	3.09
India	2.61	2.76	2.87	2.57	2.37	2.63
Rep. of Korea	2.35	2.29	2.87	2.52	2.30	2.50
Brazil	2.25	2.35	2.53	2.15	2.16	2.30
Spain	1.51	1.60	1.59	1.85	1.51	1.62
Denmark	1.51	1.16	1.49	1.76	1.59	1.51
Taiwan	1.87	1.27	1.55	1.74	1.07	1.48
Sweden	1.55	1.24	1.28	1.11	1.36	1.30
Netherlands	1.40	1.43	1.14	1.25	1.09	1.25
Belgium	1.09	1.10	1.44	1.16	1.20	1.20
Canada	1.13	1.20	1.11	1.14	0.99	1.11
China	0.72	0.83	1.13	1.15	1.22	1.07
Switzerland	0.83	1.13	0.75	0.81	0.98	0.90
Germany	0.85	0.91	0.76	0.90	0.82	0.85
Australia	0.63	0.78	0.91	0.76	0.89	0.80
Italy	0.79	0.78	0.91	0.73	0.80	0.80
France	0.98	0.76	0.83	0.70	0.74	0.79
Japan	0.74	0.72	0.74	0.80	0.90	0.78
United Kingdom	0.88	0.72	0.81	0.71	0.70	0.76
United States	0.65	0.64	0.61	0.59	0.62	0.62
World	1.00	1.00	1.00	1.00	1.00	1.00

Source: Compiled by Science-Metrix from data prepared by ISI Thomson.

The Republic of Korea is the most specialized country in the field of Biomedical Research and ranks 6th in terms of output. This high degree of specialization coupled with an average annual growth of more than 20% in this field indicates that the Republic of Korea will likely lead this field in a near future. Spain and China are also highly specialized, being ranked 2nd and 3rd. Canada does not excel in this field, since its five-year output ranks 9th behind France and Spain, and 18th in terms of

²² In fact, the Biomedical Research field groups all the major journals that publish articles related to bioproducts and bioprocesses. Here is as sample of journals classified in the Biomedical Research field by CHI Research that focus on bioproduct and bioprocess biotechnology: Applied and Environmental Microbiology; Applied Biochemistry and Biotechnology; Applied Microbiology and Biotechnology; Biocatalysis and Biotransformation; Biodegradation; Journal of Biotechnology; Bioresource Technology; Biotechnology and Bioengineering; Biotechnology Letters; Biotechnology Progress; Enzyme and Microbial Technology; Journal of Chemical Technology and Biotechnology; Journal of Industrial Microbiology and Bioengineering; Process Biochemistry. The field of Clinical Medicine & Health also includes environmental-based journals such as Environmental Pollution and Environmental Health Perspectives.

specialization. However, Canada is fairly well positioned in the Microbiology subfield, as it ranks 4th in terms of its number of papers and 5th in terms of its specialization.

In terms of scientific output at the world level, Earth & Space is the second most important field in bioproduct and bioprocess biotechnology, and Canada ranks 2nd here. Environmental Sciences is the major specialty in terms of papers, and it is an area of excellence for Canada, as it ranks 2nd in terms of number of papers and 4th in terms of specialization.

The third field of importance is Engineering & Technology. Canada ranks 4th overall in this field—2nd in the Material Science subfield and 5th in the Chemical Engineering subfield. India is a strong player in Engineering & Technology, where it ranks 2nd. Also noteworthy, is India's ranking 1st in Chemical Engineering, in front of the US. Even if the field of Biology is relatively small in bioproducts and bioprocesses biotechnology, Canada is in a good position here, ranking 5th in terms of number of papers. Japan is the most specialized country in Biology, especially in Agri-Food Science, where it ranks 1st for its output. Canada did not perform well in Chemistry (rank 11th with 35 papers). Surprisingly, Spain produced the same output as the US in Analytical Chemistry. Japan is clearly the leader in polymer research, producing nearly twice the US output and being the most specialized country.

Table XVII Papers of leading countries in bioproducts and bioprocesses by field and subfield*, 1998-2002

	United States	Germany	Japan	United Kingdom	India	France	Canada	Spain	Rep. of Korea	China	Italy	Netherlands	Brazil	Sweden	Turkey	Australia	Taiwan	Switzerland	Belgium	Denmark	World
Biology	362	92	138	90	35	58	81	56	28	29	37	25	25	30	3	48	7	15	14	22	1,249
Agri-Food Science	201	45	118	45	20	24	43	35	16	16	21	8	14	13	3	27	4	2	5	11	712
Botany	42	21	11	16	5	15	17	5	7	2	1	3	2	12		7	1	5	3	2	175
Marine Bio. & Hydrobiology	49	9	9	12	4	10	10	7	5	6	8	7	2	2		9	1	2	2	7	168
Biomedical Research	1,409	646	642	585	529	381	338	451	514	332	216	291	242	181	172	159	158	128	113	116	7,988
Biochemistry & Molecular Bio.	135	31	41	37	24	21	22	25	16	17	25	27	44	24	1	6	2	7	6	7	524
Biomedical Engineering	730	401	496	423	413	281	209	363	418	276	157	196	162	127	160	100	137	72	76	76	5,583
Genrl Biomedical Research	37	11	3	10	23	4	5	2	8	8	2	3	2	7	1	1	1	4	1	2	117
Microbiology	438	195	94	108	68	70	98	58	81	28	27	60	34	21	8	50	16	40	27	28	1,606
Chemistry	298	64	100	74	44	75	35	67	22	39	68	17	43	25	19	12	11	24	13	7	1,120
Analytical Chemistry	38	17	9	19	1	11	9	39	1	3	11	3	7	7	10	2	2	4	5	2	194
Applied Chemistry	38	7	4	7	6	5	3	6	3	2	2	1	2	2	6	3	2	4	2	2	122
General Chemistry	144	7	17	10	23	3	8	4	7	9	13	2	8	2	1	2	3	8	2	2	302
Physical Chemistry	41	18	27	23	7	35	12	14	2	7	29	7	15	12	2	5	5	8	3	2	279
Polymers	23	9	42	13	6	18	1	4	9	16	13	3	12	3	2	1	1	1	3	2	186
Earth & Space	800	216	144	189	48	166	223	91	82	101	89	134	46	55	76	89	106	61	81	87	2,823
Environmental Science	709	182	139	173	46	137	200	90	81	99	80	121	39	53	76	85	106	56	76	85	2,637
Engineering & Technology	226	88	96	121	163	73	116	91	49	48	63	26	58	62	75	28	41	16	19	16	1,601
Chemical Engineering	127	63	67	88	133	53	67	69	45	31	48	12	35	35	57	21	36	12	16	7	1,130
Materials Science	37	8	10	10	3	7	31	9	10	10	1	2	8	7	2	2	2	1	2	2	159
Misc. Eng & Technology	13	6	5	16	21	2	2	3	1	3	6	4	2	12	12		2		1	2	125
Clinical Medicine & Health	127	39	25	30	12	15	16	7	4	8	18	9	5	5	1	7	1	13	2	3	335
Total	3,767	1,309	1,292	1,251	1,011	889	887	840	761	673	583	560	534	461	407	404	344	290	285	275	17,633

Source: Compiled by Science-Matrix from data prepared by ISI Thomson.

*Fields at the world level that had fewer than 100 papers over the period studied are not shown.

Table XVIII Index of specialization of leading countries in bioproducts and bioprocesses by field and subfield*, 1998-2002

	United States	Germany	Japan	United Kingdom	India	France	Canada	Spain	Rep. of Korea	China	Italy	Netherlands	Brazil	Sweden	Turkey	Australia	Taiwan	Switzerland	Belgium
Biology	1.4	1.0	1.5	1.0	0.5	0.9	1.3	0.9	0.5	0.6	0.9	0.6	0.7	0.9	0.1	1.7	0.3	0.7	0.7
Agri-Food Science	1.3	0.9	2.3	0.9	0.5	0.7	1.2	1.0	0.5	0.6	0.9	0.4	0.6	0.7	0.2	1.7	0.3	0.1	0.4
Botany	1.1	1.6	0.8	1.3	0.5	1.7	2.0	0.6	0.9	0.4	0.1	0.6	0.5	2.5	0.0	1.8	0.2	1.7	1.2
Marine Bio. & Hydrobiology	1.4	0.7	0.7	1.0	0.4	1.2	1.2	0.9	0.7	0.9	1.5	1.2	0.3	0.4	0.0	2.4	0.3	0.6	0.9
Biomedical Research	0.8	1.1	1.1	1.0	1.2	0.9	0.8	1.2	1.5	1.1	0.8	1.2	1.0	0.9	0.9	0.9	1.0	1.0	0.9
Biochemistry & Molecular Bio.	1.2	0.8	1.1	1.0	0.8	0.8	0.8	1.0	0.7	0.9	1.5	1.6	2.8	1.7	0.1	0.5	0.2	0.9	0.7
Biomedical Engineering	0.6	1.0	1.2	1.1	1.3	1.0	0.7	1.4	1.7	1.3	0.9	1.1	1.0	0.9	1.2	0.8	1.3	0.8	0.8
Genrl Biomedical Research	1.5	1.2	0.4	1.2	3.4	0.7	0.8	0.3	0.0	1.8	0.4	0.9	0.5	2.4	0.3	0.3	0.0	2.1	0.4
Microbiology	1.3	1.6	0.8	0.9	0.7	0.9	1.2	0.8	1.2	0.5	0.5	1.2	0.7	0.5	0.2	1.4	0.5	1.5	1.0
Chemistry	1.2	0.8	1.2	0.9	0.7	1.3	0.6	1.3	0.5	0.9	1.8	0.5	1.3	0.8	0.7	0.5	0.5	1.3	0.7
Analytical Chemistry	0.9	1.2	0.6	1.4	0.1	1.1	0.9	4.2	0.1	0.4	1.7	0.5	1.1	1.5	2.2	0.4	0.0	1.3	1.6
Applied Chemistry	1.4	0.7	0.5	0.8	0.8	0.8	0.5	1.0	0.6	0.5	0.6	0.2	0.4	0.0	2.0	1.2	1.0	0.0	0.8
General Chemistry	2.2	0.3	0.8	0.5	1.3	0.2	0.5	0.3	0.5	0.8	1.3	0.3	0.9	0.2	0.1	0.2	0.6	1.7	0.0
Physical Chemistry	0.7	0.9	1.3	1.2	0.5	2.5	0.9	1.0	0.2	0.7	3.1	0.7	1.7	1.7	0.0	0.8	0.9	1.8	0.7
Polymers	0.6	0.7	3.1	1.0	0.5	1.9	0.1	0.5	1.1	2.2	2.1	0.6	2.0	0.7	0.6	0.2	0.0	0.3	1.1
Earth & Space	1.3	1.0	0.7	0.9	0.3	1.2	1.6	0.7	0.7	0.9	1.0	1.5	0.5	0.7	1.2	1.4	1.9	1.3	1.8
Environmental Science	1.3	0.9	0.7	0.9	0.3	1.0	1.5	0.7	0.7	1.0	0.9	1.4	0.5	0.8	1.2	1.4	2.1	1.3	1.8
Engineering & Technology	0.7	0.7	0.8	1.1	1.8	0.9	1.4	1.2	0.7	0.8	1.2	0.5	1.2	1.5	2.0	0.8	1.3	0.6	0.7
Chemical Engineering	0.5	0.8	0.8	1.1	2.1	0.9	1.2	1.3	0.9	0.7	1.3	0.3	1.0	1.2	2.2	0.8	1.6	0.7	0.9
Materials Science	1.1	0.7	0.8	0.9	0.4	0.8	3.9	1.2	0.0	1.6	0.2	0.5	1.7	1.8	0.4	0.0	0.8	0.3	0.0
Misc. Eng & Technology	0.5	0.6	0.5	1.8	2.9	0.3	0.3	0.6	0.2	0.7	1.4	1.0	0.7	3.5	4.3	0.0	0.7	0.0	0.4
Clinical Medicine & Health	1.8	1.6	1.0	1.3	0.6	0.9	0.9	0.5	0.3	0.6	1.6	0.8	0.5	0.6	0.1	1.0	0.1	2.4	0.5
Total	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Source: Compiled by Science-Matrix from data prepared by ISI Thomson.

* Fields at the world level that had fewer than 100 papers over the period studied are not shown.

It is clear that Canada's recent output and specialization does not signal a bright future for Canadian R&D in bioproducts and bioprocesses, with exceptions in the Environmental Science and Biology fields. Moreover, Canada performed well in Engineering & Technology in the last five years, but it will certainly be surpassed by other countries that showed larger growth in output and specialization.

Specialization by type of input, bioprocess, output and sector of application

This section presents a more detailed statistical investigation of Canada's degree of specialization compared to that of the world, looking at factors such as input (raw biological material), bioprocesses (material transformation), output (end products), and sector of industrial, commercial or societal application. This statistical exploration aims to evaluate Canada's R&D strengths and weaknesses in greater detail.

Input

Statistically, between 1998 and 2002, Canada made the same scientific effort as the world on research issues related to bioproducts (raw material). Canada is no more or less specialized than the international community in research on agricultural and forest products or by-products or on industrial and domestic waste materials.

Bioprocess

Bioremediation is one of Canada's strengths in this field. However, Canada does not put as much effort into biobleaching, biosynthesis, bioconversion, and composting as other countries do.

