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BIOCAP CANADA

An Assessment of the

Opportunities and Challenges

of a

Bio-Based Economy

for

Agriculture and Food Research in Canada

Canada

Canadian Agri-Food Research Council (CARC)
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Executive Summary

The replacement of petrochemical-based industrial chemicals with chemicals derived from renewable biological materials is a very worthy and alluring objective. The reduction of greenhouse gases (GHG), the lessening of dependence on non-renewable resources, the increase in markets for farm products, and the potential for new industries in widely distributed geographic locations across the nation are all outcomes which are attractive to many Canadians.

This study, commissioned by the Canadian Agri-Food Research Council (CARC) and the BIOCAP Canada Foundation (BIOCAP), is intended to give Canadian researchers, legislators and the public in general a better understanding of the research issues involved in this highly complex industry. Specific effort has been made to focus the study on a selected number of industrial sectors which might play an important role, not only in the control of GHG emissions, but also in providing new economic opportunities to farmers and rural communities. The potential role for biofuels including ethanol, biodiesel, methane and other bioenergy sources have been given specific attention. Also covered in this study are bioplastics, bioadhesives, biocomposites, biolubricants and platform chemicals; all sectors which could have a significant contribution to an evolving bio-based economy. Sectors such as pharmaceuticals, cosmetics, nutraceuticals, surfactants, and bio-based inks, (all of great interest to many researchers and business leaders) are not covered due to the attention they continue to receive elsewhere, and their relatively modest impact on GHG and other climate issues.

> **THIS REPORT FOCUSSES ON RESEARCH AND DEVELOPMENT RELATING TO BIOFUELS, BIOPLASTICS, BIOADHESIVES, NATURAL FIBRES, BIOLUBRICANTS AND BIO-BASED PLATFORM CHEMICALS**

The work covered in this report was deliberately focussed on research and development. Market and economic topics are touched on for context purposes, but are not dealt with in any depth, as they are the focus of other studies currently in progress. Specifically, Agriculture and Agri-Food Canada (AAFC), with assistance from Industry Canada, is currently supporting a major study aimed at identifying commercial opportunities in the same sectors as are the focus of this study.

One hundred years ago, the vast majority of the world's industrial products were manufactured from agriculture, forest and marine sources. Today, after close to a century of research and development, petrochemical-based industrial products have all but eliminated the bio-based products in most commercial fields. As impressive as the success in the petrochemical based industries has been, it has become clear that a move toward greater use of renewable materials and better stewardship of the earth's land, water and air is no longer an option, but a must.

Canada's three levels of government as well as the public at large have repeatedly demonstrated their clear support of a move toward greater use of bioproducts and to the protection of our environment. However, on closer analysis, as seen in Section 4 of this report, it is clear that in many industries, both the EU and the US have a significant lead over Canada in assessing the new opportunities for bio-based industrial products.

Recent advances in many areas of the biological sciences have become important contributors to the growing enthusiasm for the development of a new bioproducts industry. Developments in genomics, proteomics, enzyme technologies, materials science, separation science, and many other technologies have opened a host of new opportunities. The use of "biorefineries" to produce a family of end products from one, or more, raw materials is becoming a common objective among those working in this rapidly evolving field. These concepts, along with the need to develop human capital to meet the growing demands of a bio-based economy, will bring new challenges and opportunities to universities and governments alike.

OVERVIEW OF TARGET SECTORS

Ethanol: Of the sectors addressed in this report, clearly biofuels hold the greatest potential for major impact on both the agricultural economy and on greenhouse gas (GHG) reduction. Recent studies which have analyzed all of the GHG emissions from the whole production chain for both grain crops and crop residues right through to ethanol conclude that considerably fewer greenhouse gases were evolved to produce ethanol than to produce gasoline. **The box to the right shows the total GHG saving expressed as kg of CO_2 equivalents per litre of ethanol**.[1] Ethanol was assumed to be produced from cereal grains by conventional methods. Ethanol production from straw and stover assumed successful commercial production by the Iogen process or similar fermentation route processes under commercial development. The amounts of ethanol produced from crop residues, or other lignocellulosic feedstocks, depends on whether five carbon sugars, such as xylose, are fermented as well as six carbon sugars such as glucose. Five carbon sugars are produced from the hemicellulose component of lignocellulosic raw materials. A variety of engineered microorganisms have been developed to ferment the five carbon sugars (See section 6.2 of this report for details).

GHG SAVINGS	
WHEAT OR BARLEY	1.47
CORN GRAIN	1.47
CEREAL STRAW	2.25
CORN STOVER	2.07

Recent research has also shown that very high gravity fermentation can be used to produce ethanol from grains with significant reductions in costs while at the same time achieving improvements in productivity.[2] Several US companies have confirmed this to be the case.

[1]Stumborg, M. 2002. Potential for Biofuel Development. Proceedings AgFibre Conference, Winnipeg, MB. Available from the author at SPARC, Agriculture and Agri-Food Canada Research Centre, Swift Current, SK. S9H 3X2.

[2]Ingledew, W.M. 2002. Very high gravity ethanol fermentation: yield and productivity are the keys to success. ABIC 2002 Conference, Saskatoon, SK. Available from AgWest Biotech, Saskatoon, SK S7N 3R2.

The table below indicates the amounts of ethanol that could be produced from various feedstocks in Canada using current technology.[3] The assumption was made that about 15% of the total production of cereal grains could be used for ethanol production without serious conflict with other markets. Similarly the ~ 75 and 19% for straw and stover is the amount after soil protection and feed uses are met. The amount of distillers dried grain produced as the co-product would approximately equal the ethanol produced and would replace other feedstuffs in animal feed rations. Using this data, the total amount of ethanol which might be produced in Canada from these sources would be about 2.8 billion litres with a total greenhouse gas reduction of 4.24 million tonnes of carbon dioxide equivalents. For comparison, the total amount of gasoline consumed in Canada in year 2000 was 38.338 billion litres.

Ethanol Production from Selected Feedstocks

Raw material	Ethanol yield (L/t)	Total ethanol (L x 10^6)	Amount req'd (t x 10^6)	% of total available
Cereal grain	365	1182	3.24	~ 15
Corn grain	400	536	1.34	~ 15
Cereal straw	309	600	1.5	~ 75

The integration of ethanol with the adoption of more fuel efficient vehicles can further reduce GHG emissions. Recent estimates suggest that total greenhouse gas emissions from the transportation sector of the Canadian economy will rise to 179 million tonnes of carbon dioxide equivalents by 2004. To meet the Kyoto target by 2012, this report concluded that the use of renewable fuels, such as ethanol and biodiesel, would need to be coupled with major improvements in the fuel efficiency of cars and trucks. With adoption of known technologies to improve fuel efficiency, coupled with use of 1.3 billion litres of ethanol and 420 million litres of biodiesel, the report went on to estimate that greenhouse gas emissions from the transportation sector could be reduced to 133 million tonnes of carbon dioxide equivalents.[4]

TECHNOLOGICAL GAINS HAVE BEEN IMPRESSIVE, BUT MORE R&D IS NEEDED

Although impressive technology gains have been made in this sector, more of the R&D gaps remain to be filled in both the starch and lignocellulosic route to ethanol if Kyoto and other targets are to be met. These research gaps are concerned with all stages of the production and utilization process. Specifically, there is need to: improve crop yields during drought years, reduce nitrous oxide emissions from crop production, develop hay crops suitable for ethanol production, develop

[3] Stumborg, M. 2002. Potential for Biofuel Development. Proceedings AgFibre Conference, Winnipeg, MB. Available from the author at SPARC, Agriculture and Agri-Food Canada Research Centre, Swift Current, SK S9H 3X2.

[4] Torrie, R., Parfett, R. and Steenhof, P. 2002. Kyoto and Beyond. Torrie Smith and Associates, Ottawa, ON K1N 7B7. Available from www.torriesmith.com.

techniques to improve farmers' income from production of raw materials, develop new co-products from ethanol production to increase total revenue and reduce ethanol production costs, and improve methods to cheaply produce simple sugars from lignocellulosic raw materials.

An example of a new technology currently under development for harvesting seed crops (cereal, pulses or oilseeds) is the McLeod Harvest system which simultaneously harvests seed, chaff and weed seeds in the field. This mixture is then hauled to the farmyard, where a second stationary processing unit separates the crop seed from the mixture of weed seeds, chaff and shrunken crop seed. Both crop seed and the chaff mixture could be used for the production of ethanol and co-products. The new harvest system, according to economic analysis by the University of Manitoba, has the ability to increase farmers' net income by over $30/acre or $74/ha. Substantial savings in weed control costs and the economic value of the chaff mixture were factors in the increased net income.

Fermentation routes to fuel ethanol have been used in most research studies and commercial developments to date. However, a new approach is to use a gasification route. In this method, the biomass material would be gasified to a mixture of carbon monoxide and hydrogen. In the presence of the appropriate metallic catalyst, this mixture could be converted into ethanol. This approach can utilize biomass materials such as bark, which are not suitable for ethanol production by fermentation methods.

In a related study, Swedish researchers have calculated that the black liquor residue from pulp mills could be gasified and then catalytically converted into methanol.[5] A single 1000 tonne per day pulp mill could produce about 266 million litres of methanol per year. This amount is close to the total amount of ethanol produced in Canada at the present time from all sources.

An interesting research project would be to determine whether the catalyst in the Swedish study could be changed so that ethanol was produced instead of methanol. The Green Chemistry Network recently established in Canada might be interested in such a study. Canada has a very large black liquor solids production - about 24 million tonnes per year. The potential production of alcohol from this resource could also be very large - in the order of 10 billion litres per year of methanol. The potential total production of ethanol from the black liquor solids resource was estimated at 7.3 billion litres per year. Other potential raw materials could be the substantial amounts of wood and bark waste available, such as the three million tonnes of residues in British Columbia.

[5]Lindblom, M. and Berglin, N. 2001. Efficient production of methanol from biomass via black liquor gasification. Abstract of the 5th Biomass Conference of the Americas. See www.nrel.gov/bioam/.

Biodiesel: A recent study has analyzed the greenhouse gas emissions and economics of biodiesel manufactured from canola oil, soybean oil, animal fats and waste cooking oils.[6] The whole production cycle (as shown in the box to the right) was assessed.

> **GROW THE OILSEED CROPS # CONVERT TO VEGETABLE OIL + OILSEED MEAL # CONVERT THE OIL TO BIODIESEL + GLYCERINE**

The largest single greenhouse gas emission factor in the production cycle was the nitrous oxide emissions from soils during the production of the oilseed crop. Compared to diesel fuel, on an equivalent energy basis, different biodiesel sources all had considerably lower total greenhouse gas emissions: canola biodiesel = 36% of the total production cycle GHG emissions of diesel fuel, soybean biodiesel = 37%, animal fat biodiesel = 8%, waste cooking oil = 21%. These emissions assumed that biodiesel was used as a partial substitute, e.g., 20 % blends, for diesel fuel. A recent study calculated the GHG emissions from Canadian diesel fuel at 3.12 kg eCO_2/L. In comparison, canola biodiesel had GHG emissions of 1.25 kg eCO_2/L and animal fat biodiesel had GHG emissions of only 0.29 kg eCO_2/L.