Output

Biofuel research is a Canadian research specialty, when compared to the world. Biomaterials, biomolecules, biopesticides, and bioplastics are four subjects that were least covered by Canadian scientific papers in the sample of papers considered.

Sector of application

Environment is a clear specialty of Canadian science, as the country ranks 2nd in terms of number of publications and 1st in terms of its specialization index.

Table XIX Canadian and world papers by input, bioprocess, output, and sector of application, 1998-2002

	1998-2002		Basic statistics	
	Canada	World	z-value	Significance*
Input (Raw material)				
Agricultural products & byproducts	56%	61%	-0.972	
Forest products & other lignocellulosic material	24%	22%	0.351	
Industrial & domestic wastes	20%	16%	0.841	
Bioprocess				
Bioprocess - general	2.6%	2.0%	0.362	
Biobleaching	0.0%	1.7%	-2.717	○
Biopulping	0.0%	0.7%	-1.709	
Biosynthesis & bioconversion	1.3%	10.1%	-4.821	○
Fermentation	11.8%	8.8%	0.906	
Composting	0.0%	1.3%	-2.426	○
Bioleaching	2.6%	2.7%	-0.036	
Biomonitoring	1.3%	2.0%	-0.545	
Bioreactor	11.8%	12.1%	-0.080	
Bioremediation	30.3%	15.8%	3.023	●
Biotreatment	34.2%	34.7%	-0.092	
Enzyme Technologies	2.6%	5.7%	-1.619	
Genetic engineering	1.3%	2.4%	-0.788	
Output (End product)				
Biofuel	45.5%	28.1%	3.290	●
Biomaterials	0.0%	1.1%	-2.213	○
Biomolecules	30.3%	41.6%	-2.237	○
Biopesticides	0.0%	1.7%	-2.718	○
Fertilizer	12.1%	7.3%	1.419	
Bioplastics	0.0%	9.6%	-6.746	○
Bioproducts	0.0%	0.6%	-1.560	
Metals & other inorganic compounds	6.1%	4.5%	0.623	
Paper	6.1%	5.1%	0.396	
Particle board	0.0%	0.6%	-1.560	
Sector of application				
Agriculture	3.3%	3.7%	-0.168	
Aquaculture	0.0%	0.3%	-1.103	
Social sciences	0.0%	0.6%	-1.563	
Energy	14.4%	10.4%	1.086	
Power Plant	1.1%	2.3%	-0.921	
Environment	56.7%	44.2%	2.323	●
Forestry, Pulp & Paper	2.2%	2.8%	-0.364	
General bioprocesses	11.1%	8.2%	0.888	
Industrial	8.9%	25.4%	-4.760	○
Mining & Metallurgy	2.2%	2.3%	-0.020	

- Canadian is more specialized than the World
- Canadian is less specialized than the World

*Percentages are significantly different when the z-value is outside the following range [-1.96, 1.96] (=5% level of confidence)

Source: Compiled by Science-Metrix from data prepared by ISI Thomson.

6.2.4 Benchmarking of Canadian Provinces

This section aims to identify Canadian R&D dynamics and players in bioproducts and bioprocesses according to geographical, sectorial, and institutional dimensions. More precisely, scientific output will be presented by province, CMA, sector of activity, and institution.

Scientific output by province

Table XX reveals that Ontario and Quebec are clearly the leaders in bioproduct and bioprocess science in Canada, but, similar to Canada as a whole, both provinces have experienced flat growth over the last three years. This observation is also applicable to provinces with a smaller output, for example, British Columbia and Saskatchewan. Only Alberta experienced regular output growth between 1999 and 2002. Nova Scotia is the only Atlantic province with a sizeable output in the field.

Table XX Papers in bioproducts and bioprocesses by Canadian province, 1998-2002

Province	1998	1999	2000	2001	2002	1998-2002
Ontario	55	62	62	79	69	328
Quebec	50	62	71	53	63	298
British Columbia	26	25	19	25	15	110
Alberta	14	12	16	19	21	82
Saskatchewan	12	16	9	19	13	70
Nova Scotia	2	12	4	2	7	27
Manitoba	4	6	2	6	6	24
New Brunswick	6	1	4	4	4	19
Newfoundland	2	2		2		7
Prince Edward Island	1	2				2
Canada	157	182	179	189	180	887

Source: Compiled by Science-Metrix from data prepared by ISI Thomson.

Scientific output by CMA

In this section, data is presented on CMAs where more than 25 papers were published during the 1998-2002 period. Montreal is clearly the leading Canadian CMA in terms of the absolute number of papers in bioproducts and bioprocesses. It is followed by Vancouver, Toronto, and Quebec City. Each of these CMAs published more than 80 papers over the period studied. Other CMAs that produced between 50 and 60 papers (i.e.: a yearly average production of 10 papers) over the period studied are Waterloo, Ottawa, Saskatoon, Edmonton, and Guelph. Other CMAs are more marginal players in Canadian peer-reviewed scientific output.

Table XXI Papers in bioproducts and bioprocesses by Canadian CMA, 1998-2002

City	1998	1999	2000	2001	2002	1998-2002
Montreal	30	40	47	35	36	188
Vancouver	22	25	17	22	14	100
Toronto	12	17	18	21	19	88
Quebec	13	16	18	16	21	84
Waterloo	7	10	12	16	12	57
Ottawa	13	7	11	9	12	53
Saskatoon	7	12	6	16	10	49
Edmonton	10	2	11	12	15	49
Guelph	7	9	13	9	11	49
Sherbrooke	6	5	11	7	4	32
Kingston	2	7	5	8	9	31
London	3	5	5	7	8	29
Dartmouth/Halifax	2	12	4	2	7	26
Calgary	4	7	4	7	5	26
Canada	157	182	179	189	180	887

Source: Compiled by Science-Metrix from data prepared by ISI Thomson.

Scientific output by sector of activity

Not surprisingly, the university sector leads (Table XXII). Between 1998 and 2002, 38 universities participated in 80% of Canadian scientific output in bioproducts and bioprocesses. Nine federal government institutions were responsible for 21% of the output, and companies took part in 14%. More than 100 private firms participated in at least one peer-reviewed publication, which suggests that this sector has an adequate receptor capability. The near absence of the clinics and hospital sector is consistent with the non-health-related definition of bioproduct and bioprocess biotechnology that is used for this R&D strategy.

Table XXII Papers, contribution and number of institutions in bioproducts and bioprocesses by sector of activity, 1998-2002

Sector	1998	1999	2000	2001	2002	1998-2002	% Canadian papers	Number of institutions
Universities	123	150	138	152	149	712	80%	38
Federal Government	30	39	38	35	44	187	21%	9
Companies	31	26	25	23	21	127	14%	106
Others	7	7	7	9	1	31	4%	20
Provincial Governments	5	4	6	2	2	18	2%	9
Clinics and Hospitals	1	1		2	2	6	1%	4
Canada (n)	157	182	179	189	180	887	100%	186

Source: Compiled by Science-Metrix from data prepared by ISI Thomson.

Canadian scientific output by leading institution

Table XXIII lists the most active institutions (those with at least 5 papers) in bioproduct and bioprocess biotechnology in terms of number of papers and scientific impact by sector of activity, between 1998 and 2002. The top ranking institution during that period was the University of British Columbia with 82 publications: the university accounted for approximately 9% of Canadian research papers in this field. This is consistent with NSERC funding data presented earlier.

Table XXIII Papers and impact factor in bioproducts and bioprocesses by sector of activity and leading institution (5 papers or more), 1998-2002

Sector/Institution	Papers	IF	Rank (Papers)
Universities (n=38)	712	1.34	
University of British Columbia	82	1.37	1
McGill University	75	1.83	2
University of Toronto	55	1.84	5
University of Waterloo	55	1.39	5
Université Laval	50	1.38	7
University of Guelph	45	1.29	8
Institut National de la Recherche Scientifique (INRS)	41	1.27	9
University of Alberta	39	1.14	10
University of Saskatchewan	37	1.10	11
Université de Montréal	34	1.33	12
Queen's University	29	1.73	14
Ottawa University	27	1.09	15
Université de Sherbrooke	25	0.94	16
University of Western Ontario	24	0.79	17
Dalhousie University	22	0.59	18
University of Calgary	20	1.18	19
Université du Québec (UQ)	18	1.12	20
University of Regina	17	0.81	21
University of Manitoba	16	1.59	22
University of New Brunswick	14	0.86	24
Ryerson Polytechnic University	8	n.s.	27
McMaster University	7	n.s.	29
Simon Fraser University	6	n.s.	30
University of Windsor	6	n.s.	30
Memorial University of Newfoundland	5	n.s.	33
Federal Government (n=9)	187	1.53	
National Research Council Canada	66	1.91	3
Agriculture and Agri-food Canada	64	1.02	4
Environment Canada	33	1.31	13
Natural Resources Canada	16	2.54	22
Department of Fisheries and Oceans Canada	11	1.38	26
Department of National Defence	8	n.s.	27
Companies (n=106)	127	0.90	
Reid Crowther & Partners Ltd.	6	n.s.	30
CH2M HILL Canada Ltd.	5	n.s.	33
Pyrovac International Inc.	5	n.s.	33
Others (n=20)	31	1.14	
Pulp And Paper Research Institute of Canada (PAPRICAN)	12	n.s.	25
Provincial Governments (n=9)	18	2.04	
Alberta Research Council	5	n.s.	33
Clinics and Hospitals (n=4)	6	n.s.	

Source: Compiled by Science-Metrix from data prepared by ISI Thomson.

The previous table shows that McGill University ranked 2nd, with 75 publications. With 8.4% of Canadian biotechnology papers and a high impact factor, McGill University is at the core of Montreal's strength in biotechnology in terms of output and scientific impact.

Other universities with significant output in the field include the University of Toronto (55 papers; 6.2% of the Canadian output), the University of Waterloo (55 papers; 6.2%), and Université Laval (50 papers; 5.7%). The University of Toronto had a scientific impact, comparable to that of McGill University.

The 3rd and 4th places are taken by two major federal government departments: the National Research Council of Canada (66 papers) and AAFC (64 publications). The scientific impact of the NRC is remarkable, as it has the highest impact factor score measured among leading institutions with 50 papers or more. NRCan also has an outstanding impact factor, but a much smaller number of papers.

Most of the 100 companies contributed one or two papers over the five-year period studied. However, three of them produced at least five papers: Reid Crowther & Partners Ltd., CH2M HILL Canada Ltd., and Pyrovac International Inc.

6.3 Technological inventions in bioproducts and bioprocesses

This section examines the distribution of patents granted by the United States Patent and Trademark Office (USPTO) at the international and national levels. In particular, Section 6.3.1 examines the relative importance of bioproduct and bioprocess patents, and its rate of growth; Section 6.3.2 examines the distribution of patents by country, while Section 6.3.3 examines the distribution of patents at the provincial and institutional level.

6.3.1 Global trends

Between 1998 and 2001, the number of patents granted annually in bioproducts and bioprocesses by the USPTO decreased slightly, falling from 417 to 380 (Figure 22). The percentage of bioproduct and bioprocess patents granted relative to the number of total patents granted by the USPTO also decreased somewhat over the period, that is, from 0.3% to 0.2%. Canada owns between 4% and 5% of the patents granted by the USPTO over the five-year period studied, and bioproduct and bioprocess patents represents less than 1% of Canadian patents.

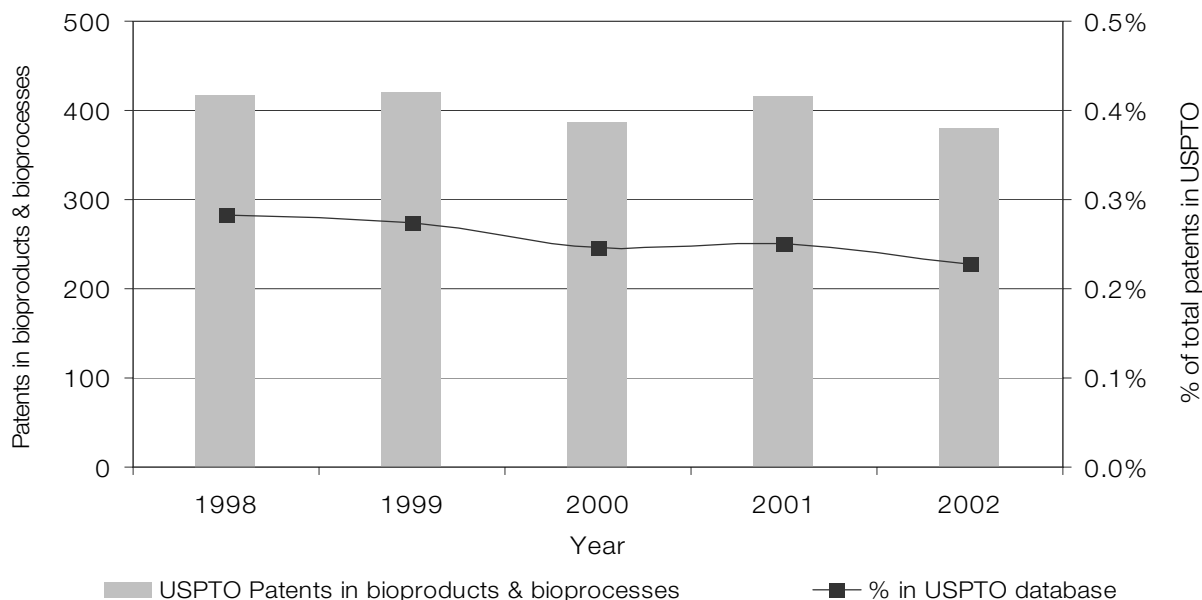


Figure 22 Patents in bioproduct and bioprocess biotechnology granted by the USPTO, 1998-2002

Source: Compiled by Science-Metrix from USPTO data.