> **GHG REDUCTIONS USING BIODIESEL ARE IMPRESSIVE**

Total amounts of oilseeds produced in Canada ranged in recent years from 5.9 to 9.8 million tonnes, animal fats production was about 640,000 tonnes and waste cooking oil supplies were about 240,00 tonnes.[7] Only some small fraction of these resources would be expected to be available for new industrial uses, such as biodiesel. For comparison, diesel fuel consumption in Canada in 2000 was about 23.2 billion litres (~19.5 million tonnes).

A totally different approach is to use biodiesel as a lubricity improvement agent added in small amounts, e.g., less than 2%, to diesel fuel. In highway and city vehicle trials, using a small diesel powered car, it was found that addition of less than 1% canola biodiesel to commercial Canadian diesel fuel resulted in fuel efficiency improvements of 5.8% and reductions in engine wear of 51%.[8] At a 0.5% canola biodiesel blend researchers estimated a 4% fuel efficiency gain, and fuel GHG savings of 56 gm eCO_2/L of fuel for a large truck. **Applied to all diesel fuel used in Canada in 1999 (i.e. 22.17 billion L), a 0.5% biodiesel lubricity additive would result in:**

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[6] Levelton Engineering Ltd. and (S&T)^2. 2002. Assessment of Biodiesel and Ethanol Diesel Blends, Greenhouse Gas Emissions, Exhaust Emissions, and Policy Issues. Report to Natural Resources Canada, Ottawa, ON K1A 0E4.

[7] Reaney, M. 2002. Success stories in the biodiesel business. ABIC Conference, Saskatoon, SK. Available from AgWest Biotech, Saskatoon, SK. Also personal communication with M. Reaney at the Saskatoon Research Centre, Agriculture and Agri-Food Canada, Saskatoon, SK. S7N 2R4.

[8] Hertz, B., Button, R., Coxworth, E. and Gray, R. 2001. Biodiesel fuel additives/lubricants to improve diesel fuel use efficiency and reduce engine wear. Prairie Sustainable Agriculture and Rural Development (Prairie SARD), University of Saskatchewan, Saskatoon, SK. Available from E. Coxworth, Saskatoon, SK S7H 0J3.

- total GHG emissions savings of 2.86 million tonnes of eCO_2 per year,
- production of 106 million L of canola biodiesel,
- vegetable oil requirements using 2.6% of the 1999 canola production of 8.8 million tonnes,
- a profit of \$279/tonne of eCO_2 saved,
- net savings in GHGs of 27 kg eCO_2/L of canola biodiesel added, due to the efficiency gain assumed.

The objective in the liquid fuel industry would be to determine how small amounts of bioproducts, such as biodiesel, might be added, along with other additives, to optimize the fuel properties of the final fuel.[9] In addition, city and highway driving cycle trials, with large trucks, are needed to determine if the fuel efficiency gains and reduction in engine wear benefits found with the trials with the small diesel powered car can be confirmed with larger vehicles.

A new process for production of biodiesel has been developed by David Boocock of the University of Toronto. The new process employs an inert solvent, such as tetrahydrofuran, to form a single phase between the oil to be reacted, the alcohol and the catalyst. This greatly increases the rate of reaction. The new method appears to be well suited for the production of biodiesel from animal fats and waste cooking oils, which are the lowest cost raw materials for biodiesel production. The process is being commercially developed by the BIOX Corporation.

ANIMAL WASTES SHOULD NOT BE OVERLOOKED AS POTENTIAL RAW MATERIAL SOURCES FOR BIODIESEL

Research gaps were found in the whole production cycle of vegetable oil production and conversion into biodiesel. Examples of gaps were:

- crop development and crop production methods to minimize the effects of drought on crop yields in western Canada;
- using new research data on nitrous oxide emissions from oilseed crop production in western Canada and eastern Canada to calculate the total GHG emissions from canola and soybean biodiesel production;
- innovations to improve the farmer's net income from canola production;
- new innovations in crop breeding to improve the feed value of canola and soybean seed meals;
- truck trials with small amounts of biodiesel added as a lubricity improvement agent (as mentioned before);
- trials with adding biodiesel to diesel fuel in diesel-electric hybrid vehicles;
- trials with adding biodiesel to low sulfur Canadian diesel fuel.

[9]Reaney, M. 2002. Personal communication with M. Reaney at the Saskatoon Research Centre, Agriculture and Agri-Food Canada, Saskatoon, SK S7N 2R4.

Methane and Other Gasification Routes to Biofuels: This section of the report provides a brief overview of: methods to reduce methane emissions from landfills; anaerobic digestion of animal manures to produce biogas (principally methane plus some carbon dioxide) fuel; methods to reduce methane emissions from the digestion processes of ruminant animals, and; close coupled gasification/combustion of biomass materials such as straw to generate heat very efficiently. All these topics relate to the development of other bioproducts. For example, development of more biodegradable plastics would lead to more emissions of methane from landfills (assuming the plastics ended up in landfills) unless the landfills were tapped to recover methane for fuel applications. Thus capture of methane gas from landfills could be an important part of the program for development of more biodegradable plastics. Other approaches to dealing with waste biodegradable plastics include composting and recycling.

METHANE CAPTURE PAYS BIG ENVIRONMENTAL DIVIDENDS

A recent study for Environment Canada calculated that the potential for reducing methane greenhouse gas emissions by capturing and using landfill gas was about 7 million tonnes of eCO_2 per year over the next twenty years.[10] Suncor, in cooperation with Conestoga-Rovers, has announced a major program to capture landfill methane gas to generate electricity.

Similarly, increased production of ethanol from grain in Saskatchewan is intended to help increase livestock production. But unless the emissions of methane from ruminant livestock were reduced and methane were recovered from livestock manures, the system reduction in greenhouse gas emissions, caused by substitution of ethanol fuel for gasoline, would be partially offset by increases in greenhouse gas emissions from the increase in livestock. Thus the development of methods to reduce methane emissions from these sources would help to increase the overall system greenhouse gas reductions from the development of the grain-to-ethanol industry.

Close coupled gasification/combustion, using straw as the raw material, has been found in commercial trials in Manitoba to offer cost savings for heating barns and small commercial buildings. The system has been measured to have high efficiencies of combustion and low emissions of air pollutants. It may be of interest to locations where straw and other bioresources are abundant and cheap. It is also of interest in that it is suited for small to medium scale businesses, including new bioproduct development operations.

New methods to reduce methane gas emissions from livestock or livestock manures are at too early a stage in development to calculate the greenhouse gas reduction potential. Preliminary results indicate that anaerobic digestion of livestock manure in eastern Canada had the potential to reduce GHG emissions by 1.2 million tonnes of eCO_2 per year.[11]

[10]Conestoga-Rovers & Associates and The Delphi Group. 1999. Identification of Potential Landfill Sites for Additional Gas Recovery and Utilization in Canada. Report to Environment Canada, Ottawa, ON K1A 0H3.

[11]Helwig, T., Jannasch, R., Samson, R., DeMaio, A. and Caumartin, D. 2002. Agricultural Biomass Residue Inventories and Conversion Systems for Energy Production in Eastern Canada. Report to Natural Resources Canada, Ottawa, Ontario. Available from REAP-Canada, Ste. Anne de Bellevue, QC H9X 3V9.

An anaerobic digestion system has been established at a Hutterite colony in Alberta to produce heat and electricity from digestion of poultry, hog and cattle manure. The system generates peaking electrical power which is sold at a premium into the electrical grid. The process has been in operation long enough to calculate the electricity, heating, manure disposal and water savings and the electrical power earnings. The colony expects to recover the capital cost in about 8 years.

RESEARCH IS ONGOING WITHIN AAFC AND ELSEWHERE AIMED AT METHANE EMISSION REDUCTION FROM LIVESTOCK

Several new methods to reduce methane emissions from the digestion process of ruminant animals are under investigation. In studies at the Lethbridge Research Centre of Agriculture and Agri-Food Canada, studies on feeding vegetable oils to ruminant animals were found to increase the amounts of conjugated linoleic acid (CLA) in the meat and milk, as well as reducing methane emissions from the ruminant digestion process. CLA is a desirable nutraceutical. It will be interesting to determine the economics and market potential of this new method of improving the food value of meat and milk from ruminant animals.

In Scotland, the Rowett Institute has found that feeding certain methane oxidizing bacteria, isolated from the gut of piglets, to ruminant animals and isolated rumen fluid reduced the emissions of methane considerably.[12]

Other research topics and gaps included: determining the GHG emission reduction potential of the anaerobic digestion system installed on the Hutterite colony in Alberta, and its potential for application at other sites with high manure production; and further information about the close coupled gasification/combustion process developed and applied in Manitoba.

INVESTMENTS IN THE EU AND THE US IN BIOPLASTICS MAY SOON PAY DIVIDENDS

Bioplastics: Starch-based biodegradable plastics are gaining market momentum in Europe as a result of government regulations promoting the composting of biodegradable materials. Long term market opportunities for bioplastics in the European Union (EU) are estimated to be about 300,000 tonnes per year by 2010. US markets are also expanding, but they are being driven by more traditional economic drivers like price and performance. Cargill Dow Polymers has built a 140,000 tonnes/year polylactic acid (PLA) plant in Blair, Nebraska. DuPont has built a new factory in Kinston, North Carolina that will produce a co-polymer made from 1,3 propanediol based on the microbial conversion of corn starch. Canada has a few small startup companies producing biofilms and biofibres from animal proteins, and there are efforts in both Quebec and Alberta aimed at producing polyhydroxy alkanoates (PHA) in plants. So far, Canadian companies and R&D efforts have focussed on niche markets that will not have a significant impact on greenhouse gas reduction. There is a need for industry-led, large scale starch, PLA, PHA, and soy protein product applications if CO_2 reduction potential is to be realized in

[12]Nelson, N., Valdes, C., Hillman, K., McEwen, N.R., Wallace, R.J. and Newbold, C.J. 2000. Effect of a methane oxidizing bacterium isolated from the gut of piglets on methane production in Rusitec. Reproduction Nutrition Development. 40 (2): 212.

Canada.

Adhesives: The adhesives industry has undergone considerable change in recent years due to increasing legislative control of the emission of volatile organic chemicals (VOC). 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 an expanding research interest in bio-based adhesives. The vast majority of this research is occurring in the US and EU.

A significant adhesives industry currently operates in Canada, but current imports from the US are approximately three times greater than exports. Of greater concern is the low level of investment in adhesives research in Canada in either the public or private sector, with virtually none of the effort directed toward bio-based adhesives. Much of the current research in the US is focussed on bio-based adhesives with corn and soy being used as the starting material with funding from their respective grower associations.

Clearly research opportunities exist in Canada. Our significant wood and paper products industry, our manufacturing industries, and our expanding export of the finished products from these sectors provide a significant and expanding market for adhesives and an ongoing need for new technologies. The growing use of adhesives in medical applications also plays to Canadian strengths.

ARE BIO-BASED ADHESIVES AN OPPORTUNITY WAITING TO BE DEVELOPED?

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 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 collaboration with researchers in the US and EU.

Biocomposites: The use of natural fibres in the automotive and construction biocomposites sectors has begun to develop and gain momentum in Europe. While interest in North America is high, the markets have not yet developed. Biocomposites made from flax crop residues and industrial hemp fibres have the potential to reduce GHG emissions in Canada by lowering component weight, reducing the use of energy-intensity products (e.g. glass fibres, cement) and limiting the need for energy-intensive pesticides and herbicides (in the case of industrial hemp). Several regions in Canada may have strategic advantages in the biocomposites area, but further research, development and demonstration is required along all stages of the supply chain to reduce prices, improve quality, ensure fibre availability, and demonstrate the viability of current fibre processing technologies and new product developments. Developing resins made from bio-based sources, and ensuring adhesion between natural fibres and the polymer matrix, are two key research areas that need to be addressed. A long term strategic R&D plan for this product area could be beneficial.

THERE IS NO SHORTAGE OF OPPORTUNITY IN THIS SECTOR, ONLY THE CHALLENGE OF FINDING THOSE WHICH CAN LEAD TO PROFITS

Biolubricants: According to a European study, biolubricants and hydraulic fluids represent one of the most important bioproduct areas for reducing GHG emissions.[13] Markets for biolubricants are expected to reach 20% by 2010. Considerable research has been conducted over the last 10 years in North America and Europe where complete supply chains have been created in many countries. Canada is one of the leaders in the development of high oleic canola and high erucic rapeseed oils that are used to make industrial lubricants and other products in the plastics and cosmetics industries. A complete supply chain for high oleic canola has been established. Expansion of this supply chain to include high oleic soybean and high erucic rapeseed oils may also be possible. A national R&D program in support of this sector is needed, and could provide important economic as well as environmental benefits to the nation. There may be additional research required in Canada to improve the economics of lubricant production using new advances in chemical processing and reactor design. The development of new canola and rapeseed varieties with high oleic and high erucic content, that are drought tolerant, and have lower fertilizer and pesticide requirements, should be a priority. More detailed studies of end use applications may help to expand markets. Lifecycle analyses should be performed to provide policy justification for more supportive federal and provincial policies.

CANADIAN RESEARCHERS AND LAWMAKERS SHOULD KEEP IN TOUCH WITH THE EU BIOLUBRICANT INDUSTRY

Platform Chemicals: There are a number of potential platform chemicals that can be produced from agricultural feedstocks, including: citric acid, lactic acid, levulinic acid, succinic acid, and 1,3-propanediol, to name some of the more commonly discussed platforms. Each of these platforms has created interest in Europe and the US, but the applicability to the Canadian context remains unclear. In the long term, North American industry intends to focus on using cheap lignocellulosic wastes to make sugars, which can be used as a platform for deriving various biochemicals. Under this scenario, three key factors must be present for the production of platform chemicals to be economically viable: access to large amounts of cheap lignocellulosic feedstocks; a ten-fold reduction in enzyme costs; and access to an existing ethanol and/or starch processing infrastructure that can act as a "bridge" for the production of other chemicals. Compared to the US, Canada does not have a large supply of cheap agricultural wastes, nor a well developed ethanol and starch processing infrastructure to provide the "bridge". At the moment, Canada also appears to lack an industry champion. As a result, capital investment in platform chemicals will likely flow to the US. There may be two exceptions. Southwestern Ontario does have a significant ethanol and starch processing infrastructure and could easily import corn from the US mid-west to supplement domestic raw material supplies. Canada's prairies, on the other hand, could develop a domestically supported methyl ester platform involving biodiesel and biolubricant production from canola and other oilseed crops. More research is needed in this area to determine what is technically and economically feasible.

RESEARCH OPPORTUNITIES ABOUND IN THIS SECTOR, PARTICULARLY RELATING TO COST/PERFORMANCE RATIOS FOR ENZYMES

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[13] Johnson D., Renewable Raw Materials: A way to reduce greenhouse gas emissions from EU industry? DG Enterprise/E.1 July 2000.

For each of the sectors covered in this study, specific research recommendations have been prepared. These can be found in full context in the body of this report, but have also been summarized in the following addendum to this Executive Summary. Similarly, a few broad recommendations and conclusions have been prepared and highlighted in the following addendum.

Summary of Research Recommendations

Note: These recommendations have been extracted from Section 6 of this report. The reader is encouraged to read the appropriate segments of these Sections so as to benefit from the full context in which these research opportunities were presented.

Ethanol

1. Ongoing research on raw material selection and process optimization is recommended to assist in determining which of the several ethanol production options warrant the significant development costs required for commercialization. This ongoing research should continue to look at both starch-based and lignocellulosic-based raw materials/systems.
2. Research should continue to look at the recovery of co-products from the various raw product and processing options so that maximum potential competitiveness is understood.
3. Studies should continue on life cycle analysis of each of the products and processes under study to allow true environmental assessments to be made.
4. The use of supercritical solvents for the reaction of biomass materials to produce new products warrants continued study.

Biodiesel

1. A field of R&D which may yield large dividends for the biodiesel industry lies in collaborative investigations with the oil refinery industry and with designers of car and truck engines of various types. Focus should be on the costs and benefits relating to use of plant and animal based biodiesel both as a fuel and as a lubricity agent.
2. Significant scope exists for research on traditional and new crops which could yield greater amounts and/or superior quality of oils suited to biodiesel applications.
3. In coordination with the previous recommendation, research is needed on yield maintenance under drought conditions.
4. Ongoing research is also needed to not only accurately quantify the impact of farming practices on GHG emissions but also in finding ways to reduce this occurrence.
5. Ongoing research on new approaches to farming such as row seeding of canola and full crop harvesting is a logical approach to finding new ways to increase farm income.
6. The continuation of research/demonstration aimed at quantifying the benefits of biodiesel in "real-life" vehicle trials is highly recommended.

Bioplastics

1. Research opportunities in this sector are almost endless. However, the fact that bioplastics still seem to be "a few years away from commercialization" after two decades of research indicates that the challenges this sector is encountering in competing with the petrochemical-base products are considerable.
2. Genetically engineered crops such as switchgrass, tobacco, canola, pea and potato are also being investigated for the production of PHA for use in a range of bioproducts including bioplastics. Greater knowledge is needed in identifying ways of increasing the PHA levels in the plant without encountering negative physiological consequences.

3. Similarly, research is required if lignocellulosic waste materials are to be used to produce lactic acid which in turn can be used to produce polylactic acid and ultimately a range of bioplastics.
4. The use of Genetically Modified (GM) bacteria to convert glucose and starch into propanediol is another field of active research in which Canadian scientists may find opportunity.
5. Research continues to focus on the development of starch and protein-based plastics which show greater resistance to breakdown in an aqueous environment and under high temperatures.
6. The chemical pre-treatment and polymerization of natural fibres for subsequent use in fibre reinforced plastics continues to be an area of focus.
7. Research will be needed in finding efficient extraction and processing methods if the genetically modified (GM) approach begins to show promise from a production perspective.

Adhesives

1. There is potential for a major research program focussed on the use of bio-based adhesives to supplement and/or replace both formaldehyde and isocyanate based resins in panel board manufacturing.
2. It is worth investigating the use of the fairly extensive US research on soy protein in bioadhesives for application in Southern Ontario and/or for guiding Canadian research on canola, flax, field pea, wheat or barley protein as the starting material for new plant protein based adhesives.
3. Similarly, the use of derivatives from wheat, barley or potato starch in place of corn starch in adhesives formulations is worth investigating.
4. Effort 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 the 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.
5. Given Canada's world class expertise in both medical and fisheries technologies, it may prove beneficial to actively search out bio-based opportunities in the medical adhesives using marine species as the raw material field.

Biocomposites

1. There is opportunity for Canadian researchers to work with industry and agronomists in Europe in developing new lines of hemp and flax with superior fibre qualities and more favourable processing characteristics.
2. The use of proteomics to isolate genes involved in the biosynthesis of cell wall lignins and hemicellulose in flax and other Canadian fibre crops could well lead to increased biofibre performance and increased competitiveness with competing materials.
3. If industry shows sufficient interest, there are numerous physical and chemical processing options for natural fibres which could be researched and developed for use with Canadian fibre crops. Again, Europe has shown leadership in this area.
4. Specific opportunities may lie in developing dual purpose flax varieties where the

combination of the seed and the stock provide maximum returns to the farmer. However, the impact which this may have on end product quality must be determined.

5. There are opportunities to improve fibre yields and quality by focussing additional agronomic research on developing improved and less costly Canadian fibre seed varieties, finding optimum seeding rates, and improving fertility management appropriate to different regions.
6. There are opportunities to improve the economics of large-acreage, commercial harvesting by developing new or modified harvesting and baling equipment.
7. Research is required to improve the retting process with the aim of improving fibre quality and reducing costs.
8. Research is needed to improve the bond between natural fibres and the polymer matrix where fibres are used in biocomposite materials.
9. There is a need to improve short fibre injection moulding systems by controlling fibre size and developing new compounding technologies if this industry is to be developed.
10. In addition to continued study of automotive composites, there is also a need for new product development in the construction composite sector e.g. new forms of natural fibre-based insulation, fibreboard, fibre-reinforced cement, drywall, and ceramic tiles.

Biolubricants

1. Given the projected increase in biolubricant use in the EU and the US, Canadian researchers have an opportunity to use their considerable expertise in oilseed breeding and processing to assist Canadian companies in capturing some of the expanding market.
2. It is recommended that Canadian researchers seek out collaborative programs with EU researchers who are at the cutting edge in biolubricant research.
3. Ongoing research is required to find oilseed varieties which can produce acceptable yields and oil quality under semi-drought conditions.
4. Through both conventional breeding and genetic modification techniques, the development of dual and multi-use oilseed crops should be investigated.
5. Research opportunities exist regarding the development of biodegradable additives used in lubricants.
6. Opportunities exist in developing better testing protocols (including life cycle analysis methods) in this expanding bio-based industry.

General Recommendations

1. If Canada is to achieve sustainable growth and development of the bio-based industries discussed in this paper, it is recommended that for each specific bio-based initiative a preliminary business analysis be conducted, and, to the degree possible, a development plan prepared. Although the business analysis and research findings are a "chicken and egg" situation, a preliminary economic assessment based on potential and probable research outcomes will greatly assist the research funding bodies in identifying where scarce resources are best directed.

Note: A study is currently in progress with funding from AAFC which will identify specific business opportunities in the sectors discussed in this paper. A review of the AAFC report (to be completed in the summer of 2003) will help identify those bio-based products and sub-sectors which may hold the most opportunity for rewards for Canadian investors and researchers. (It is intended that this report be posted on both the AAFC and CANUC web sites)

2. It is recommended that prior to committing support for research, a determination should be made as to the general scope of the business which might develop if the outcome of the research is positive. Certain markets and technologies have become the domain of the multi-national corporation, others the domain of the entrepreneur. It is important to understand these differences prior to assembling an R&D and investment team.

3. Assuming that the R&D costs for developing a significant bioeconomy in North America are in the neighbourhood of $20 billion over 20 years, it is recommended that Canadian researchers and others involved in the bioproducts industry work collaboratively with their counterparts in the US and the EU not just on the scientific issues, but also on harmonized legislation and support programs so as to minimize the potential for trade disputes.

4. Given the complex nature of these bio-based industries, it is recommended that governments take the lead in developing a full understand of both the environmental and financial costs and benefits which will accrue from the use of selected bio-based industrial products. Governments should also continue to take a lead role in helping to win public support for environmentally friendly bioproducts.

5. When assessing the potential for the introduction of a new bio-based product, it is recommended a comprehensive life cycle analysis be carried out on both the bioproduct and the petrochemical-based product it is replacing so that there is as little ambiguity as possible with regard to the net environmental impact of the two options.