6.3.2 Benchmarking Canada's technological inventions at the international level

With 93 patents, Canada ranks 4th in terms of number of bioproduct and bioprocess patents at the world level (Table XXIV). The clear leader is the US with 1,195 patents, followed by Japan with 205, and Germany with 167. Canada's performance is excellent considering that it has more patents than countries that are much larger in terms of population, such as the UK and France.

Even if Canada holds only a small percentage of its patents in this field (Figure 23), Canada ranks high in terms of specialization compared to other leading countries. In fact, for the five-year period studied, Canada owns twice the percentage of world IP in this field as in all fields combined.

Between 1998 and 2002, the number of Canadian patents granted by the USPTO was quite stable and ranged between 17 and 20 patents a year (Table XXIV). This flat technological output is similar to that observed by other leading countries. In fact, when the small number of patents is taken into account, no individual country can be identified as an emergent producer of bioproduct and bioprocess inventions.

Table XXIV Number of patents and index of specialization of leading countries in bioproduct and bioprocess biotechnology, 1998-2002

Country	1998		1999		2000		2001		2002		1998-2002	
	Patent	I.S.	Patent	I.S.	Patent	I.S.	Patent	I.S.	Patent	I.S.	Patent	I.S.
United States	255	1.1	249	1.0	237	1.1	236	1.0	218	1.1	1,195	1.1
Japan	40	0.5	44	0.5	43	0.6	43	0.5	35	0.4	205	0.5
Germany	31	1.3	31	1.3	31	1.3	44	1.6	30	1.2	167	1.3
Canada	17	2.2	20	2.4	20	2.5	18	2.1	18	2.4	93	2.3
United Kingdom	11	1.5	9	1.2	7	1.0	11	1.5	13	2.2	51	1.5
France	8	0.8	12	1.2	8	0.9	8	0.8	12	1.4	48	1.0
Netherlands	3	1.2	9	3.8	6	2.7	9	4.0	6	1.5	33	2.5
Switzerland	7	1.9	5	1.2	10	2.7	4	0.9	5	1.3	31	1.6
Denmark	5	4.7	6	4.9	3	2.9	7	6.1	7	7.6	28	5.2
Rep. of Korea	4	0.4	6	0.6	3	0.4	4	0.4	8	0.9	25	0.6
Finland	4	2.2	9	4.6	2	1.2	5	2.3	2	0.9	22	2.2
Sweden	2	0.6	4	1.0	7	1.7	4	0.9	5	1.2	22	1.1
Israel	2	1.2	3	1.9	1	0.6	5	2.7	5	2.8	16	1.9
Italy	4	1.0	4	1.1	1	0.3	2	0.5	3	0.9	14	0.8
Australia	5	2.7	1	0.6	3	1.9	1	0.5	1	0.6	11	1.2
World	417	1.0	421	1.0	387	1.0	416	1.0	380	1.0	1,021	2,021

Source: Compiled by Science-Matrix from USPTO data.

6.3.3 Benchmarking Canada's technological inventions at the national level

Table XXV shows that Ontario has the largest number of patents (37); Quebec follows with 25 patents. British Columbia and Alberta are the two other main players in patenting bioproduct and process biotechnologies. Other provinces are absent or quasi-absent, resulting in that Ontario and Quebec are accountable for the great majority of Canadian technological invention in the field.

Table XXV Patents in bioproduct and bioprocess biotechnology by Canadian province, 1998-2002

Province	1998	1999	2000	2001	2002	1998-2002
Ontario	7	7	9	8	6	37
Quebec	6	7	4	1	7	25
British Columbia	1		6	4	3	14
Alberta		5	1	3		9
Nova Scotia	1					1
New Brunswick		1				1
Prince Edward Island				1		1
Manitoba						0
Saskatchewan						0
Newfoundland						0
Unknown	2	1	1			5
Canada (n)	17	20	21	17	16	91

Source: Compiled by Science-Matrix from USPTO data.

6.3.4 Canadian technological inventions by sector of activity and institution

This section presents statistics on US patents owned by Canadian institutions that were granted at least one patent per year, on average, during the period examined (1998-2002). There are 86 Canadian institutions and individuals with at least one patent in bioproduct and bioprocess biotechnology. Table XXVI presents the leading institutions (with more than one patent) and the sectorial distribution of IP in bioproduct and bioprocess biotechnology patents in Canada. There are nearly five times as many corporations (n=32) than university-sector (n=7) and government-sector (n=6) institutions who own patents in the field. Individual inventors are more numerous than any other sector of activity.

Table XXVI Number of patents in bioproduct and bioprocess biotechnology by sector of activity and institution, 1998-2002

Sector/Institution	Patent
Individual (n=38)	25
Corporation (n=32)	42
logen Corporation	5
Ensyn Engineering Associates Inc.	2
RTI Resource Transforms International Ltd.	2
Zenon Environmental Inc.	2
Ballard Power Systems Inc.	2
Cargill, Limited	2
Echo Bay Mines, Limited	2
Government (n=6)	13
National Research Council of Canada	4
Agriculture and Agri-Food Canada	3
Natural Resources Canada	2
Alberta Research Council	2
University (n=7)	8
McGill University	2
Other (n=3)	3
Canada (n)	91

Source: Compiled by Science-Metrix from USPTO data.

With 42 patents over the five-year period, corporations clearly lead in Canadian technological output in the field. The second major producer is the government-sector. Surprisingly, universities were not granted many patents in the field, when observed in relation to their IP portfolio in the broad field of biotechnology, which includes health and biomedical patents (Parent *et al.* 2003). The intellectual property in bioproducts and bioprocesses is clearly in the hands of the same corporations that published in peer-reviewed papers. This, again, suggests that the private sector is highly receptive to research and technological innovation in the field of bioproducts and bioprocesses.

7 R&D on bioproducts and bioprocesses in Europe and North America

The purpose of this section is to describe current practices in funding and fostering non-food, non-medical research on bioproducts and bioprocesses. This study looks at both international and Canadian perspectives to obtain a better understanding of the sources, structure, and general functioning of funding and of its beneficiaries.

The policies and organizations involved are analyzed country by country, except for the International Energy Agency's (IEA) IEA Bioenergy, which is briefly analysed here. Established in 1974 by the IEA, itself a part of the Organisation for Economic Co-operation and Development, IEA Bioenergy's aim is to improve cooperation between member countries to develop efficient bioenergy technologies. IEA Bioenergy has been promoting the use of electricity, liquid fuel, and green chemicals in industry. This organization does not fund R&D; rather, it brings together industries, governments, and research institutions from different countries for the accomplishment of defined tasks, with each participant providing a share of the cost and the work. IEA Bioenergy is thus an umbrella organization that coordinates work between actors from different countries.

The EU and European countries such as Finland, France, and the United Kingdom have drafted policies and programs to foster research in the field of bioproduct and bioprocess R&D. Finland has developed bioenergy uses for the residues of its wood industry (Wood Energy Technology Programme). The United Kingdom has explored the field of industrial biotechnology with a few policies and programs (BIOWISE and Link Programme) and is planning to release a strategy for non-food crops in 2004, with the help of the newly created National Non-Food Crops Centre. France also has its own program (Agriculture for Chemicals and Energy). The EU has no initiative exclusively dedicated to bioproducts and bioprocesses. Most projects are funded through programs directed at developing renewable energy sources or bringing together the agricultural base with industries (Sixth RTD Framework Programme, AIR Programme, FAIR Programme, ECLAIR Programme).

The US is the only country to have a cohesive, articulate, and thorough policy concerning research and development in bioproducts and bioprocesses. The departments in charge are clearly established (DOE and USDA); legislations regulating research in the field have been adopted (Energy Policy Act of 1992, Title XII; Farm Bill of 2002; Biomass Research and Development Act of 2000) and relevant programs and operating bodies have been created (Biomass Research and Development Initiative, Biofuels Program). In comparison with those of the EU, US policies are targeted more specifically at bioproducts and bioprocesses. US programs also seem to be driven in great part by business opportunities and a policy based on energetic independence, while the European initiatives often place a greater emphasis on environmental concerns.

As for Canada, a variety of organizations are involved in funding and fostering research and development in the field of bioproducts and bioprocesses. A number of provincial and federal bodies (Canadian Forest Service and NRCan, Technology Partnerships Canada, Climate Change Action Fund, AAFC, Genome Canada) are involved in supporting Canadian research in the field, as well as some independent bodies (BioProducts Canada, Sustainable Development Technology Fund,

BIOCAP Canada). Canada, however, does not have a comprehensive framework to steer R&D on bioproducts and bioprocesses. Funding is available, but through bodies and measures that encompass a broad range of topics, usually environmental or agricultural in nature.

7.1 European support for R&D in bioproducts and bioprocesses

This section paints a picture of the situation in Europe in general, providing some examples of funding and promotional programs. First, the EU Framework Programme is examined, followed by programs in Finland, France, and the United Kingdom.

7.1.1 EU-level initiatives

Described as the funding arm of the European Research Area, which endeavours to improve European research in the context of a global market, the **Sixth Framework Programme** (FP6) began in 2002 and will continue until 2006 with a total funding amount of €17.5 billion. The goal of the program is to “[strengthen] the scientific and technological bases of industry and encourage its international competitiveness while promoting research activities in support of other EU policies” (EC 2002).

FP6 funding is available only to partnerships including members from two or more eligible European countries. The program only funds a portion of research, the applicants having to invest their own resources. Selection of projects is done by peer review. The main target groups for the FP6 program are research groups at universities or research institutions and innovative companies, in particular small or medium-sized enterprises, for which 15% of the budget has been set aside.

The program’s resources have been divided into three blocks, the main and most interesting one within the confines of this study being *Focusing and Integrating European Research*. Under this block, seven research priorities have been identified. Within these priorities, research on bioproducts and bioprocesses is funded through the *Sustainable Development, Global Change and Ecosystems* thematic priority. This priority, too, is divided into three fields, the one of particular interest being *Sustainable Energy Systems*, which deals mostly with bioenergy. The second call for projects, which closed in December 2003, had a €107 million budget²³.

Previous Framework Programme Initiatives: A number of initiatives were designed under previous Framework Programmes to fund research in areas encompassing bioproducts and bioprocesses. The ECLAIR Programme ran under the Second Framework Programme from 1988 to 1993, with the goal of fostering cooperation between agriculture and industry in research and development. Renewable bioproducts from non-food crops were developed in 40% of the 42 projects funded through the program, resulting in products such as detergents, bioplastics, and biomaterials (Mangan and Coombs).

²³ <http://www.dti.gov.uk/ent/energie/fp6.htm>

The AIR Programme (Agriculture and Agro-Industry including Fisheries Programme of Research and Technological Development) was adopted as part of the Third Framework Programme and ran from 1990 to 1996. Here again, the goal was to foster cooperation between the production base and the agro-industrial processing sector. Implementation was ensured through shared-cost research, technological development, demonstration projects, and similar measures. Of the 429 proposals selected for funding through the programme, 133 were non-food projects²⁴.

The FAIR program (Agriculture and Fisheries) ran from 1994 to 1998 with the goal of promoting and harmonizing research in food and non-food sectors and in agriculture, horticulture, forestry, fisheries and aquaculture. The program also wanted to establish links between research and industries and consumers; €646 million were spent by the European Commission²⁵. Six thematic areas were developed, two of which are of particular importance in the present document. Area 1, Integrated Production and Processing Chains, represented 15% of the budget and included 1.1) the biomass and bioenergy chain; 1.2) the “green” chemical and polymer chain, and 1.3) the forestry-wood chain. Area 2, Scaling-up and Processing Methodologies, accounted for 7% of the total FAIR budget and included point 2.2, bioprocessing²⁶.

The Joule-Thermie programme, under its renewable energies heading, also provided funds, for bioenergy research in particular. The program ran from 1994 to 1998. The goal of the program was to encourage research in new, clean, and efficient energies, and to foster cooperation between industries, universities, end users, and operators of energy networks.

7.1.2 National initiatives in Europe

Finland describes itself as the world leader in bioenergy, which contributes to 20% of the country’s total energy production. In 1999, Tekes, the Finnish National Technology Agency, established the **Wood Energy Technology Programme**. The purpose of the program, which ran until 2003, was to bring the forest chip production from wood-cutting residues to a large-scale, efficient level. The two guiding principles were close cooperation between researchers and practitioners and the application of R&D activities to commercial and practical uses. Funding was available to both research institutes and enterprises. The program was divided in three, with *projects undertaken by research institutes*, *projects dealing with product development* done by enterprises and *demonstration projects*. The program included an envelope totalling €35 million for R&D, of which €11 million were provided by TEKES for R&D, while the Finnish Ministry of Trade and Industry contributed €4 million for demonstration projects. The rest of the funding was provided by industries (mainly) and research institutes. As of November 2002, 85 projects in total had been initiated, with 35 by research institutes and companies and the remaining 15 being demonstration projects (Hakkila 2003). Figure 23 shows that developing technology for the bioeconomy requires sustained R&D over a long time.