General Conclusions

1. There is a need to separate hype from reality in several of the sectors studied. Bioproduct research and development is one of the current "hot" topics. However, all involved with the industry must be aware that under current economic and political conditions, only a few of the many ideas/opportunities will lead to the establishing of viable businesses and therefore careful judgement will be required before limited R&D resources are committed.

2. The challenge which Canada and other nations face lies in pursuing bio-based business opportunities which provide balanced rewards for the private investor and the public at large where public support is involved. Environmental stewardship and free enterprise may not be compatible in fields of international trade without meaningful international environmental protection agreements in place. Although on the surface this appears not to involve research, where global environmental and trade issues are involved, the importance of intellectual properties must not be underestimated.

3. Researchers and investors should not overlook the benefits of recovering high valued end products as by-products or co-products from established food and non-food processes. In fact, over time, reliance on a specialty crop (either natural or genetically manipulated) may be unwise if competitors are able to use the co-products/biorefinery approach.

4. The need for raw material consistency and availability must be fully understood in assessing any bio-based product opportunity. Researchers involved in production, harvest, storage and transportation fields should be aware of their important role in strengthening this important link in the chain.

5. Clearly the ultimate success of Canada's bioproducts industry lies in large measure in the degree of coordination and cooperation among governments, companies, universities, industry associations, and the general public. The issues are too complex to be left to one group to address on their own.

6. All involved in bio-based product introduction must understand there is a catch up situation with the petrochemical industry. The 50+ year R&D lead it currently enjoys in many product areas will not be overcome quickly. Revolutionary approaches are not likely to be successful. However, rapid evolution of new generation bioproducts is something for which the industry can strive.

Table of Contents

Section 1: Introduction

One hundred years ago, the petrochemical industry faced the challenging task of building an industry in competition with an established bio-based industry. Today, the situation is somewhat reversed. Environmental realities and an ever shrinking supply of oil and gas are forcing a fundamental re-evaluation of the petrochemical-based economy. Researchers and others working in the agriculture, forestry, and fisheries sectors which hold the potential to offer a wide array of bio-based non-food/non-feed products, are excited about the prospects of competing with the petrochemical industry both in traditional markets and in a wide array of innovative new product fields.

EXCITING TIMES LIE AHEAD FOR PEOPLE WORKING IN BIO-BASED PRODUCTS FIELDS.

The Canadian Agri-Food Research Council (CARC), and the BIOCAP Canada Foundation (BIOCAP), both of which are directly involved with the advancement of science and technology in the bioproducts field, have collaborated in developing this joint discussion paper outlining some of the opportunities and challenges in this intriguing old/new field of research and development. Key members of the Canadian Agricultural New Uses Council (CANUC) were commissioned to work with the Bio-based Working Group of CARC/BIOCAP in drafting this discussion document.

Although this paper will touch on a fairly wide cross-section of topics relating to greenhouse gas (GHG) emissions, waste utilization, and other environment-related topics, the primary focus is on research and development issues pertaining to the replacement of non-renewable raw materials with bio-based materials in selected business sectors. The positive impact which this industry can have on Canada's agricultural community, including farmers, will also be identified. Target sectors/products addressed in this paper include: biofuels, biolubricants, bioplastics, adhesives, biofibres and platform chemicals. These sectors were selected based on their potential for combined environmental benefits and overall return to agriculture. Products not specifically addressed in this paper but which offer important economic and/or environmental opportunity, include: bio-based surfactants, paints and coatings, pharmaceuticals, cosmetics, nutraceuticals, pesticides, and inks. In fact, a growing number of successful ventures can be found in these sectors, particularly in pharmaceuticals and cosmetics where plant and animal based materials are re-capturing markets lost to the petrochemical industry over the past half century.

FOCUS IN THIS PAPER IS ON RESEARCH RELATING TO GHG REDUCTION RESULTING FROM USE OF BIOFUELS AND OTHER SELECTED BIO-BASED PRODUCTS

This document is meant to provide Canadian researchers, government officials and the public with a general understanding of this interesting yet highly complex topic, as well as a specific understanding of many of the research issues involved. A more detailed analysis of the business potential of the selected sectors and other sectors not addressed in this document were beyond the scope of the assignment. However, much of this information can be obtained from a concurrent study.[14] Readers are also cautioned that both bioproducts manufacturing and GHG emissions control are not only extensive topics, but are currently going through a stage of rapid evolution. For these reasons, CARC and BIOCAP encourage readers to consider this as a discussion paper and not a definitive statement or position paper, on these selected fields of research and development.

Section 2: Specific Focus for this Paper

It is intended that this discussion paper will contribute significantly to an overall plan which Canadian researchers and others can use to focus their efforts on topics of greatest importance in these emerging technologies. The specific purposes of the paper are to:

- Identify key research opportunities through which new bioproducts might come to replace petrochemical-based products which will in turn lead to reduced GHG emissions

- Analyse the research and development environment to identify current gaps in research, R&D challenges and barriers, enabling technologies, human resources strengths and weaknesses, and themes for future research;

- Provide an international and Canadian perspective to bioproduct opportunities and research; and,

- Provide specific and general recommendations for research which will lead to the development of bioproducts in Canada.

Because transportation and the burning of fossil fuel in the process is the major contributor to GHG build-up, particular focus is placed on this topic and on the potential role which bio-based fuels might play in helping to manage this expanding global problem.

The first five sections of the report are intended to give the reader an overview of this rapidly evolving industry. Information is provided on the progress being made in the US and in several countries in Europe. The current state of development of bioproducts in Canada is also outlined in these sections. Section 6 looks at the target sectors in more detail and identifies some of Canada's strengths and weaknesses with particular emphasis on the research component.

The final two sections (7 and 8) present some general recommendations and conclusions.

[14]CANUC/PRA reports (Phases 1 and 2) prepared for the Horticulture and Special Crops Division, MISB, Agriculture and Agri-Food Canada.

Section 3: Environmental Policies and Programs

The Kyoto Agreement - In December 1997, Canada, along with 160 other countries, committed to a Protocol that called for reductions in GHG emissions over 15 years. Canada's specific commitment is to reduce average annual GHG emissions for the 2008-2012 period to 6% below 1990 levels.[15] This represents a formidable challenge, but at the same time a real opportunity for farmers and others in the agricultural value-added chain.

By current calculation methods, primary agriculture alone (i.e. excluding related transportation and food processing) is responsible for about 10% of Canada's GHG's. Primary agriculture in Canada accounts for 61%, 38%, and less than 1% of Canada's total emissions of nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2), respectively.[16] By ratifying the Kyoto Protocol agreement in December 2002, the Government of Canada has re-affirmed its commitment to do its part in meeting this unprecedented global challenge.

Canada is not alone in searching for answers and solutions to the GHG issue. Europe is currently in its "Sixth Community Environment Action Programme". In this, the latest of the EU's environmental programs (July 2002), the EU parliament has laid out a plan designed to limit the long-term impact of global warming to a maximum of 2 degrees C over pre-industrial temperatures. In order to accomplish this goal, a global reduction of 70% of GHG emissions, from 1990 levels, will be necessary. The legislation also calls on European manufacturers to account for the environmental costs in their product development programs.[17]

Although the US is yet to ratify the Kyoto agreement, one needs only browse the various government and university websites to see the degree of commitment and attention being paid to the GHG issue in that country.

The following excerpt from a recent news release from Environment Canada sets out our nation's current position:

> *The Government of Canada released the Climate Change Plan for Canada on November 21, 2002. This Plan is the result of intensive consultation with the provinces and territories, as well as with stakeholders and individual Canadians and reflects the Government of Canada's commitment to action on climate change while ensuring our economic competitiveness and growth. The Plan provides a clear framework for the way forward while allowing for continuous adjustment as we assess our progress. Participating in the global effort to address climate change will require a national effort, one that summons the best from our citizens, entrepreneurs, scientists, communities, and governments. With commitment and resolve we can*

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[15] http://www.agr.gc.ca/policy/environment/eb/public_html/ebe/climate.html

[16] ibid.

[17] http://europa.eu.int/comm/environment/newprg/

create the healthy environment and dynamic economy we want for ourselves and for future generations of Canadians.[18]

To encourage Canadians to participate in this high priority initiative, support funding has been made available to researchers and innovators through a range of programs, starting with the Climate Change Action Fund which was established in 1998 by the federal government. Since that time, each of the provinces has brought in similar legislation and support programs.

Although each province has taken a slightly different approach to dealing with the GHG issue, all recognize the important role which renewable biomass has to play in contributing to the ultimate solution to this global problem.

Section 4: Bioproducts Industry Overview

4.1 Introduction

Bio-based products which were the norm in the marketplace in the first half of the 20th century were relatively simple to produce. This might lead one to assume that a return to these products should not be a major challenge. Unfortunately, this is generally not the case. The advanced standard of performance which has come with petroleum-based industrial products and with modern scientific and engineering approaches has elevated end user expectations to levels well beyond those of earlier generations. Overcoming the resulting gap in both perception on the part of the non-scientific community and understanding on the part of the research community are significant challenges which should not be underestimated.

The following three sections present an overview of the current status of the bioproducts industries and approaches to GHG issues in the US, the EU, and Canada. They serve to show not only the opportunities in this exciting field, but also the very significant R&D investments which are being made by Canada's most important trading partners.

4.2 The United States

4.2.1 Overview

Biomass currently accounts for 3% of the US energy needs and more than 300 billion pounds of products annually, primarily derived from forest products.[19]

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[18] http://climatechange.gc.ca/plan_for_canada/index.html

[19] Fostering the Economic Revolution in Bio-based Products and Bioenergy: An Environmental Approach. January 2001. An interagency strategic plan prepared in response to the US Biomass Research and Development Act of 2000 and the Executive Order 13134: Developing and Promoting Bio-based Products and Bioenergy by the US Biomass Research and Development Board.

There are about 250 companies in the US that produce bio-based products ranging from plastics to lubricants, inks, enzymes, absorbents, adhesives, biocontrol products, solvents, coatings and paints, cosmetics and personal care items, landscaping products, and pharmaceuticals.[20]

In August of 1999, the President of the US established a national goal of tripling the production of bioenergy and bioproducts by 2010.[21] In June 2000, the US Congress enacted the Biomass Research and Development Act[22] which complemented many aspects of the Presidential Order, and required the Secretaries of Agriculture and Energy to submit a report setting out the R&D goals and resources needed to achieve the goal of tripling bioproduct and bioenergy production.

In fiscal 2001, the Departments of Agriculture and Energy jointly requested $289 million for R&D for bioenergy and bioproducts, of which $230 million was appropriated by Congress.

To reach those goals, the US has identified the development of low cost sugars from starch and lignocellulosics as a key strategy.[23] This sugar platform can be used to make:

- alcohols (ethanol, glycol, sorbitol)
  - ethanol is used as a fuel
  - glycol is used to make anti-freeze, brake fluids and solvents
  - sorbitol is used to make adhesives and sweetners.
- acids (lactic acid, succinic acid, etc.)
  - lactic acid is used in food processing, cosmetics, pharmaceuticals, and as a starting material for bioplastics
  - succinic acid can be used to create pharmaceuticals, toiletries, paper, beverages and detergents and polymer fibres.
- polymers (e.g. xanthum gum)
  - xanthum gum is used as a food thickening agent as well as in toothpaste, medicines and paints.

Another important platform involves the production of biosynthesis gas using gasification

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[20]Ibid.

[21]Executive Order 13134: Developing and Promoting Bioproducts and Bioenergy. August, 1999.

[22]Title III of the Agricultural Risk Protection Act of 2000 - H.R. 2559 - Public Law 106-224.

[23]Fostering the Economic Revolution in Bio-based Products and Bioenergy: An Environmental Approach. An interagency strategic plan prepared in response to the US Biomass Research and Development Act of 2000 and the Executive Order 13134: Developing and Promoting Bio-based Products and Bioenergy by the US Biomass Research and Development Board, January 2001, p. 7. James Hettenhaus and James Robert Wooley. Draft Executive Summary: Sugar Platform Colloquies. Office of Fuels Development, Department of Energy. January, 2001. Also see Enzyme Sugar-Ethanol Platform Project Status Report. National Renewable Energy Laboratory. October 22, 2001. Corn stover is the feedstock of choice. Genencor International and Novozymes Biotech Inc. are leading the search for low cost enzymes. Access to cheap raw materials; reducing the cost of enzymes by 10-fold; and limiting processing capital costs (through loan guarantees, tax benefits, production of co-products, and co-locating with a dry mill and/or a coal-fired plant) are the three keys to making the system economically viable.

technologies.[24] Biosynthesis gas can produce:

- electricity to drive advanced turbines or fuel cells
- alcohols (e.g. methanol)
  - methanol can be used to make anti-freeze
  - or formaldehyde (which is used in plastics, germicides, fungicides)
- acids (e.g. acetic acid)
  - acetic acid is used to make films, textiles, vinyl plastics and polyesters.
- clean hydrocarbon fuels using a Fischer-Tropsch process.

4.2.2 Key Opportunities

One can get a quick sense of the potential market opportunities that may emerge in the US by the end of this decade by examining their public policy goals and targets for market expansion.[25] If successful, their markets in key bioproduct areas would triple (either individually or in combination) from the following baselines:

- ethanol - 1.5 billion gallons
- biodiesel - 6 million gallons
- electricity - 60 billion kWh (from 10 thousand megawatts of capacity) or about 1% of US generating capacity. Most of this energy is used to provide electricity and heat for the pulp and paper, and the solid and engineered wood industries.
- emerging bioproducts - 10-15 billion pounds (5 - 7.5 million tons)

4.2.3 Key Organizations

Government Laboratories

The US Federal Government has established a multi-agency Biomass Research and Development Initiative to coordinate and accelerate Federal bioproducts and bioenergy research and development. The Initiative was first established by an Executive Order in 1999, and later formalized in legislation when the Biomass Research and Development Act was passed by Congress in 2000.

The Initiative is coordinated through a Biomass Research and Development Board, which is a cabinet level council co-chaired by the Department of Energy (DOE) and the US Department of Agriculture (USDA), and an Advisory Committee comprised of 25 individuals from industry, academia, non-profits, and the agricultural and forestry sectors. The day-to-day operations are managed by a National Biomass Coordination Office staffed by both DOE and USDA experts. The

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[24] Ibid.

[25] Fostering the Economic Revolution in Bio-based Products and Bioenergy: An Environmental Approach. January 2001, p. 5, 12. An interagency strategic plan prepared in response to the US Biomass Research and Development Act of 2000 and the Executive Order 13134: Developing and Promoting Bio-based Products and Bioenergy by the US Biomass Research and Development Board.

Coordination Office acts as an executive secretariat for the Biomass Research and Development Board.

The Initiative maintains a web site that publishes a newsletter, keeps abreast of activities on Capital Hill, manages an events calendar, announces solicitations, and stores key government reports.[26]

Both the DOE and the USDA conduct bioenergy and bioproducts research at their various national and regional labs.[27] Appendix A contains a brief summary for each lab describing their product focus, and their key research strengths according to each stage in the product supply chain.

US Government labs are engaged in a wide range of product research, including bionergy, biofuels (ethanol, biodiesel), platform chemicals (e.g. lactic, succinic, and levulinic acids), bioplastics, adhesives, lubricants, surfactants, solvents, pharmaceuticals, biopesticides and herbicides, soil amendments, etc.

Selected Universities

There is a large and growing number of university-based centres for bioproduct research. Some examples include:

- The Ag-Based Industrial Lubricants (ABIL) Program at the University of Northern Iowa which is studying the use of soybeans to produce industrial lubricants and hydraulic fluids, fifth wheel grease, chain bar oil, etc.[28]
- The Biocomposites Group, within the Center for Crops Utilization Research, Iowa State University, which is researching protein-based adhesives made from soy flour that could be used as a binder for wood and plastic composites. It is also studying composite materials made from crop and saw mill residues and fast growing poplars.[29]
- The Biodegradable Polymer Research Center, University of Massachusetts at Lowell, is studying the microbial production of polymeric materials, organic transformations, plastics processing, materials characterization, biodegradation testing, and environmental impact analysis.[30]
- The Center for Plant Products and Technologies at Michigan State University is studying how to genetically engineer plants to express the cellulase enzymes in plant tissue and then develop processing technologies to release these enzymes during the biorefining stage of lignocellulosics. Another research project focuses on the genetic engineering of the biochemical pathways for plant fatty acid and triacylglycerol production to expand the range

[26] http://www.bioproducts-bioenergy.gov/

[27] For a detailed listing of the capabilities of US Government labs, see Participating Laboratory Capabilities, DOE National Bioenergy Center, Strategic Partners Workshop, April 11-12, 2001, Colorado.

[28] http://www.uni.edu/abil/index.html

[29] http://www.ag.iastate.edu/centers/biocom/

[30] http://bprc.caeds.eng.uml.edu/

and value of industrial uses for oil seed crops. Other areas of research include advanced bioreactor and fermentation engineering, the development of high yield succinate fermentation, separation of fats and fatty acids, and catalytic upgrading of organic acids.[31]

- The Starch Institute for Non-Traditional Applications for Starch (SINAS) at Michigan State University which is studying the biochemical, chemical, and genetic modification of starch for use as bioplastics.[32]
- The Center for Composite Materials, University of Delaware, has formed the ACRES Group (Affordable Composites from Renewable Resources). This group is studying the use of soybeans, starch, and natural fibres like straw and hemp in composite materials. The group also received an $11 million grant from the Department of Energy to study low-cost adhesives and resins from soy oil and soy protein.[33]
- The Industrial Agricultural Products Center, University of Nebraska-Lincoln, which is studying industrial uses for proteins found in soybeans and wheat e.g. as films, coatings and adhesives.[34]
- The Purdue Center for New Crops and Plant Products, which holds a national symposium on new crops and new uses. The Center has now held five symposia.[35]
- The Thames Research Group, University of Southern Mississippi, which is a 51 member research group that has more than 32 years experience in inks, coatings and adhesives, including the use of oilseed crops as feedstocks.[36]

Non-Profit Organizations

Among the most well known non-profit organizations promoting the industrial uses of crops are:

- The US New Uses Council - which produces a newsletter, calender of events, bioproducts database, and annual meeting that showcases advances in R&D.[37]
- The Association for the Advancement of Industrial Crops - an international, educational and scientific organization that has held international conferences since 1997.[38]
- The Institute for Local Self Reliance (ILSR) - a nonprofit research and educational organization that produces The Carbohydrate Economy Newsletter, and various on-line ILSR research publications.[39]

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[31] http://www.cppt.msu.edu/

[32] http://www.bch.msu.edu/%7Esinas/

[33] http://www.ccm.udel.edu/research/acres/

[34] http://agproducts.unl.edu/research.htm

[35] http://newcrop.hort.purdue.edu/newcrop/default.html

[36] http://www.polymercoating.com/

[37] http://newuses.org/index.html

[38] http://www.aaic.org/index.htm

[39] http://www.ilsr.org/

Trade Associations

The US National Corn Growers Association and the American Soybean Association (ASA) are both very active in funding bioproduct research and development in the United States.

- The National Corn Growers Association, for example, has funded research on: polyols (propylene glycol, ethylene glycol and glycerol) which can be used to produce anti-freeze and plastics; 1,3-propanediol, which can be used to make polyesters; and polylactic acid, which can be used to make packaging materials and apparel and industrial fibres.[40]

- The American Soybean Association fosters industrial uses research that focusses on improving plant breeding, cultivation, and the identification of new industrial use markets. The ASA, for example, has studied markets for inks, paints and coatings, composites, adhesives, solvents, lubricants and hydraulic fluids.[41]

Leading Companies

There are about 250 companies in the US that are engaged in bio-based research and development. Some examples of the leading companies, by product, include:

- Ethanol - Archer Daniel Midlands, Cargill, World Energy, and Minnesota Corn Processors
- Biodiesel - Ag Environmental Products LLC, World Energy Alternatives, West Central Soy
- Lubricants and Hydraulic Fluids - Cargill Industrial Oils and Lubricants, Environmental Lubricants Manufacturing, John Deere, Lubrizol
- Bioplastics - DuPont, Cargill Dow Polymers
- Ethyl lactate (a green solvent) - Vertec Biosolvents, Archer Daniel Midlands, Cargill Dow Polymers
- Polylactic acid - Cargill Dow Polymers, Purac North America

4.2.4 Key Research Themes and Gaps

In January 2001, the US Biomass Research and Development Board published an inter-agency strategic plan in response to the President's Executive Order 13134, Developing and Promoting Bio-based Products and Bioenergy, and the Biomass Research and Development Act of 2000.[42] The Board established an integrated set of technology, market and public policy goals and targets:

"*Technology Goals*

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[40] http://www.ncga.com/research/technology/index.htm

[41] http://www.asa-europe.org/library_e.shtml

[42] Fostering the Economic Revolution in Bio-based Products and Bioenergy: An Environmental Approach. January 2001. An interagency strategic plan prepared in response to the US Biomass Research and Development Act of 2000 and the Executive Order 13134: Developing and Promoting Bio-based Products and Bioenergy by the US Biomass Research and Development Board.

- *Reduce by two- to ten-fold costs of technologies for integrated supply, conversion, manufacturing, and application systems for bio-based products and bioenergy by 2010.*
- *Accelerate commercial readiness and acceptance of integrated bio-based products and bioenergy systems for fuels, heat, power, chemicals, and materials.*
- *Assess environmental and ecosystem impacts of, and enhance the benefits of, bio-based products and bioenergy systems at all stages of development.*
- *Foster innovation-driven science of biomass feedstocks, bio-based products, and bioenergy and quickly incorporate these scientific results in the relevant technology-development activities.*

Market and Public Policy Goals

- *Coordinate policies to achieve early market adoption of bio-based products and bioenergy and create demand for bio-based products and bioenergy.*
- *Increase federal government purchases or production of bioenergy to 5 % and relevant bio-based products purchases to 10% by 2010.*
- *Facilitate tripling the use of emerging bio-based products and bioenergy by 2010 in a manner that is consistent with federal resource conservation and environmental policies*."[43]

The US Biomass Research and Development Technical Advisory Committee published a report in December 2001, that provided recommendations to the US Departments of Agriculture and Energy.[44] The recommendations were "designed to advance the availability and widespread use of bio-based industrial products and promote rural economies" and to facilitate a tripling in the production of bioenergy and bioproducts by 2010. The Committee's recommendations represented a "preliminary overview" with more "finite" recommendations to come over the next two years. The following sections summarize some of the main points.