²⁴ <http://www.nf-2000.org/secure/Air/S31.htm>

²⁵ <http://europa.eu.int/comm/research/agro/agro3.html>

²⁶ *Idem*

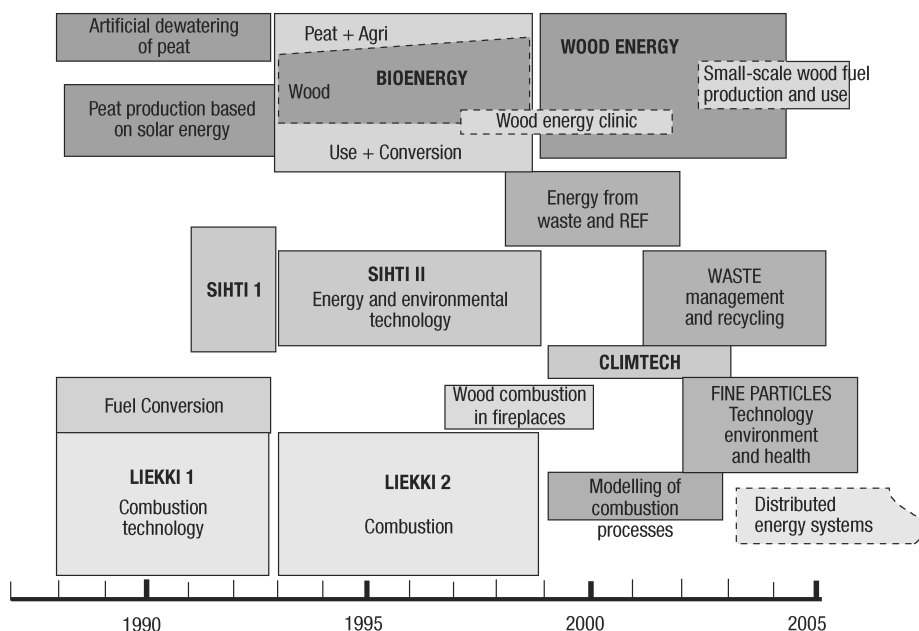


Figure 23 Tekes' bioenergy programs

Note: The area of a rectangle indicates the relative size of expenditure.
 Source: Hakkila 2003

Founded in 1994 by ADEME, the French *Agence de l'Environnement et de la Maitrise de l'Énergie* (the agency for the environment and energy efficiency), **Agriculture for Chemicals and Energy** (AGRICE) “focuses on new uses and enhanced value for agricultural products and by-products as energy, chemical and materials feedstocks. AGRICE is committed to coordinating, funding, monitoring, and evaluating research and development programs that further these goals.”²⁷

The group is composed of both public and private sector organisms, including research groups, businesses, and professional organizations. The ADEME manages the funds and monitors the group. A group council defines directions and grants for research, while a scientific council is responsible for helping to define orientations and conducting the selection process. 40% of the organization's funding comes from the ministries of Agriculture, Environment, Industry, and Research through the ADEME. The remaining sum is provided by research institutes (such as the CNRS, IFP, INRA), industries, and trade associations on a project-by-project basis. Projects to be funded are selected following requests for proposals, by a peer-review process involving experts and thematic working groups.

From 1994 to 2002, AGRICE funded 220 projects. The organization provided €19.8 million in public grants to these projects (AGRICE 2002). One project funded under the program is the *Direct Use of Ethanol as an Alternative Fuel for Fuel Cells*. This project, led by the Université de Poitiers and involving an engineering firm and a technical research organization studying beet crops, aims to develop catalysts that will eventually lead to the use of ethanol in automobile transport. The crops used are

²⁷ http://www.ademe.fr/partenaires/agrice/htdocs_gb/about.htm

beets and various grains. The cost of the project is €506,000, of which ADEME is contributing €141,000²⁸.

The German **Fachagentur Nachhaltende Rohstoffe eV** (Agency of Renewable Resources) was created in 1993 by the German Federal Ministry of Consumer Protection, Food, and Agriculture to coordinate activities in the field of renewable biological products. It is a registered association, with members including companies, interest groups, and representatives from the federal and local governments. Aside from promotion, advice, and public relation activities, it is responsible for project management on behalf of the government. It provides support for R&D activities from their very first stages to commercialization. It is currently in charge of two programs: the *Förderprogramm Nachhaltende Rohstoffe* (R&D program on renewable biological resources), with an annual budget of €26 million, and the *Markteinführungsprogramm Biogene Treib- und Schmierstoffe* (a market introduction program for biofuels and biolubricants), which benefits from €10 million annually²⁹.

In the UK, funding for bioprocesses and bioproducts was available, in part, through the **Competitive Industrial Materials from Non-Food Crops LINK Programme**. Run from 1996 to 2002 by the Department for Environmental, Food, and Rural Affairs (DEFRA) Arable Crops, Pesticide Safety, and Non-Food Research Unit, the program provided funding for the development of technology allowing the use of crop-derived material in industrial processes. The program benefited from £4 million in funding from the DEFRA and the Biotechnology and Biological Sciences Research Council, with other Departments participating in some cases³⁰. As with all LINK programs, funding was available to consortia formed of partners from the industry and the research base. The results are expected to be used for industrial and private purposes.

Part of the Rural Development Program overseen by DEFRA, the **Energy Crops Scheme** provides payments to farmers growing coppiced willow or miscanthus for bioenergy purposes. The program, which is an incentive program rather than one that supports R&D, is worth £29 million and pays farmers between £920 and £1600 per hectare of land reserved for these crops³¹. The payments are made under a five-year agreement between farmers and DEFRA. A number of requirements must be met before the agreement is finalized, such as proximity to end-users, compliance with environmental standards, and exclusive use of the crops for power or heat purposes.

The UK Department of Trade and Industry (DTI) developed the **BIO-WISE** program, which aims to improve performance of industries through the use of biotechnology and promote the development of the biotechnology industry. Aside from general promotional activities, BIO-WISE provides funding for demonstration projects using new biotechnologies. £3 million were awarded on a

²⁸ http://www.ademe.fr/partenaires/agrice/Fiches_GB/card_0101009.htm

²⁹ <http://www.nf-2000.org/secure/Other/S476.htm>

³⁰ <http://www.ost.gov.uk/link/foocim.html>

³¹ <http://www.nf-2000.org/secure/Other/S1368.htm>

competitive basis to 21 projects involving collaborations with UK industry³². These projects involved topics such as biomaterials, biosensors and bioremediation. Industrial sectors concerned include engineering, textiles, chemicals and construction.

In addition, the **Bioenergy Capital Grants Scheme** awards funding to organizations investing in heat and electricity production from biomass projects. This incentive program provides support for the cost of equipment. More than £66 million are available in funding, with £30 million being provided by the DTI and £36 million by the National Lottery New Opportunities Fund (DTI 2002). The scheme being competitive, applications are evaluated by an external contractor with a team of independent experts. The contractor also manages the awards process.

7.2 The US

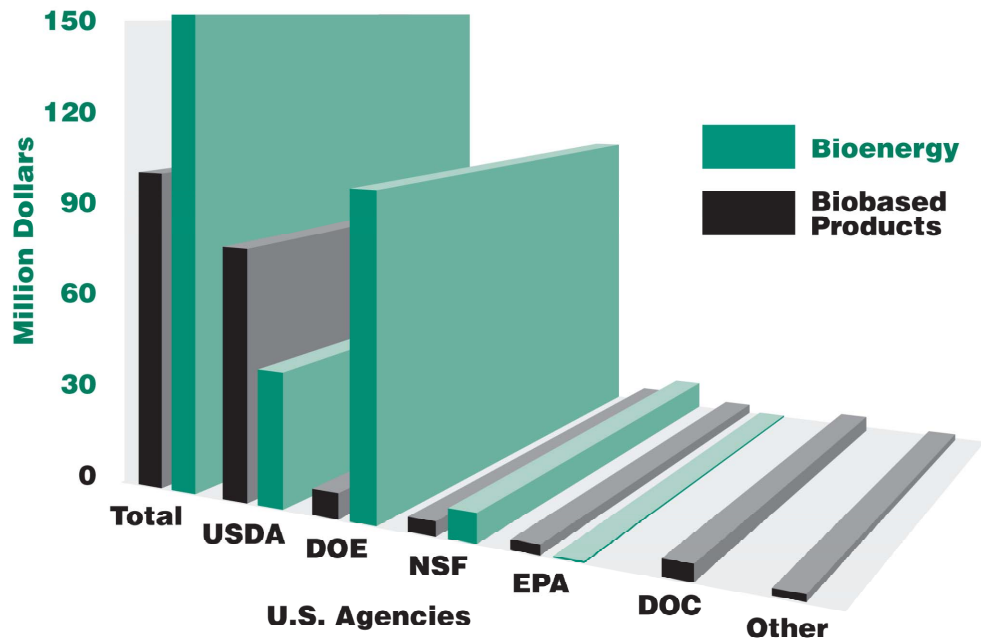
The US is the leader in the bioproducts and bioprocesses field, especially when it comes to biomass. A number of laws were passed in the past ten years that greatly strengthen the country's already leading position (section 7.2.1). Funding is substantial, with several million dollars being spent on R&D every year (Section 7.2.2).

7.2.1 The legislative framework

As early as 1978, the *Public Utilities Regulatory Policy Act* (PURPA) helped develop a US biomass industry. Environmental measures such as the *Clean Air Act* of 1990 further increased the demand for bioproducts as substitutes for traditional industrial products. Title XII of the 1992 *Energy Policy Act* provided funding for research projects dealing with the use of biomass for energy production. During the late 1990s, biobased products and bioenergy R&D already accounted for a quarter billion US dollars in federal budget expenditure (Figure 24).

³² <http://www.biowise.org.uk/list.asp?type=grantsupport&menucode=00100008¤tPage=1>

Fiscal Year 1998 Federal R&D Funding – \$253 Million



AREA	Funding		AREA	Funding	Percent
Percent	in millions of \$ of total			in millions of \$	of total
Bioenergy Science	\$53.5	21.1%	Biopower	\$23.7	9.4%
Biofuels	\$47.5	18.8%	Natural Structural Materials	\$17.6	6.9%
Crosscutting Science of	\$34.8	13.7%	Natural Fibers	\$12.3	4.9%
Biobased Products			Integrated Assessments	\$5.2	2.1%
Green Chemicals and Plastics	\$34.7	13.7%			
Biomass Resources	\$24	9.5%			

Figure 24 US federal funding for R&D on biobased products and bioenergy, 1998
 Source: BRDB, 2001

An important turning point in the field can be traced to the year 2000, with the adoption of the *Sustainable Fuels and Chemicals Act* and the *Biomass Research and Development Act*. These acts directed the Department of Energy (DOE) and the Department of Agriculture (USDA) to coordinate their efforts in developing efficient biobased fuels, chemicals, and power. The goal of the US administration was to triple the production of bioproducts and bioenergy by 2010. Through this act, the US Congress granted US\$230 million to the DOE and the USDA for funding R&D activities in the field (BRDB 2001). The 2001 *National Energy Policy* (NEP) restated the importance of biomass and bioprocesses in the country’s development. In addition, the 2002 *Farm Bill* contained five programs with mandatory funding for bioenergy.

Through the attributions provided by the *Biomass R&D Act*, the DOE and USDA are the key players in fostering and funding research in the field of bioproducts and bioprocesses. On the DOE side,

most projects fall under the responsibilities of the Office of Energy Efficiency and Renewable Energy (EERE).

Table XXVII shows that in fiscal year 2000, the USDA received US\$72 million (excluding payments done through the Commodity Credit Corporation—see below); this was increased to US\$116 million in 2001, and the DOE received US\$125 million (US\$175 million in 2001) to engage in activities including “research, development, demonstration, commercialization, analysis, outreach, and education activities for biobased products and bioenergy” (DOE and USDA 2000).

Table XXVII Main sources of R&D funds for bioproducts and bioprocesses in US

Fiscal Year 2000 Funding Summary

	U.S. DOE					USDA				
Programs	Biofuels	Biopower	Industries of the Future	Fossil Energy	Science	ARS	CSREES	FS	NRCS	OEPNU
Funding (\$M)	\$38.9	\$31.8	\$11.0	\$13.5	\$29.5	\$45.7	\$11.0	\$9.5	\$5.4	\$0.6
Total	\$124.7					\$72.2				

Fiscal Year 2001 Funding Summary

	U.S. DOE				USDA							
Programs	Bio-fuels	Bio-power	Industries of the Future	Science	ARS	CS REES	FS	NRCS	OE PNU	OSEC	RD	RMA
Funding (\$M)	\$54.4	\$46.0	\$43.8	\$29.5	62.5	18.7	19	8.6	1.6	0.8	3.5	1
Total	\$173.7				\$115.7							

Source: DOE and USDA (2000)

This clearly shows that the US has strong legislation and the financial means to support the use and development of bioproducts and bioprocesses. The next section presents, in greater detail, the programs specifically enacted to support R&D on bioproducts and bioprocesses.