4.2.4.1 Basic Science

Advances are needed in the following frontiers:

- genomics, proteomics, structural biology, metabolic engineering, molecular biology
- information technologies
- merging nanotechnology with biological systems
- chemical sciences
- molecular design - chemical and biological
- *in silico* biology
- computational modelling
- robotics and automation to improve crop production, harvesting, molecular biology, genetic screening, combinatorial screening, etc.

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[43]Fostering the Economic Revolution in Bio-based Products and Bioenergy: An Environmental Approach. January 2001, p. 3. For more details on strategies and possible milestones, see pages 16-18.

[44]Biomass Research and Development Technical Advisory Committee Recommendations. December, 2001. A report submitted to the US Secretaries of Agriculture and Energy in accordance with the Biomass R&D Act of 2000.

- sciences of complex systems
- molecular farming

More specifically, there is need for:
- enhanced knowledge of fundamental plant physiology, cellular biology, cellular enzymes and their functions, and their controlling mechanisms in plants
- improved functional properties of biomaterials to meet future needs
- maintaining high value uses of biopolymers, lipids, extractives, etc.
- analytic tools to identify viable opportunities for commercial and societal impacts
- ability to employ flexible chemical, thermochemical and biological processes
- tools to shorten cycle time for developing new commodity crops and strains
- novel approaches to separation and pretreatment
- life-cycle analyses of both ecosystems and processes

4.2.4.2 Biofuels

Production-related R&D issues include:
- feedstocks - need to effectively use all available environmentally appropriate feedstocks including: agricultural crops and trees, wood and wood wastes and residues, grasses, crop residues, animal wastes, municipal wastes, and other underutilised biomaterials
- harvesting - integrate effective management of crop production, transportation and analysis

Processing-related R&D issues include:
- development of less expensive pretreatment processes
- development of efficient and inexpensive conversion technologies, e.g.
  - improved catalytic and chemical conversion technologies - biodiesel
  - enzyme and fermentation methods that can handle a greater variety of feedstocks and process them more efficiently into fuels e.g. ethanol
  - additional research into the fundamental structure of lignocellulosic materials (e.g. chemistry of cell wall structures; transport properties; genetic properties) is needed to improve growth rates and processing characteristics - lignocellulosic ethanol
- development of sensors for quick, cost-effective, on-line, real-time analysis of feedstock collection, storage, processing and transportation
- development of integrated biorefineries from concepts into real world models:
  - integration of thermochemical and catalytic processing for conversion of multiple feedstocks (starches, sugars and cellulosic materials) into fuel
  - better integration of by-product waste streams
  - finding higher value uses for co-products
- demonstration sites
- technology transfer to industry

Market-related issues include:
- development of distribution infrastructure to transport biofuels from production locales to a broader market area on a large scale
- market development for co-products

- life cycle impacts of harvesting lignocellulosic materials
- analysis of performance characteristics among various biodiesel feedstocks (e.g. soybean, canola, sunflower, animal fats)

4.2.4.3 Bioproducts

Includes, for example: polylactic acid, propanediol, soy polyurethane, soy protein adhesives, water-borne soy coatings, soy and corn solvents, vegetable oil lubricants, soy and corn thermoset plastics, organic acids, etc.

Production-related issues:
- genetic engineering of crops for both edible and industrial uses e.g. by increasing the yield of a specific protein or fatty acid, by creating new chemicals that reduce the number of manufacturing steps, and by increasing the physical size, speed of growth, and durability of feedstocks
- environmental impact studies of genetic engineering, at the species-specific level

Processing-related issues:
- improved fractionation and separation technologies
- enhanced fermentation and hydrolysis of fibre, oil, starch and protein fractions including the development of genetically engineered microorganisms with the ability to provide useful, high-value products from a wide variety of feedstocks
- new catalysts and biocatalysts
- new reactor designs
- pilot plant demonstrations using a variety of raw material inputs
- negotiation of IP rights
- encouragement of farmer-owned cooperatives
- expanded efforts to develop high-value protein polymers and resins from vegetable and animal proteins

4.2.4.4 Cross Cutting R&D Themes

- feedstock availability and properties database
- new composition analysis tools - fast, inexpensive, rugged
- database on industrial enzyme systems - structure and function
- improved recovery, handling and storage technology and procedures (e.g. residue recovery and utilization, separation technology, densification)
- better understanding of residue removal impacts
- need for low-cost chemical and biological processes including new chemistry and thermochemical synthesis that can treat, break down these molecules and separate the resulting components into purified feedstock streams
- need to combine engineering and biological principles to improve product purification
- enhanced enzymes and chemical catalysts, including polysaccharide degrading enzymes, chemical catalysts, and enzymes for efficient extraction of oils
- genetically enhanced microbes, through genetic prospecting and metabolic engineering

- improved system design and optimization, e.g. biorefineries
- technologies that benefit multiple pathways
- tailor feedstocks to conversion processes
- process intensification and consolidation, i.e. cut out as many processing steps as possible
- integrate upstream and downstream processing
- improved process monitoring and control
- integration of complementary technologies, e.g. biofuel with hybrid fuels/energy storage devices
- better integration and coordination of systems of production, processing, transportation and distribution to end users, using best management practices
- use and development of computational tools to better understand biomass systems
- comparison of product performance, life-cycle analysis, and environmental footprint compared to competing products
- identification of new products (as opposed to copying existing ones)
- identify target markets
- develop tools to understand market dynamics and identify market drivers
- expand performance based contracting where metric advances in productivity or cost reduction are required for project funding
- evaluate the cost effectiveness and environmental impacts of plant biotechnology vs bioprocessing
- emphasis on decentralized conversion processes, and farm/community ownership
- encourage expansion of existing production facilities, as well as greenfield facilities

4.2.4.5 Related, Non R&D Issues

- better R&D coordination between public private sectors including roadmaps and visions to assist in identifying collaborative, long-term R&D priorities and goals
  - database of product research
  - clearinghouse for R&D information
- better R&D coordination between federal and state efforts
- consistent, long-term policies e.g. tax incentives
- infrastructure development to effectively develop products and move them to market
- standards development, e.g. for machinery, management practices, environmental quality of feedstocks, fleet standards, oxidation standards, etc.
- non-biased product certification standards and labels
- independent performance verification of technologies in order to accelerate permitting and marketing
- market development through laws, regulations, tax incentives, e.g. tax incentives to act as market pull mechanisms, incentives for non-profits, production tax credits, etc.
- social research, including a greater understanding of the environmental impacts and perception of GMO use
- affirmative government procurement
- education in the public schools
- multi-disciplinary undergraduate and graduate education including biomass systems
- customer and consumer education and outreach

- targeted public education and outreach
- intra and inter-departmental education and outreach on bioproducts
- promotion of partnerships
- development of national vision, goals, milestones

4.3 The European Union

4.3.1 Overview

Europe has invested heavily in nonfood, industrial uses research over the last 10-15 years. As much as $10 billion euros has been spent to create a "science push". However, with the exception of markets for starch products, and some oils, there has been a noticeable lack of "market pull".[45]

Notwithstanding the limited commercial success of industrial crops (given the massive European R&D investments to date), there is widespread and growing interest on the part of industry. The UK-based Alternative Crops Technology Interactive Network claims a database of over 2100 contacts in 1200 organizations with more than 80% in industry. Industry participation ranges from "boutiques" to major multi-nationals including BP Amoco, British Sugar, Cargill, Dow, DuPont, ICI, Monsanto, Sainsbury's, Shell and Syngenta.

In general, Europe has concluded there needs to be more focus on an industry or market-driven approach to R&D investments. More specifically, there needs to be improvement in bioproduct price and performance compared to petroleum-based products. And there needs to be quality assurance at each stage in the supply chain.

While R&D is important, Europe has identified several key non-technical issues that need to be addressed in order for research and development to achieve its potential:
- biomass availability - is there enough to meet industry demands?
- regulations - do they support this emerging industry? Or are they fragmented and conflicting?
- harmonization of standards
- creation of public awareness through labelling systems
- evaluation of environmental impacts through Life Cycle Analysis (LCA) that inventory a broad range of environmental impacts throughout a product's life cycle.
- a better understanding of the cost-competitiveness of crop-derived materials.[46]

[45]Askew, M. Background Scenario and Executive Summary to European Overview. IENICA Report. August, 2000. Several explanations have been advanced: lack of awareness of opportunities; lack of incentive to change; lack of capital to re-tool; lack of political direction; lack of market organization and guaranteed supply of raw materials.

[46]Oliver, B.N. Realizing the economic potential of UK-grown crops industrial crops: A review by ACTIN. April, 2001.

4.3.2 Key Opportunities

Potential EU-15 market penetration:

Oils[47]

- The overall potential market for oils in the non-food sector is approximately 3 million tonnes per annum.
  - Biodiesel - about 20 plants producing 1 million tonnes[48]
  - Biolubricants - 370,000 tonnes/annum[49]
  - Bioprinting inks - 120,000 tonnes/annum[50]
  - Biosolvents - 500,000 tonnes/annum[51]
  - Linoleum - likely rise to 56 million m^2 by 2003[52]

BioPlastics[53]

- European consumption of bioplastics was estimated to be 10,000 tonnes in 2000
- Estimated to reach 60,000 tonnes/annum in 5 years with food packaging, compost bags, paper coatings, and dishes and cutlery accounting for over 10,000 tonnes each

Fibres[54]

- Clothing - no significant opportunity
- Cars and Aircraft - about 350,000 tonnes/annum
- Low value uses e.g. geotextiles

Specialty product markets[55]

- Essential oils world market is approximately 45,000 tonnes/annum
- Aromatic oils has a world market over 50,000 tonnes/annum
- Medicinal plant markets estimated at 70,000 tonnes/annum

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[47]Askew, M. IENICA at the SEEDA Industrial Crops Conference, July 18, 2002.

[48]As reported by the European Biodiesel Board (2001).

[49]However, Fuchs Lubricants UK Plc believes high impact legislation could drive the market to 1.5 million tonnes/annum. It is technically possible for the market to reach 4 million tonnes/annum. Presentation by Cliff Lea, Development of Lubricants from Harvestable Resources: Applications and Market Development. Presented at Renewable Resources: Becoming a Reality, December 11, 2001.

[50]Askew, M. Background Scenario and Executive Summary to European Overview. IENICA Report. August, 2000.

[51]Ibid.

[52]Ibid.

[53] Report on the 3rd Annual Biodegradable Plastics Conference. European Plastic News, January 2002.

[54]Askew, M. IENICA at the SEEDA Industrial Crops Conference, July 18, 2002.

[55]Askew, M. IENICA at the SEEDA Industrial Crops Conference, July 18, 2002.

4.3.3 Impact on GHG Emissions

A sub-group of the European Climate Change Program (Renewable Raw Materials) has conducted a study to estimate the impacts of using renewable raw materials in five key sectors: plastics, lubricants, solvents, surfactants, and fibres/composites. Compared to the total EU greenhouse gas emissions, converting to the use of renewable raw materials will have only limited reduction potential in the short term (i.e. by 2010). In total, the five sectors where thought to have the potential to reduce GHG emissions in Europe by 5,600,000 tonnes, or about 1.5% of the EU's Kyoto commitments. The time frame for reaching these targets was 10-20 years.[56]

However, in the longer term, biotechnology may contribute to larger savings. And it should be emphasized that use of renewable raw materials may have other positive impacts, such as reduced VOC emissions, reduced smog, reduced soil and water contamination, and social and economic benefits for rural and northern communities.

4.3.4 Key Organizations

As discussed above, there are at least 1200 organizations in Europe involved in developing industrial uses of agricultural feedstocks. A few organizations have emerged that provide a coordinating function, and serve as a useful starting point, or "portal" into European activities.

- Alternative Crops Technology Interactive Network (ACTIN)[57] - a UK industry-led initiative to promote the use of renewable raw materials derived from agricultural crops. Founded in 1996.
- Agriculture for Chemicals and Energy (AGRICE)[58] - was founded in 1994 by the French government ministries for Agriculture, Environment, Industry and Research, in collaboration with the Agence de l'Environment et de la Maitrise de l'Energy (ADEME). In 2000 the group's charter was renewed for another six years. It is a scientific group "committed to coordinating, funding, monitoring and evaluating research and development programmes that furthers these goals".
- Facchagentur Nachwachsende Rohstoffe e. V (FNR)[59] - the German Agency for Renewable Resources was formed in 1993 and acts as a central coordinating agency for R&D.
- Chemical-Technical Utilization of Vegetable Oils (CTVO-net)[60] - funded by DG Research of the European Commission under the FAIR Program. A 30 month project that ended September 2000.

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[56]Johnson, D. Renewable Raw Materials: A way to reduce greenhouse gas emissions from EU industry? DG Enterprise/E.1 July 2000.

[57]http://www.actin.co.uk/

[58]http://www.ademe.fr/partenaires/agrice/index_gb.htm

[59]http://www.fnr.de/en/indexen.htm

[60]http://www.fnr.de/ctvo/

- Interactive European Network for Industrial Crops and Their Applications (IENICA)[61] - a clearinghouse for information for EU-15, eastern European states, Israel, Switzerland, Canada and the US. Market focussed.
- BioMatNet[62] - disseminates the results of non-food RT&D projects funded by the European Union. Successor to Non-Food Agri-Industrial Research Information Dissemination Network (NF-2000).
- European Renewable Resources and Materials Association (ERRMA)[63] - "seeks to promote the market-led use of renewable raw materials, to advise in the setting up of appropriate regulatory frameworks, and to establish contacts with major players in the production, use, and regulation of renewable raw materials worldwide". Members include: BELBIOM (Belgium), ADEME/AGRICE (France), FNR (Germany), The Dutch Platform (The Netherlands), and ACTIN (UK).
- Anaerobic Digestion Network (AD-NETT)[64] - a network of professionals working in anaerobic digestion of agro-industrial wastes in Europe and Canada.
- Agriculture and Forestry Biomass Network (AFB-Net)[65] - a European bioenergy network established in 1995 to promote the use of biomass.
- The European Biogas Network (Waste for Energy)[66] - biogas from manure.
- The Non Technical Barriers Network (NTB)[67] - established in 1995 to remove non-technical barriers to the development of liquid biofuels (used in engines and boilers).
- European Bioenergy Networks (EUBIONET) - includes AFB-Net (solid fuels), Waste for Energy (Biogas), and NTB (liquid biofuels).
- A Global Overview of Renewable Energy Resources (AGORES)[68] - focuses on policy and market utilization.

[61] http://www.ienica.net/

[62] http://www.biomatnet.org/

[63] http://www.errma.com/

[64] http://www.ad-nett.org/index.html

[65] http://www.vtt.fi/virtual/afbnet/index.html

[66] http://websrv5.sdu.dk/bio/eubionet/

[67] http://www.ademe.fr/anglais/webaltener/defaultbiocarb.htm

[68] http://www.agores.org/default.htm

4.3.5 Broad R&D Themes[69]

It should be emphasized that many research organizations and companies have data, and are working on new technologies, that have not been made public. In many cases, this development work is confidential.[70]

In general, many of the same R&D themes described above for the US are mirrored in Europe. The list below supplements the US list, and reflects the greater interest in Europe in wheat starch, oil co-products, and the processing of hemp and other fibres for the auto industry.

R&D themes related to basic science include:

- better understand the role and relative importance of enzymes responsible for starch synthesis in order to increase the ratio of amylose to amylopectin
- expand knowledge of other carbohydrate crops, i.e. barley, oats and peas
- fundamental research on structure-function relationships and chemical modification of plants

Themes related to production include:

- improved agronomic studies need to be linked to sustainable production and end product specifications
- logistical studies designed to reduce the cost of crop collection and transportation
- creation of a potato which produces pure amylose starch
- develop new carbohydrate crops such as quinoa and sweet sorghum to improve biodiversity and rotational benefits (i.e. to maintain soil fertility and pest and disease control)
- development of "designer" oil profiles to meet industry needs
- establish criteria for crop quality, uniformity and volume of supply
- identity preservation system that safely segregates possibly several hundred different oilseed rape types; use of colour markers to help with segregation of edible from industrial crops
- need for additional knowledge about the interaction of crop management, weather, and harvesting processes on fibre quality and consistency
- identification of hemp cultivars with zero tetrahydrocannibinol delta-9 or THC (the psychoactive chemical found in cannabis), and visual or simple field tests for the identification of THC in order to reduce administrative overhead costs required for regulatory compliance

Themes related to processing include:

- improve processing technology to handle multiple feedstock inputs and product outputs

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[69]Broad R&D themes and gaps have been summarized in a number of European publications. For example: B.N. Oliver. Realizing the Economic Potential of UK-Grown Crops Industrial Crops: A Review By ACTIN. April, 2001. CTVO-net Final Conference Proceedings, FNR, June 20-21, 2000 Bonn Germany. Melvyn Askew. Background Scenario and Executive Summary to European Overview. IENICA Report. August, 2000. Preparing for the Future. Foresight Food Chain and Industry Crops Panel Report. December, 2000. IENICA has also published over a dozen national reports which can be found on their web site.

[70]Oliver B.N., Realizing the economic potential of UK-grown crops industrial crops: A review by ACTIN. April, 2001.

(applicable to both carbohydrate and oil crop processing)
- adopt a "whole crop" approach that captures additional value-added co-products beyond low value animal feed
- need to optimize fractionation of crop components, e.g. with respect to wheat straw, this would involve separating the components such polysaccharides and phenols
- extraction of seed oils using eco-friendly solvents
- chemical modification of vegetable oils into fatty acids, alcohols and esters
- improve collaboration between chemical industry and carbohydrate experts to develop new product and production technologies
- need for novel extraction and purification procedures to exploit secondary metabolites
- need to demonstrate processing and extraction processes that are environmentally benign and located near the source of raw materials supply
- need for government funding of demonstration projects to reassure industry that problems associated with scale up can be resolved
- development of small-scale pulping systems
- development of more modern, low energy intensive fibre processing systems, with "cleaner" fibre processing lines
- improved impact strength and recyclability of natural fibre composites for the auto industry
- improved decortication of natural fibres into higher value added textile markets
- adaptation of manufacturing equipment to accept new bio-based inputs e.g. bioplastics, paints and coatings, composites

Themes related to market utilization include:
- development of fiscal and regulatory measures/incentives e.g. processing subsidies and penalties for using polluting products
- establishment of environmentally friendly production practices that minimize pollen transfer and public anxiety so GMO varieties can be commercialized
- public education about biodegradability
- encouragement of organic fibre production and a labelling system
- international standardization of lifecycle assessment (LCA)
- comparative LCAs which focus industrial uses research in areas where crop-based industrial products have a comparative advantage

Cross cutting themes include:
- greater infrastructure integration among supply, manufacturing and distribution activities
- development of production standards and specifications and communication to producers and processors
- development of structured contract systems among producers, processors, and end-users.

4.4 Canada

4.4.1 Selected Facts and Figures[71]

As of April 2002, Industry Canada reported approximately 75 to 100 domestic companies either actively engage in bioproduct R&D or already manufacturing product. Employment was estimated at 1,500 to 2,000 people with sales in the $100 to 150 million range. Annual R&D was estimated to be in the $50 to 75 million range[72]. Understandably, the vast majority of these companies and investments are focussed on bio-based pharmaceuticals and other high value products where there is a greater probability of capturing acceptable returns on investment.

4.4.2 Key Organizations and Facilities

4.4.2.1 Federal Government

AGRICULTURE AND AGRI-FOOD CANADA (AAFC) - Through a series of actions, AAFC has provided leadership in the bioproducts field. The following excerpt from the Department's web site serves as an example.

> "In August 2000, Agriculture and Agri-Food Canada completed a background paper entitled *"Discussion Framework: Developing Bio-based Industries in Canada"*[73]. This discussion document summarizes recent European and US research trends in bioenergy, biofuels and biochemicals, and identifies promising market opportunities for biomass feedstocks from soybean, corn, wheat, canola and lignocellulosic materials. The paper concluded that bio-based programs should be carefully crafted to facilitate cluster-based regional development, coordinated science and technology investments, commercialization centres, pilot plants and research parks, and close networking among public, private and non-governmental organizations stakeholders from the core of these clusters."[74]

AAFC – Horticulture and Special Crops Division, Market and Industry Services Branch - This branch has taken a pro-active approach in identifying, proposing and coordinating an important three phase study focussed on the industrial uses of plant and animal products. The aim of the study is to identify opportunities for plant and animal products and co-products to be used in new industrial markets. The study is due for completion in the summer of 2003.

AAFC – Research Branch - Over the past decade, there has been significant attention paid to biotechnology in almost all of the 19 research stations scattered across the country. Although

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[71]For additional information and data on markets and investment see Section 6.

[72]http://www.innovationstrategy.gc.ca/cmb/innovation.nsf/SectoralE/Bioproducts

[73]http://www.agr.gc.ca/misb/spcrops/framework_e.phtml

[74]http://atn-riae.agr.ca/invest/business2c-e.htm

most of the focus to date has been on increased benefits to farmers, an increasing emphasis is now being placed on environmental issues such as GHG emitting practices and the development of bioproducts for industrial markets. Stations which have been more heavily involved in research which would impact directly on the bioproducts industry include:

Lethbridge Research Centre – Bioproducts and Bioprocesses Section. Research activities in the Bioproducts and Bioprocesses Section focus on the areas of Beef Cattle Genetics, Livestock Physiology, Livestock Pests, Nutrition and Management, and Feed Microbiology and Biotechnology.

Saskatoon Research Centre – The BioProducts and Processing Section of this Centre is focussed on adding value to crops grown in the Prairie region through "isolating, identifying and commercializing economically important crop components and the processes to extract them. They have the capabilities and facilities to conduct comprehensive investigations in natural product chemistry in support of value-added opportunities with plants".[75] This Centre had developed particular skills in assessing the potential for biodiesel blends with specific focus on canola oil as the starting material.

Swift Current Centre – "The Semiarid Prairie Agricultural Research Centre (SPARC) has been designated as a national centre for research on dryland farming systems. It has the mandate to conduct research and development in the following areas: land resource conservation, cereals, forages and field crops".[76] Within the Applied Science and Technology Transfer Section there resides considerable expertise in the analysis and commercial production of biofuels in general and bio-based ethanol in particular.

Food Research and Development Centre – Saint-Hyacinthe. The focus on bioingredients, coupled with a strong engineering capability and a well equipped pilot plant, allows this Centre to offer significant support to the industrial bioproducts industry.