7.2.2 Main initiatives

The first program analyzed here is the **Biomass Research and Development Initiative**. It can be described as “the multi-agency effort to coordinate and accelerate all Federal biobased products and bioenergy research and development”³³. The program is in joint control of both the US Department of Energy and the US Department of Agriculture. The DOE participates through the Office of the Biomass Program, and the USDA through its Natural Resources Conservation Service. The initiative

³³ <http://www.bioproducts-bioenergy.gov/>

is coordinated by both the Biomass Board (DOE and USDA staff) and an advisory committee (members from industry, academia, and other sectors) and managed by the National Biomass Coordination Office (again staffed by the DOE and USDA). The initiative is responsible for activities in the area of biofuels, biopower, and bioproducts.

The initiative's solicitation process for fiscal year 2004 is following the standard pattern. Both the DOE and the USDA offer funds and financial assistance, with the first contributing an estimated US\$10 million and the second US\$12 million (DOE 2003c). Grants are given to projects that run for up to three years. Applicants can be private-sector entities, institutions of higher education, national laboratories, Federal research agencies, state research agencies, non-profit organizations, or consortia of two or more listed bodies. The research for which the grant is desired has to fall under one of eight technical topics selected by the DOE and USDA (DOE 2003c):

- DOE-1: Thermochemical Conversion - SynGas Cleanup & Conditioning and Pyrolytic Bio-Oils - Handling and Blending Characteristics
- DOE-2: Thermochemical Conversion - Fundamental Breakthrough Research
- DOE-3: Biomass - Petroleum Refinery Evaluations
- DOE-4: Thermochemical Gasification - Kraft Black Liquor Gasification
- USDA-5: Feedstock Development and Production
- USDA-6: Biobased Products - Environmental and Economic Performance
- USDA-7: Biomass Focused Forest Management Training
- USDA-8: Incentives

The project is evaluated based on technical relevance, merit, the proposed work plan and technical approach, the expected benefits, the team's capacities, and the quality of the equipment and facilities involved. The applications are reviewed by a group of scientific and technical peers, overseen by the DOE and the USDA. Finally, projects that request funding have to provide a cost share of at least 20% from non-federal organizations. Applicants must thus seek industry funding as well.

Although DOE's **Office of the Biomass Program** is responsible for providing funds through the Biomass Research and Development Initiative, it also provides support on its own. The Office had available funds of US\$109 million in fiscal year 2003 and US\$94 million in fiscal year 2004 and has requested US\$81 million for fiscal year 2005 (DOE 2004). John E. Ferrell, Co-Director of the National Biomass Coordination Office, confirmed this decrease in a telephone interview. He also mentioned that activities in the Biomass Program have decreased accordingly. However, he felt that financial resources available overall for research on biomass, bioproducts, and bioprocesses in the US had remained approximately the same and that they had simply been redistributed, shifting from one department to the other. Interestingly enough, he feels that the USDA is getting more resources as a result of an increased interest in crop-based bioproducts.

At its creation, the Office of the Biomass Program was also given the responsibility for two pre-existing programs, the Biofuels and BioPower programs. The Biofuels Program aims to "develop

cost-effective technology for producing liquid transportation fuels from biomass—plant or plant-derived—materials that are currently unused or used only for low value”³⁴. The Biofuels Program does not provide traditional research grants, but it does offer partnership opportunities with private companies, trade associations, and non-profit organizations. About half of the program’s research budget goes toward subcontracted research. In 2000, the DOE signed three-year contracts with Genencor and Novozymes through the program, for a value of US\$17 million and US\$15 million, respectively (OECD 2001). These two leading enzyme producers are to cut enzyme production cost to a level permitting widespread ethanol production.

The BioPower Program’s goal is to make biomass an efficient and accepted process for energy production, through research, development, education, and promotion. Research is mostly conducted through four national DOE laboratories, with development projects often including external partners. In fiscal year 2000, the BioPower Program used US\$32 million for bioproduct-related R&D activities (DOE and USDA 2000).

USDA’s Bioenergy Program: Through the Commodity Credit Corporation, the USDA has made available US\$150 million as incentive payments to farmers for the production of ethanol and biodiesel from grain in fiscal year 2003. With the Bioenergy Program, the USDA hopes to increase the use of agricultural products by industry³⁵. Although not an R&D fund, this large incentive program will no doubt have an impact on ethanol and biodiesel research.

Funding for research projects is also available through USDA’s **Cooperative State Research, Education and Extension Service**. The purpose of the service is to maximize cooperation between the public and private sectors. It funds research on new uses of industrial crops through an Agricultural Materials program, National Research Initiative and Small Business Innovation Research Program. In 2000, these programs had combined budgets of US\$11 million (DOE and USDA 2000). Points of interest are paints and coatings, fuels and lubricants, new fibres, natural rubber, and biobased polymers. Applications are open to private organizations, institutions of higher education, non-profit organizations, and state or federal agencies.

The USDA’s **Agricultural Research Service** does in-house research for the department. Part of its mandate is to conduct research on new uses for crops. In fiscal year 2002, its budget for research and information activities was worth US\$970 million³⁶. It is not known precisely how much of this funding was used for research on bioproducts or bioprocesses, but the overall budget was US\$46 million in fiscal year 2000 (DOE and USDA 2000). Projects initiated by the service are selected through peer-review evaluations.

DOE’s Genomes to Life program: Following the success of the Human Genome Project, DOE has initiated the Genomes to Life program. Through fundamental research on protein machines and

³⁴. http://www.ott.doe.gov/biofuels/what_we_do.html

³⁵ http://www.fsa.usda.gov/daco/bio_daco.htm

³⁶. <http://www.usda.gov/agency/obpa/Budget-Summary/2004/12.REE.htm>

gene regulatory networks in plants and on microbial communities, DOE hopes to one day greatly increase the efficiency of bioprocesses. The program also places a strong emphasis on the development of computational systems able to manage the complex data involved in this research.

The first solicitations, issued in fiscal year 2002 by the DOE's Office for Advanced Scientific Computing Research and Office of Biological and Environmental Research, called for large projects involving many institutions and disciplines. The applications were then reviewed by a group of 40 scientists. Genomes to Life awarded five applicants, three of which were DOE National Laboratories and two academic or private research institutions, with a total of US\$103 million over five years³⁷.

One beneficiary of the Genomes to Life awards is the Oak Ridge National Laboratory. The team is under the supervision of Michelle Buchanan and composed of a partnership that also includes the Pacific Northwest, Argonne and Sandia National Laboratories, as well as the University of North Carolina at Chapel Hill. The project received a US\$23.4 million award over five years to identify and characterize protein complexes in microbes that play a role in the carbon cycle and in metal bioremediation³⁸. The other beneficiaries are partnerships respectively led by the Lawrence Berkeley National Laboratory, the Sandia National Laboratory, the University of Massachusetts, Amherst, and the Harvard Medical School.

Other sources of R&D financing: Other federal bodies are also involved in research and development on bioproducts and bioprocesses, though to a lesser extent. The USDA's Forest Service often collaborates with the DOE to perform research on forest biomass. The DOE Office of Science also conducts research on bioproducts and bioprocesses, benefiting from US\$29.5 million in fiscal year 2000. These funds mostly go to fundamental research performed in universities. The DOE Office of Transportation Technologies had an R&D budget for ethanol, biodiesel, feedstock, and biomass of US\$38.9 million in fiscal year 2000. However, since that time, the Office has been replaced by the FreedomCAR & Vehicle Technologies Program, and biomass fuels seem to be of lesser importance. The DOE's Office of Industrial Technologies benefited from US\$11 million in fiscal year 2000, as part of the Industries of the Future to conduct research on new uses for forest and agricultural products. Lastly, the Office of Fossil Energy received US\$13.5 million in fiscal year 2000 for the technological development of black liquor/biomass gasification (DOE and DOA 2000).

³⁷ <http://www.doegenomestolife.org/research/index.shtml>

³⁸ <http://www.doegenomestolife.org/research/ornl.shtml>

7.3 Canada

This section comprises three parts: Section 7.3.1 examines pan-Canadian programs that support R&D in bioproducts and bioprocesses, whereas Section 7.3.2 examines provincial programs that support R&D. Section 7.3.3 lists stakeholders that support the development of bioproducts and bioprocesses in Canada, even though they do not necessarily provide funding for R&D.

7.3.1 Federal government and non-governmental programmes

The **Bioenergy Development Program**, funded by the Panel on Energy Research and Development (PERD), falls under the responsibilities of the Canadian Renewable Energy Network (CanREN), which itself is formed of NRCan and its partners. It provides financial incentives for R&D on processes essential to bioenergy, including biomass handling, combustion, and biochemical and thermochemical conversions.

The **Climate Change Action Fund** was established in 1998, following ratification of the Kyoto Protocol, to help Canada comply with its obligations concerning GHG emission. It is now in its last year of operation. The component of the fund that deals with research and development is called *Technology Early Action Measures* (TEAM). During the 2001-2002 to 2003-2004 fiscal years, the program managed an investment of CDN\$35 million³⁹.

Projects that are eligible for funding under TEAM must create GHG-reducing innovations in the transportation, energy, agriculture, and various industrial sectors. Here again, priority is given to projects involving a number of partners, such as the private sector, provinces, and municipalities. Projects to be funded by TEAM must first be approved by another federal funding program. That is, TEAM does not provide funding on its own, but is rather a complementary investment source. TEAM partners with other programs from NRCan, Industry Canada, Environment Canada, the National Research Council, the Canadian International Development Agency, AAFC, and Transport Canada. An example of such a partnership is Technology Partnership Canada. The total funding provided by federal programs does not exceed 50%⁴⁰.

Genome Canada funds research in the area of genomics and proteomics, with the goal of making Canada a world leader in the field. Genome Canada invests and manages large-scale research projects and science and technology platforms. The organization functions through its five Genome Centres, located across Canada. It will fund up to 50% of a submitted project's cost, with the rest having to come from industry, other governmental organizations, or non-profit organizations. Since its inception in February 2000, Genome Canada has received CDN\$375 million, the last allocation of CDN\$75 million having been made in February 2003. Of this amount, it has invested CDN\$309

³⁹ http://www.climatechange.gc.ca/english/actions/action_fund/techno.shtml

⁴⁰ *Idem*

million in research projects and other initiatives⁴¹. Although the organization is most often associated with health research, bioproducts and bioprocesses can be funded through the forestry, agriculture, and environmental areas. So far, only one project funded by Genome Canada can be said to be truly in the field of bioproducts and bioprocesses. It is the project of Prof. Adrian Tsang of Concordia University. The project was awarded CDN\$7.5 million in 2002 by Genome Canada and Genome Quebec to finance research on fungal enzymes with potential applications in the pulp and paper industry⁴².

Although it does not support R&D per se, the **National Biomass Ethanol Program** is certainly relevant, as it aims to encourage firms to adopt ethanol and renewable fuels, thus investing in the Canadian ethanol industry. The program is funded by AAFC and managed by Farm Credit Canada. It is worth CDN\$140 million, which are to be given to firms building or expanding an ethanol fuel biomass plant that use biomass from agriculture, forestry, or municipal waste as feedstock. Funding takes the form of a guaranteed loan, which reduces the impact of the planned reduction or elimination of the excise tax exemption on fuel ethanol currently in effect. Applicants can be individuals, corporations, companies, cooperatives, or partnerships and must be able to prove that at least 25% of the fuel produced in the first year will be sold through letters of intent or business agreements⁴³.

Section 6 has shown that **NSERC** provided about CDN\$62 million in financial support for university-based research in bioproducts and bioprocesses between 1991 and 2002. The Council provides grants to university professors and researchers, supports students, and offers awards to industries conducting joint R&D activities with universities. The organization reports to Industry Canada and is monitored by a council of 22 members coming from universities, the government, and the private sector. NSERC awards are granted through a peer-review process. NSERC will invest a total of CDN\$760 million during fiscal year 2003-2004. Given existing trends, approximately CDN\$9 to \$10 million of this sum should go to R&D on bioproducts and bioprocesses. Section 8 recommends using NSERC's expertise of project selection within the framework of a Canadian R&D strategy for the bioeconomy.

Along with the Social Sciences and Humanities Research Council and the Canadian Institutes of Health Research and Industry Canada, NSERC funds the **Networks of Centres of Excellence** program. This program provides substantial funding to large-scale projects involving universities, companies, and the government. Although no project on bioproducts or bioprocesses has been approved so far, the field might be able to benefit from this source of funding in the future.

An interdepartmental program under the coordination of the Office of Energy Research and Development at NRCan, the **Program of Energy Research and Development** (PERD) funds 40% of

⁴¹ <http://www.genomecanada.ca/AboutGenomics/faqCP.asp?l=e>

⁴² http://ctr.concordia.ca/2001-02/Apr_11/02-Genomics/index.shtml

⁴³ http://www.infoentrepreneurs.org/rsea/english/display.cfm?Code=3035&coll=FE_FEDSBIS_E

non-nuclear energy R&D in Canada⁴⁴. When providing investments to a project, PERD funds the relevant department directly. The department then teams up with federal laboratories, the private sector, universities, other funding agencies, provincial or municipal governments, or other types of organization. The other departments with which PERD teams up include AAFC, Environment Canada, Industry Canada, NRC, and NRCan. In fiscal year 2000-2001, PERD gave out CDN\$57.6 million in awards⁴⁵. PERD has established six strategies to address energetic priorities, three of which include bioproducts and bioprocesses. These are Strategy 2, Cleaner Transportation for the Future, Strategy 3, Energy-efficient Buildings and Communities, and Strategy 4, Energy-efficient Industry.

The **Renewable Energy Deployment Initiative** development program aims to increase the use of biomass combustion systems, among other renewable energies, by the private sector for space and water heating and cooling. It gives a refund to companies and individuals who acquire such systems. It benefits from CDN\$24 million, which is managed by NRCan. It has been running since 1998⁴⁶.

Technology Partnerships Canada (TPC) has the broad mission of sustaining Canada's development through investments in research, development, and innovation. It aims to increase the technology base and technological capabilities of Canadian industry. Because one of the programme's goals is to stimulate private-sector investments, the average target sharing ratio is 33%, with the balance coming from companies⁴⁷. The TPC program also collects an equal part of the resulting benefits to further fund technological initiatives. TPC does not only cooperate with the private sector, but also with other governmental bodies or funds, such as the Climate Change Action Fund. An example of this is the case of Iogen, whose research project revolved around ethanol. The company received a joint CDN\$10 million investment from the TPC and CCAF programs. PetroCanada has, for its part, invested CDN\$15.3 million in the project (OECD 2001).

From 1996 to June 2003, TPC invested in 539 projects for a total of CDN\$2.4 billion⁴⁸. Bioproducts and bioprocesses are funded through the following areas of activity: Preserving Our Environment (Cleaner Fuel, Cleaner Air) and Biotechnology for Life (Agricultural Biotechnology, Environmental Biotechnology: Waste Reduction).

AAFC has not yet created a program dedicated to funding or promoting bioproducts or bioprocesses. As of 2001, an action plan was in development, but it is unclear if this plan has since been finished. AAFC does however get involved in research on bioproducts and bioprocesses through its Research Council. Under the supervision of AAFC, the **Canadian Agri-Food Research Council** acts as a catalyst for research in the agriculture and agri-food sector. It engages in networking

⁴⁴ <http://www2.nrcan.gc.ca/es/oerd/english/View.asp?x=665>

⁴⁵ <http://www2.nrcan.gc.ca/es/oerd/english/View.asp?x=668>

⁴⁶ <http://www2.nrcan.gc.ca/es/erb/erb/english/View.asp?x=455&oid=134>

⁴⁷ <http://tpc.ic.gc.ca/en/mandate.html>

⁴⁸ <http://tpc.ic.gc.ca/en/stats.html>

activities, promotes partnerships, and prioritizes research objectives in the field. The council recently conducted an assessment of the potential of a biobased economy in Canada (CARC, 2003).

Industry Canada's Life Sciences Branch aims to improve the economic growth of the life sciences field in Canada, providing companies with strategic intelligence, generally promoting the industry and helping to create partnerships. This is one of many such organizations, but the Life Sciences Branch occupies a specific niche as the only *governmental* body to act exclusively as a promotional body.

NRC is one of the most important organizations in Canada conducting research on biotechnology. NRC has five institutions performing R&D in biotechnology: the Biotechnology Research Institute in Montreal, the Institute for Biodiagnostics in Winnipeg, the Institute for Biological Sciences in Ottawa, the Institute for Marine Biosciences in Halifax, and the Plant Biotechnology Institute in Saskatoon. The Biotechnology Research Institute is performing research on a bioprocess platform as well as on the environment, while the Plant Biotechnology Institute is working on seed oil biotechnology and transgenic plants.

7.3.2 Provincial government programs and bodies

Ontario's Biotechnology Cluster Innovation Program aims to stimulate regional economic growth in Ontario by fostering innovation by consortia in the biotechnology sector. Such partnerships involve companies, their suppliers and service providers, companies in related fields, research centers, universities, trade associations, municipalities, and both provincial and federal governments. Aside from accelerating research in the biotechnology sector and building the needed infrastructure, the program has a clear mandate to foster the creation of "bio-industries" by promoting the use of biotechnology in fields such as chemicals, plastics, and agriculture.

The first phase of the program supported the development of a Biotechnology Cluster Innovation Plan worth up to CDN\$200,000⁴⁹. Consortia who had received a positive answer to their initial Expression of Interest were then funded to elaborate a detailed plan for their proposed cluster. The first phase ended on December 1, 2003. Phase two will fund infrastructure initiatives, such as incubators and research parks. The program has an envelope worth CDN\$30 million⁵⁰.

The **Canada-Saskatchewan Agri-Food Innovation Fund** ran from 1995 to 2003 and supported over 300 projects for a total investment of CDN\$91 million. Of this amount, \$8 million went to research in the "non-food processing" area. The goal of the program was to support research, development and infrastructure needs in Saskatchewan's agri-food industry to ensure its growth and

⁴⁹ http://www.ontariocanada.com/ontcan/en/rts/rts_bcip_bkgrnd.jsp

⁵⁰ http://www.ontariocanada.com/ontcan/en/rts/rts_bcip.jsp

success⁵¹. The program's structure included a board of directors, a strategic area committee, and program managers.

Quebec's *Centre québécois de valorisation des biotechnologies* helps SMEs in the bio-industry field to innovate and conduct technology transfer and development activities. Their activities include science and technology strategic intelligence, liaison and technology transfer projects. To conduct such activities, the organization works principally through the *Réseau Bio-Innovation*, a network of partners, including members from the scientific, industrial, and socio-economic bases. The organization contributes to the creation of alliances and networks that put together financial and human resources. The Centre also provides funding through its *Fonds de préamorcage* and *Fonds Bio-Innovation*. These grants provide support for the exploratory and experimental phases of research projects respectively. Besides the health and food sector, they provide services to companies working in green chemistry, bioenergy, biomaterials, and other bioproduct- and bioprocess-related fields.

Quebec's *Programme d'aide au développement des technologies de l'énergie* provides financial support for research in new energies, which includes biomass and, to a lesser extent, ethanol. The program engages in four types of support activity. Support first goes to R&D activities performed by companies, universities, and research centres. The program also funds feasibility studies and demonstration projects and provides support to associations acting in the field. Projects are evaluated by an internal committee of the *Ministère des Ressources naturelles, de la Faune et des Parcs*. The program awards up to CDN\$300,000 for R&D projects and will provide up to 75% of a project's budget. Since its creation, the program has invested CDN\$22.7 million in research projects⁵².

7.3.3 Other stakeholders

The organizations studied in this section do not necessarily offer funding for research on or the development of bioproducts or bioprocesses, but instead engage in promotional activities, link together partners from the processing industry, farms and research base, and perform other actions to foster economic growth in the field.

AVAC Ltd. is a non-profit organization created by industry members in the agricultural sector. AVAC finances research that aims to increase the value of crop products in Alberta. Aside from companies in the agricultural industry, AVAC also includes members from research institutions and financial institutions. It is coordinated by a board of directors. It was created in 1997 following a CDN\$35 million investment by the Government of Alberta⁵³. Of the four areas of research that the organization funds, one is non-food industrial applications. AVAC funds up to 50% of approved projects. Since 1997, it has provided a total of CDN\$16 million to different initiatives. These funds are provided through four programs: the Idea Builder Program, the Pre-Commercial and

⁵¹ <http://www.agr.gov.sk.ca/afif/Homepage.htm>

⁵² <http://www.mrn.gouv.qc.ca/energie/aide/aide-description.jsp>

⁵³ <http://www.avactd.com/about/corporateprofile.shtml>

Entrepreneurial Projects Program, the Academic and Strategic Initiatives Program, and the Knowledge Initiatives Program⁵⁴.

BIOCAP Canada is a non-governmental organization that provides financial support to university, industry, and governmental research in the field of biological GHG management. Topics covered are divided into three areas: agriculture, bioproducts, and forestry and natural ecosystems. The organization works first with stakeholder groups (industry, government policy makers, producer groups, and environmental non-profit organizations) to define research priorities. It then works with the federal granting agencies (NSERC, SSHRC, CFCAS, NCE) for the selection process through peer review and to co-fund the selected research initiatives. BIOCAP works with the research groups, and makes sure the results are later used in policy making and investment decisions. To help achieve these goals, BIOCAP has a research overview committee and four research and development advisory councils, one of which is in charge of biobased products.

Partners, sponsors, and stakeholders involved in the initiative include Abitibi-Consolidated Inc., Ducks Unlimited, Shell Canada, DuPont, BioProducts Canada, as well as various federal and provincial agencies and universities. In fiscal year 2002-2003, which ended March 31, 2003, CDN\$2.1 million were distributed in research funding. The total funding commitment for 2002-2007 in the climate change solutions field (including from federal funding agencies) is CDN\$31 million, of which BIOCAP plans to provide 18% (BIOCAP 2003).

BioProducts Canada and its provincial counterparts, **Bioproducts Saskatchewan** and **BioProducts Alberta**, are industry-led organizations that work to identify market opportunities for bioproducts. The organizations also create links between the people, infrastructure, and scientific capabilities needed to commercialize bioproducts. Thus, the goal of these bodies is to foster and promote the growth of the bioindustry by facilitating communication, hosting conferences, promoting the formation of partnerships, and acting as business incubators. BioProducts Alberta has a small staff, with an advisory committee made up of industry, academic, and governmental representatives and additional independent advisors. BioProducts Canada and BioProducts Saskatchewan have similar structures, with a board of directors monitoring the organization's activities. Sponsoring partners from industry, academic, or governmental sectors also get to defend their interests, through the Bioproducts Canada steering group for example.

Biotechnology and bio-industry associations: As bioproducts and bioprocesses very often derive from the use of biotechnology, many of the bodies acting in the field are represented through biotechnology associations. These organizations tend to have similar missions, roles and structures and, as such, a detailed description of each of these associations would be repetitive. Therefore, the following is a description of a typical biotechnology association and the organizations that can be classified thusly.

⁵⁴ *Idem*

Biotechnology associations act as speakers on behalf of the biotechnology and bio-industry. Their mission is to foster the growth of the biotechnology industry and the bioindustry. As such, they promote the activities of companies in the field to governments, the general public, the media, and other associations. This may take the form of lobbying activities or the creation of education and information resources, for example. They will also provide services to their members, such as helping in the formation of alliances and partnerships, or encouraging the diffusion of information. Some also collaborate with local universities to link students and companies. Others even operate for-profit companies (in the case of BioAtlantech for example).

Membership typically includes a majority of companies, with some governmental bodies, research centres, and different trade associations also joining the organization. These associations are often coordinated by an elected board of directors and may have advisory committees on specific topics. Biotech Canada is the best example of such an organization at the pan-Canadian level. Provincial-level organizations fitting this description are:

- BC Biotech, British Columbia;
- BioAlberta, Alberta;
- Ag-West Biotech, Saskatchewan;
- Ontario Agri-Food Technologies, Ontario (agricultural biotechnologies only);
- Toronto Biotechnology Initiative, Toronto region, Ontario;
- Ottawa Life Sciences Council, Ottawa region, Ontario;
- BIOQuebec, Quebec;
- BioAtlantech, New Brunswick;
- BioNova, Nova Scotia;
- Bio-East, Newfoundland.

The **Biotechnology Human Resource Council** is an industry/government partnership, aimed at ensuring that biotechnology companies have the human resources needed for their growth. It offers a variety of services, such as job banks, training opportunities, and providing intelligence to biotechnology companies. This organization, too, is composed of a board of directors and advisory committees.

Since 1998, the **Canadian Association for Renewable Energy** has been promoting the use of feasible applications for renewable energies. The main activity of the association is a distribution service that publishes daily news and periodicals about renewable products.

The industry-led **Canadian Bioenergy Association** (CANBIO) works for the promotion of bioenergy by organizing workshops and trade shows and representing the industry. It also strives to bring together partners within the field to stimulate its growth and success.

The **Canadian Chemical Producer's Association** represents the interests and promotes the activities of about 70 companies dealing in the chemical industry. It provides information, policy development and other services to its members, with the goal of making the Canadian chemical industry as competitive as it can be.

An international not-for-profit organization, the **Green Chemistry Network** promotes the use of green chemistry as a way to improve human health and protect the environment. It brings together

the industries, governments, universities, and national laboratories involved in research in this field. It also acts as an information centre and organizes conferences. Members of the **Canadian Green Chemistry Network** include a number of universities, government bodies, and associations such as BIOCAP, Industry Canada, and McGill University.

A non-profit organization incorporated in 1994, the **Canadian Renewable Fuels Association** promotes the use of bio-fuels such as ethanol and biodiesel in transportation. Activities include raising consumer awareness (with trade shows, media releases, etc.), government liaison, and research prioritization. Members of the association range from researchers, to individuals, to industries in the engineering, agricultural, and forestry sectors.

Crop producer associations: Trade associations representing farmers play an important role in funding research on crops. However, few of these associations provide substantial research funding for bioproducts and bioprocesses, as most research is geared towards improving the food value of these crops. Following are the associations that promote the non-food uses of crops or directly fund research on this topic. On the national level, the Canadian Wheat Board and the Western Grains Research Foundation are the two organizations that have funded research on new uses for crops. On a provincial level, the Saskatchewan Canola Development Commission and [Saskatchewan Flax Development Commission](#) (both under the supervision of the Saskatchewan Agri-Food Council), the Saskatchewan Hemp Association, and the Ontario Corn Producer's Association all engage in R&D funding.

The **GreenHeat Partnership** was launched in 2001 by the Canadian Association for Renewable Energy and includes members such as the Canadian Bioenergy Association and a number of private companies. The organization promotes the use of renewable, environmentally sound technologies, including biomass, for heating and cooling.

Set up in 2001 by the federal government, **Sustainable Development Technology Canada** is a foundation that acts as the “primary catalyst” to “foster the rapid development, demonstration and pre-commercialization of technological solutions, which address climate change and air quality”. The structure of the foundation includes a board of directors, which coordinates the foundation's activities and is accountable to the member council, which represents the interests of the shareholders. Members of the two bodies include actors from the industry, universities, governments, and the public.

Over a five-year period, the program will provide CDN\$100 million to partnerships developing technologies that address sustainable development. As with many other programs, an average limit of 33% of a funded project's cost is provided by the foundation, with a maximum of 75% in total coming from federal bodies. The funding applicant must be a company or industry with partners from the academic, private, or governmental sectors⁵⁵.

⁵⁵ <http://www.sdtc.ca/en/mandate/index.htm>

The funding allocation process has four “decision points”, with review of the applications being executed by the SDTC, an external body of international experts, an investment committee made up of leaders from the financial and sustainable development field and finally by the SDTC’s board of directors. Funding for research and development in the bioprocesses and bioproducts field may be obtained under the following headings: Waste Management (biomass) and Transportation (renewable fuels).

7.4 Observations

It appears from the data presented above that Canada, unlike the United States and, to a lesser extent, Europe, does not have any funding sources dedicated exclusively to bioproducts and bioprocesses. While funding is available for R&D in the field, it is often included with other topics such as GHG reduction or biotechnologies. The situation is exactly the opposite in the US, where programs designed specifically for bioproducts and bioprocesses and an office coordinating the efforts of the various departments involved in the field have been established. The European Commission works through general programs, but national initiatives tend to be more focused than those found in Canada.

The industry plays a major role in every country studied, but Canada has taken matters a step further by leaving funds in the hands of foundations, as in the case of BIOCAP Canada and Sustainable Technology Development Canada. Although these foundations do receive a substantial amount of their funding from the government, they are not directly coordinated by federal bodies; a situation that is also true for some European countries. This is quite different from the US, where the USDA and DOE are still very much in charge of managing research funds. However, the attribution of such responsibilities to private foundations is still not generalized in Canada.

Finally, it is quite evident that R&D investments in bioproducts and bioprocesses in Canada are minimal compared to those made in the US and Europe. Since there is no fund dedicated to this field, companies and researchers have to compete with other interests to obtain funding. It is estimated that only a small portion of the funding made available by the bodies and programs mentioned above goes to research on bioproducts and bioprocesses.

8 Recommendations for a Canadian R&D strategy for the bioeconomy

In this section, Science-Metrix presents its recommendations for a Canadian R&D strategy in bioproducts and bioprocesses. Canada could be among the greatest beneficiaries of a more rational approach to the harnessing of the biomass. However, despite the promises and considerable market potential of platform and versatile bioproducts (sections 3 and 5) and bioprocesses (Section 4), Canada's scientific output does not match its position as a potential world leader in the global bioeconomy (Section 6). Compared to the other countries and particularly to the US (Section 7), and considering the relative importance of agriculture and forestry in both countries, Canada does not support R&D on products and bioprocesses at a level that is commensurate with its potential role in the Canadian economy.

Compared to other countries, and more specifically to the US, it is clear that Canada: 1) lacks a robust framework to coordinate the efforts of stakeholders; and 2) lacks funds to carry out R&D on bioproducts and bioprocesses at a level consistent with the importance of natural resources in the Canadian economy.

Section 8.1 recommends guiding principles for R&D project selection. Section 8.2 provides recommendations concerning R&D on feedstocks, bioproducts, bioprocesses, and governance and demand-side research. Section 8.3 recommends implementing an organizational structure to oversee the development and implementation of a Canadian bioproduct and bioprocess strategy and Section 8.4 provides recommendations on three basic scenarios as to the level of investment that would allow Canada: 1) to catch up with the US; 2) to establish itself as a leader in the field; 3) to become a centre of excellence in the field of products and bioprocesses.

8.1 Guiding principles for project selection

This section provides guiding principles for project selection. These principles take into consideration both lessons learned and current trends in science and technology policy. It is worth recounting that after World War II scientists had finally found that governments were eager listeners and that scientists strongly encouraged governments to invest important sums of public funds in scientific research. Scientists demanded an act of faith on the part of governments, promising that investments in scientific research would produce knowledge that would eventually percolate through the economy and foster economic development. During the 1980s and 1990s, governments increasingly concluded that disinterested scientific research was certainly important for national standing and long-term economic development, but that there had to be other means to increase the impact of public spending in research. What was originally called "science policy" therefore eventually gave way to strategic research programs. Scientists could obtain funding as long as they carried out research in fields and/or for aims that were judged of strategic importance. In the 1990s, science and technology policy went one step further by insisting on the concept of innovation. Producing new knowledge was not merely enough; it had become paramount to effect changes in the

economy, industry, markets, and even society. It is recommended that Canada develops a strategic R&D program for the bioeconomy that is squarely oriented toward innovation.

Here, strategic research should be seen as *enabling* research, that is, "foundational, generic, and crosscutting work, with results potentially applicable to multiple difficult challenges and critical capability gaps and "opening up the board" for subsequent applied work"⁵⁶. In addition, the research to be carried out should be *applied*, that is, "leading work that involves empirical development/prototype demonstration for specific applications, with results and experience relevant to one or more technology- or issue-focused challenges and gaps and laying the groundwork for follow-on developmental work"⁵⁷.

Proposals submitted for funding should clearly illustrate how their R&D projects fit in the value-adding cycling. For instance, a project may state that it is going to use a feedstock which is: 1) one where Canada has a natural advantage (e.g. barley; canola; linseed), 2) one which is highly optimized for a specific endpoint (e.g. industrial triticale, which would be optimal for ethanol), or 3) some form of biowaste. In addition to stating the type of feedstock that will be used, the proposal should mention the market segments it is aiming at and the target market's characteristics (e.g. consumer or industrial use; market is decreasing, stable, or increasing). Finally, the proposal should mention how the bioproduct could be re-introduced in the value-adding cycle after its useful lifetime.

Proposals on bioprocesses should mention how projects will contribute to value-added cycling. For instance, will the process proposed allow the use of biowaste, or will it favour a more efficient means of transforming feedstocks (biological or not) into products. Efficiency could comprise production of smaller quantities of waste, production of wastes that can be converted into valuable products more easily, or use of a smaller quantity of energy, particularly non-renewable energy.

Projects supported within the Canadian R&D Biostrategy should be pre-competitive and collaborative. In order to leverage the knowledge created in the various economic sectors, (i.e.: government, university, and industry), project selection should favour collaborative research projects. Ideal projects should involve members of government, university, and industry. Inter-sectorial collaboration should also be supported between any two sectors and every project should, at a minimum, include collaboration between two organizations, i.e. each project should involve at least two government departments, two universities, or two companies. However, it is important to combine the origins of the researchers and analysts involved in research projects, and priority should definitely be given to inter-sectorial collaboration projects.

⁵⁶ <http://www.epri.com/>

⁵⁷ *Idem.*

8.2 Recommended R&D priorities

This section provides recommendations for research on biological feedstocks, enabling technological platforms, versatile bioproducts, bioprocesses, and tools to facilitate the development of the Canadian bioeconomy. Figure 25 illustrates the core aspects of the recommended strategy.

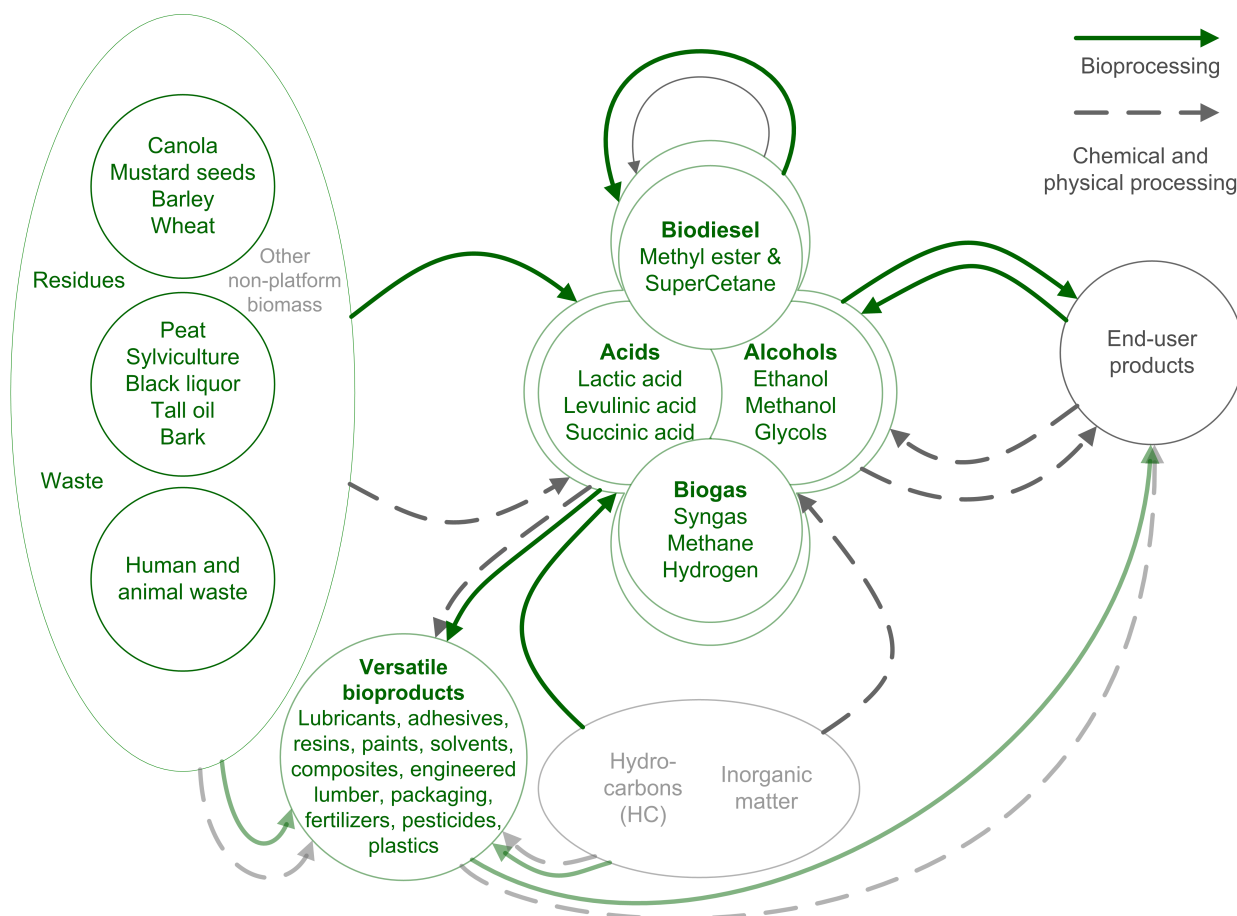


Figure 25 Target areas of a Canadian bioproduct and bioprocess R&D strategy

Source: Science-Metrix

Biomass research

There are several pressing R&D questions related to biomass characteristics that affect the bioeconomy, including how to increase the level of usable biomass and photosynthetic energy capture as well as carbohydrate contents, how to optimize intakes of nutrients and water and how to increase resistance to frost. There is also a need to augment our understanding of feedstock biochemistry and genomics, to design feedstocks that meet user requirements and to study the effects of the introduction and leaking of genetically-modified species into ecosystems.

Although production of biological feedstocks is the prerogative of existing departments such as AAFC (agricultural feedstocks), NRCan (forest-based feedstocks), and Environment Canada (anthropogenic waste), there is a need to coordinate their efforts under the umbrella of a national

strategy. Optimization should be effected at the national rather than the departmental level, which is why horizontal initiatives are necessary to managing global issues.

It is recommended that:

- Canada leverages its clear competitive advantage in the production of canola, linseed, barley, and wheat. Although mustard seeds are not yet harvested in large quantities, Canada currently produces about 40% of the world output. The Canadian strategy should emphasize the transformation of these crops, thus contrasting with US strategies which often stress the development of corn and soybeans for which the US is better positioned;
- Development of new species that are optimally adapted to Canada's various regions and for specific uses (e.g. industrial triticale for ethanol production). Several varieties should be made available to ensure the protection of Canadian supplies and to favour bioindustrial diversity;
- Research be conducted on the ideal biological feedstocks for each of the enabling platforms prioritized in the biostrategy;
- Additional efforts be made on the transformation into platform biochemicals of the large amounts of black liquor and tall oil available;
- More research be conducted on agroforestry, particularly in conjunction with the use of sanitized and detoxified urban waste (e.g. biosolids) as fertilizers;
- More research be performed on the use of human and animal waste, either as a source of energy or as fertilizers. More research should be conducted on sanitizing and detoxifying waste, and on how it can be used safely and in an environmentally sustainable manner.

Enabling platforms

It is estimated that Canada currently has the capacity to produce 5% of its transportation fuel and 10% of its organic chemicals from biomass. It may be able to double that figure by 2020 (Duchesne and Wetzel 2003). If Canada implements policies to meet those targets, it could stimulate \$3-5 billion in investments and create between 6,000 and 10,000 new jobs in less than seven years (AAFC 2002). Those opportunities could be beneficial for rural communities, especially for First Nation communities which are highly dependent on forest resources and economy. Therefore, the Canadian R&D biostrategy should accelerate the pace of research aimed at the development of biofuels. Importantly though, chemical products play an increasingly important role in the economy. Many of these products are derived from non-renewable fossil-based feedstocks. It is essential for Canada's medium- to long-term security and economic growth to develop biobased alternatives to hydrocarbon feedstocks to lower GHG emission in the short term and to replace hydrocarbon feedstock in the longer run.

It is recommended that:

- Emphasis be placed on the development of enabling technologies to provide the means for Canadian industry to respond to market demand in a flexible manner;
- Research on enabling platforms be centred on precursors biochemicals and biofuels;
- A biodiesel platform be developed, and emphasis be placed on the methyl ester platform because of its interrelationship with other enabling platforms (such as the methane and methanol platforms);

- Alcohol platforms such as methanol, ethanol, and polyol be developed, given their capacity to act as precursors to several other products;
- Acid platforms, such as lactic, levulinic and succinic acid be developed, considering their enabling role in industrial production;
- Biobased gases such as syngas, methane, and hydrogen be developed, considering their role as a source of power and as biochemical precursors.

Versatile bioproducts research

Versatile biomaterials and bioproducts identified in Section 3 typically have applications in several industrial and some consumer sectors. These are not single products; rather, each represents a family of products that takes a wide variety of forms and uses, thus the expression “versatile”. These versatile bioproducts have important local and international markets. Biobased products present some clear advantages for Canadians and their environment because of their lower toxicity, decreased VOC emissions, and greater biodegradability.

It is recommended to carry out research in the following families of versatile bioproducts:

- Adhesives and resins;
- Composites;
- Lubricants;
- Pesticides;
- Fertilizers;
- Plastics.

Biobased fertilizers and pesticides are especially important in a biobased economy since current agricultural production methods would consume significant quantities of fossil-based feedstock, which would run counter to the efforts being made in the bioeconomy; that is, to reduce and substitute the use of hydrocarbons.

Bioprocess research

Bioprocessing usually operates at atmospheric pressure and room temperature and mostly in an aqueous medium, whereas chemical processing often uses pressure, heat, and solvents other than water. This is an important factor to consider when it comes to process economics: the fact that bioprocessing requires neither heat or pressure means that equipment is often cheaper to build and operate, and the use of water in place of other solvents often reduces the environmental impact of these solutions. Because process heat is often derived from hydrocarbon-based energy, chemical processing is more likely to produce GHG. However, a great deal of research must still be performed, since bioprocessing competes with process chemistry, which has achieved a great mastery of conventional catalysers and is often very efficient and fast. Biocatalysts are often incompatible with high pressure, high temperature, and the use of solvents. Therefore, what is an advantage in terms of environmental impact is a disadvantage regarding the progressive introduction of bioprocesses in existing plants. There is a need to rethink the whole concept of refinery.

It is recommended that:

- Research be conducted on biorefineries to produce platform biochemicals and versatile bioproducts;
- R&D on large-scale bioreactors be supported;
- Basic research including genomic be carried out on fungi, bacteria and enzymes that form the basis of bioprocesses;
- Research on biological remediation and biological treatment methods be supported.

Other platforms, bioproducts and bioprocesses

Although the platforms and versatile bioproducts mentioned in this report should receive considerable R&D support to help Canada make the most from its natural resources, some funds should also be available for other platforms and versatile products, provided that:

- They make use of feedstocks where Canada has a competitive advantage or some form of waste available in large quantity or that create severe liabilities;
- The platform or product addresses a wide range of needs;
- The market potential is clearly demonstrated.

Governance and demand-side research

To scale up the returns from the Canadian biomass as much in the short as well as the longer term, there is a need to improve agricultural and silvicultural practices to increase output while also guaranteeing the sustainability of land use. For higher value to be generated from the biomass, corrective measures should be developed to help transform liabilities into assets, and to identify and cut down on exports of biological products with the lowest local value-added. Therefore, there is a need to develop not only new practices, but also new models to increase the returns from Canadian natural resources.

Clearly, there are areas requiring input from the social and management sciences, and a substantial part of this research could be conducted collaboratively between universities, government and industry. There is a need to collate information to ease the work of decision makers. For example, a unified inventory of biomass, including production cost and relevant physical, chemical, and biological characteristics, is needed. A publicly available national database of biological stocks and residues and up-to-date statistics would certainly help decision makers set priorities for using natural resources in a sustainable manner, transforming liabilities into assets. There is also a great need for sound market data to help companies decide where to invest in R&D.

Many bioproduct and bioprocess development barriers must be lowered or squarely eliminated to facilitate the development of the bioeconomy. For instance, many side-effects of fossil-based products are not taken into account in their current price, whereas bioproducts may be more expensive but are often less polluting and safer to use. Healthcare costs are currently externalized from fossil-based products, providing them with an unfair advantage relative to safer bioproducts.

Thus, it is recommended that:

- Drivers, barriers, and measures that fall within the boundaries of internationally accepted regulatory and fiscal incentives be identified, in order to increase the market potential of bioproducts in Canada;
- Research be conducted on how variables that are currently considered as "externalities" provide unfair advantages to dangerous and wasteful products and processes, and how these variables could be internalized;
- Investigation be carried out on how government procurement policies could support the biobased industry (e.g. systematic use of a ethanol blend in government fleet) and whether these policies add unreasonable burden to the sound management of public finances;
- Research be conducted on the identification of bioproducts and bioprocesses that are safer for Canadians and their environment than their chemical counterparts;
- Research be conducted on the optimization of the location of different stages of transformation relative to feedstock availability, product demand, and existing transport capabilities;
- Research be conducted on carbon-cycle assessments of bioproducts and bioprocesses;
- Research be conducted on value-adding cycle assessments of bioproducts and bioprocesses;
- Research be conducted on returning end-user products into value-adding cycles, rather than disposing of them;
- Research be conducted on the integration and combined use of value-adding cycle, carbon-cycle, and life-cycle assessments of bioproducts and bioprocesses;
- An inventory be made of biochemicals that can be produced with the enabling platforms selected for the strategy and the size of the Canadian, North American, and international markets for these biochemicals;
- Market research on versatile bioproducts, as well as on bioprocesses supported in the strategy, be conducted along with identifying user needs and market size;
- Life-cycle assessments be conducted on the combined production of several biochemicals in biorefineries, as opposed to classical hydrocarbon-centric refineries;
- An inventory be made of biomass produced in Canada, including waste and residues;
- A finer understanding be developed of the ecotoxicology of biowaste-based fertilizers;
- Stringent standards and regulation be developed on biowaste-based fertilizers to safeguard groundwater and to protect the health of Canadians and the sustainability of ecological systems.

8.3 Recommended organizational structure for a strategic R&D initiative

Because there are several organizations that oversee the development of biotechnology in Canada, it appears more appropriate to expand their mandate and group them under an umbrella organization, rather than create new institutions from scratch. It is suggested that horizontal coordination of the strategy be performed by the Canadian Biotechnology Secretariat. This organization is already up and running, it has an expertise in horizontal coordination and it has contacts in government, academia, and industry. These are clear advantages for rapidly and efficiently operationalizing the Canadian Biostrategy.

The Secretariat would be responsible for bringing stakeholders to the same table and for coordinating their work to set priorities and objectives. In addition to central coordination, there would be six governing functions in the R&D strategy: 1) project selection; 2) performance monitoring; 3) governance issues and resources and industry intelligence; 4) resource-push; 5) demand-pull; and 6) science and technology transfer. Steering committees would see to it that specific tasks are carried out rapidly and economically with relevant stakeholders.

Project selection: It is recommended that project selection be based on peer-review and draw upon the expertise of the Natural Science and Engineering Research Council, the Social Science and Humanities Research Council, and Genome Canada. These organizations could be responsible for the selection of R&D projects involving cooperation between universities, government, and companies, and could charge a fee for this service. The strategy would support pre-competitive and collaborative R&D, and a minimum of two independent organizations would be required to apply for funding. Intersectorial collaboration would be encouraged to facilitate knowledge flow. Genome Canada would be put in charge of evaluating projects whose core activity is genomics. When a project would involve collaboration solely between private firms, the NRC's Industrial Research Assistance Program could fulfill the project selection function.

Performance monitoring: From the beginning, clear objectives as to the output and outcomes of the strategy should be defined. Performance would be monitored on a continuous basis, not only in terms of financial efficiency, but also in terms of maximizing social returns. The monitoring could be organized by the Office of the Auditor General of Canada and/or the Treasury Board Secretariat, who could also appoint independent experts to audit the scientific and technological outputs and economic outcomes of projects. The coordination of the strategy, selection of projects, and performance monitoring would ideally cost no more than 2.5% of the strategy's envelope (excluding counterpart funds).

Governance issues, resources, and industry intelligence: A focused strategy with maximum impact relies on possessing robust data and intelligence. In addition to private firms that may be called upon to provide expertise in this area, four departments could play an important role in providing stakeholders with strategic data. In collaboration with relevant departments, Statistics Canada could play an important role by providing and updating an inventory of resources and residues. Environment Canada would provide a link with efforts already under way on climate change, thus eliminating a potential duplication of efforts. Additionally, Environment Canada could play an important role in life-cycle and carbon-cycle assessments. The department would act as the watchdog for sustainable development and guarantee that the development of bioproducts and bioprocesses has a positive impact on the environment. Similarly, Health Canada would provide data on the safety of existing chemicals, as well as on replacement bioproducts and bioprocesses. New technologies would be checked to minimize adverse effects on workers and consumers. Finally, Industry Canada would provide detailed knowledge on the potential markets for bioproducts and bioprocesses. It would identify barriers and drivers and suggest ways to smooth the entry of new products on the market. Industry Canada could also be in charge of performing value-adding assessments in order to transform the Canadian natural advantage into a robust competitive one.

Resource-push and demand-pull: It is important to bring to the table not only the departments that manage biological feedstocks (AAFC and NRCan), but also industry representatives. On the opposite side of this "resource-push" group, a "demand-pull" group composed of industry representatives in addition to organizations would help capitalize the industry, such as the Canadian Venture Capital Association. On the demand-pull side, Public Works and Government Services Canada could ensure that the Canadian government acquire and use Canadian bioproducts in its buildings, vehicles, and furniture. Similarly, Transport Canada would ease the entry of biofuel blends and biobased lubricants on Canada's roads and off-road.

Science and technology transfer: One of the most important functions would be played by a science and technology transfer group. This could be composed of the Association of University Technology Managers, the National Research Council, and BioProducts Canada. It seems essential to have a group dedicated to bringing universities, government, and private firms to the table. The science and technology transfer group, in collaboration with other members sitting at the Canadian Biostrategy Roundtable, would have to oversee the development of an adequate receptor capacity in Canada. This means favouring change in existing firms and supporting both spin-offs and start-ups.

8.4 Recommended financial envelope

Considering the importance of natural resources in the Canadian economy and the promises of bioproducts and bioprocesses for sustaining economic growth while reducing the environmental footprints of Canadians, investing in R&D should be considered one of the highest priorities for research in Canada.

Science-Metrix recommends injecting sufficient money into R&D to help Canada become a leader in the field, with a view to creating economic growth by transforming Canada's natural advantage into a competitive advantage and to lowering the ecological footprints of Canadians by transforming liabilities (pollution) into assets (bioproducts).

Considering the relative importance of agriculture and forestry in Canada and the US and the investments already made by these countries in R&D, Science-Metrix recommends that Canada invests at least CDN\$425 million during the next five years (2005-2009) to catch up with the US. This would bring investments on bioproduct and bioprocess R&D to a level consistent with the importance of agriculture and forestry in Canada, compared to the U.S.

Canada could also decide to make bioproducts and bioprocesses a national priority and invest 50% more than the amount required to catch up; this investment of about CDN\$650 million over five years would help transform Canada into a leader in the field.

A third option would be to declare bioproducts and bioprocesses a top national priority by investing twice the amount necessary for catching up with the US, that is, by investing about CDN\$850 million over the next five years.

It is recommended that about 10% of the funds be spent on developing new species and improving yields of industrial crops and agroforestry as well as methods for using biowaste; that about 30% of the envelope be devoted to enabling platforms; that 25% be spent on developing versatile bioproducts; that 25% be spent on developing process technologies; and, finally, that 10% of the funds be committed to governance, modelling, operational research, demand-side research, and intelligence gathering. These recommendations are summarized in Table XXVIII.

Table XXVIII Financial scenarios for a five-year Canadian biostrategy

	Scenario 1	Scenario 2	Scenario 3
	Catching up	Becoming leaders	National priority
Envelope (CDN\$ million)	425.0	650.0	850.0
Biomass improvement (10%)	42.5	65.0	85.0
Enabling platforms (30%)	127.5	195.0	255.0
Versatile bioproducts (25%)	106.3	162.5	212.5
Bioprocesses (25%)	106.3	162.5	212.5
Governance research (10%)	42.5	65.0	85.0

Source: Science-Metrix

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