INDUSTRY CANADA (IC) – In recent years, Industry Canada has played an increasing role in the development of the bioproducts industry. The Life Sciences Branch has helped spawn BioProducts Canada, and is actively working on the preparation of a vision statement and a technology roadmap for future development of the bioproducts industry similar to those prepared recently in the US.[77] Industry Canada has also played a key role in assisting Maritime Canada in developing a PEI/Atlantic Canada "Roadmap" for development of their bio-based economy.

NATURAL RESOURCES CANADA (NRCan) - "Natural Resources Canada is an economic, science-based department with a mandate to promote the sustainable development and responsible use of Canada's mineral, energy, and forestry resources; to develop an understanding of Canada's landmass; and to collect and disseminate knowledge on sustainable resource development. The Department conducts

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[75] http://res2.agr.ca/saskatoon/prog/bioproducts-produitsbio_e.htm

[76] http://res2.agr.ca/swiftcurrent/index_e.htm

[77] http://strategis.ic.gc.ca/SSG/bo01934e.html

research and technical surveys to assess Canada's resources, including the geological structure and legal boundaries. NRCan is also authorized to provide the national framework of reference for spatial positioning; prepare and publish maps; conduct scientific and economic research related to the energy, forestry, mining and metallurgical industries; and to establish and operate scientific laboratories for these purposes."[78] NRCan is also playing a lead role in assessing Canada's opportunities in biomass energy generally and biofuels in particular. This effort includes project funding through the Panel on Energy Research and Development (PERD) program and other climate change initiatives.

ENVIRONMENT CANADA (EC) – One of EC's primary contributions to the management of GHG emissions is through the implementation of the Environmental Assessment (EA) program. The EA program's objectives are to ensure Departmental compliance with the Canadian Environmental Assessment Act (CEAA) and the 1999 Cabinet Directive on the EA of policy, plan, and program proposals; define Environment Canada's position with respect to projects; co-ordinate and integrate our science and policy objectives into decision-making; and ensure national consistency in the application of CEAA.[79] EC also represents Canada on the Intergovernmental Panel on Climate Change.

FISHERIES AND OCEANS (DFO) - Fisheries Research provides the scientific basis for conservation and sustainable economic use of Canadian fishery resources. Scientists provide advice to the fishing industry on the status of fish stocks and on conservation objectives as well as provide information on marine ecosystem issues.[80] DFO operates the Aquaculture Collaborative Research and Development Program (ACRDP) which distributes $4.5 million annually in research funding grants.

NATIONAL RESEARCH COUNCIL CANADA (NRCC) – "The National Research Council Canada is the premiere biotechnology research agency of the Canadian federal government. The NRCC Biotechnology Program was established in 1983 under the guiding principles of the National Biotechnology Strategy."[81] The NRCC operates 19 separate research facilities distributed across the country. For biotechnology, the most notable research stations are the Biotechnology Research Institute (Montreal), the Plant Biotechnology Institute (Saskatoon), the Institute for Biological Sciences (Ottawa), and the Institute for Marine Biosciences (Halifax).

4.4.2.2 Provincial Governments

Each of Canada's ten provinces has an active interest in bioproducts but some are more advanced than others in their coordination and development. To date, much of this interest has centred around genetic engineering and/or high valued end products such as pharmaceuticals and nutraceuticals. Interest has also been building for the adoption, or extension of incentive programs to encourage

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[78] http://www.nrcan-rncan.gc.ca/sd-dd/role/role_e.html

[79] http://www.ec.gc.ca/ea-ee/home/home_e.asp

[80] http://www.dfo-mpo.gc.ca/science/fisheries-hallieutique/fisheries_e.htm

[81] http://www.nrc-cnrc.gc.ca/randd/areas/biotechnology_e.html

greater production of fuel ethanol. Most provinces have also established a provincial body charged with the task of developing and/or coordinating bioproduct development. Most of these provincial bodies are members of the Biotech Accord and can be found listed in Appendix B. The following illustrates some of the leadership being shown in provinces which appear to be the most advanced in this field:

THE ALBERTA AGRICULTURE RESEARCH INSTITUTE (AARI) - "is the primary agency in Alberta for funding, coordinating and promoting strategic agricultural research initiatives and technology transfer in the agriculture and food sector".[82] In September 2000, AARI released the document *Research and Development for Alberta's Agriculture and Food Sector: Part 1 Strategic Directions*. This document emphasizes the need for a highly attractive research and development system for sustained, world-class research excellence. This system will be complemented by an equally responsive and seamless research and innovation system, leading to increased technology commercialization and use in Alberta. The proposed strategy recommends the involvement of new, collaborative research approaches, including the formation of new Alberta networks of excellence and expertise in order to improve the focus and capacity of the current research and innovation system and to attract and retain leading edge people, projects and investors".[83] Based on this direction, AARI is continuing to focus on the following key strategic research priorities for the 2002/2003 fiscal year:

- Agri-food and Health - Functional Foods and Neutraceuticals
- Basic Research in Genomics, Proteomics and Bio-Informatics
- Environmental Sustainabilty
- Non-Food, Fibre, and Industrial Uses (including Molecular Farming)
- Primary Agriculture and Food Safety
- Value-Added Processing[84]

BIOPRODUCTS ALBERTA - On January 16th, 2003, BioAlberta was launched in Calgary, as Alberta vigorously pursues it's own bio-based agenda.

AG-WEST BIOTECH INC., "a non-profit venture funded by Saskatchewan Agriculture and Food, has delivered a wide variety of services to the Saskatchewan biotechnology industry, including mediation between business and government, project facilitation, project financing and visible leadership and direction for the biotechnology sector".[85]

BIOPRODUCTS SASKATCHEWAN INC. – "Incorporated May, 2001, this organization will lead and champion the development of a new industrial sector for Saskatchewan. Their mission is to promote and support the growth of Saskatchewan's food and non-food agriculture-based bio-products sector,

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[82]AARI's funding partners include: Alberta Crop Industry Development Fund, Alberta Livestock Industry Development Fund, Ag&Food Council, and AVAC Ltd. Research totalling approximately $12 million is currently in progress.

[83]http://www.aari.ab.ca

[84]http://www.acidf.ca/paari.htm

[85]http://www.agwest.sk.ca/index.shtml

through the development and commercialization of products and processes, and the development of associated technologies, by working with industry, government, and academic stakeholders."[86]

THE ONTARIO MINISTRY OF AGRICULTURE AND FOOD - is leading a multi-ministry study of ethanol and biodiesel markets in Ontario. The Biotechnology Secretariat of Ontario Ministry of Entreprise, Opportunity and Innovation has established a biotechnology strategy that is very supportive of biofuels and bioproduct development. The Ontario Ministry of Finance was the first in Canada to announce it will be removing the excise tax on biodiesel fuel. Ontario Agri-Food Technology (OAFT) has been very active in promoting industrial uses and has been instrumental in bringing government, industry, and researchers together in pursuit of a broader industrial strategy. The Ontario Adaptation Council has been active in funding research into bio-based products. Ridgetown Agricultural College (affiliated with the University of Guelph) has been actively involved in studying biochemicals from corn.

4.4.2.3 Municipal Governments

In recent years, municipal governments from across the country have begun to collaborate on their mutual interest and challenge of dealing with household and industrial wastes. Studies have shown that dump sites have become major contributors to GHG buildup. Some of the new approaches to dealing with this problem, particularly those relating to energy recovery, are discussed in Section 6.3.

The Federal Government is assisting municipalities in addressing waste issues in a number of ways. One of these is the Green Municipal Investment Fund (GMIF) which is *a $200 million permanent revolving fund that supports the implementation of innovative environmental projects that improve the energy and/or process efficiency in energy and energy services, water, solid waste management, sustainable transportation services and technologies, and integrated community projects.*[87] Through the GMIF, local governments can borrow funds for qualifying projects at the preferred interest rate of 1.5 per cent below the Government of Canada bond rate. Several Canadian cities including Montreal, Saskatoon and Calgary have used this and other federal support programs to assist in trials on buses fuelled with biodiesel.

4.4.2.4 Not for Profit Organizations

THE CANADIAN AGRI-FOOD RESEARCH COUNCIL (CARC) provides leadership in coordination and networking of research and technology transfer and is a catalyst for building consensus on research prioritization in Canada. In this regard, research and technology transfer is directed to assist the agriculture and food industry to be: *globally competitive, environmentally sustainable, and socially responsible.* See CARC's web site for additional information.[88]

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[86] http://www.bio-products.sk.ca

[87] http://www.fcm.ca/scep/support/support_pdfs/

[88] http://www.carc-crac.ca

BIOCAP CANADA FOUNDATION - "BIOCAP is a nationally incorporated, not-for-profit organization for building partnerships while funding and communicating research in science, technology, economics and social science. BIOCAP is exploring how Canada's biosphere – its plants, animals and other living organisms – can help reduce greenhouse gases at their source, remove them from the atmosphere, and, as much as possible, replace fossil fuels with alternative, environmentally friendly sources of energy and materials".[89]

BIOTECanada Inc. – This national organization's mission statement reads: "to provide a unified voice fostering an environment that responds to the needs of the biotechnology industry and research community, both nationally and internationally". Through a Biotech Accord, BIOTECanada serves to coordinate efforts of common concern to the member organizations and companies spread across Canada.[90]

BIOTECHNOLOGY ACCORD - "The idea of a common vision for the Canadian biotechnology community was discussed in a roundtable workshop and led to the creation of the Biotechnology Accord in November of 1996. The Accord fosters cooperation and provides a framework for common activities and service delivery for organizations representing Canada's biotechnology community".[91] A list of the members of this accord along with Email addresses can be found in Appendix B.

BIOPRODUCTS CANADA INC. - located in Ottawa, is; "an industry-led, not-for-profit coalition funded by the private and public sectors. They identify the market demand for products needed now and in the future. This will result in funding, research and commercialization of bio-based products sourced from the agriculture, forestry and aquaculture sectors. Their initiatives focus on product outcomes and benefits such as: High-value consumer products; Bioenergy and biofuels; Sustainable production of biomass; Biochemical feedstocks; Greenhouse gas management and carbon credits.[92]

THE AGRICULTURAL ADAPTATION COUNCIL (AAC) - is a coalition of 47 agricultural, agri-food and rural organizations, incorporated in 1996 to administer Ontario's share of the Canadian Adaptation and Rural Development (CARD) Fund. See the AAC website for additional information.[93]

CANADIAN RENEWABLE FUELS ASSOCIATION (CRFA) - Officially incorporated in 1994, CRFA is a non-profit organization mandated to promote renewable bio-fuels (ethanol, biodiesel) for automotive transportation through consumer awareness and government liaison activities. The membership includes representatives from fuel marketing, fuel producing/processing, energy, agriculture, agri-business, forestry, engineering and environmental organizations, researchers and individuals

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[89] http://www.biocap.ca

[90] http://www.biotech.ca

[91] http://www.biotech.ca

[92] http://www.bio-productscanada.org/about.html

[93] http://www.adaptcouncil.org/

who all share a common interest in developing alternative fuels from renewable resources.[94]

The POS Pilot Plant, Inc. - is "a confidential contract research organization for grams-to-tons process and product development, which specializes in the extraction, fractionation, purification and modification of biologically derived materials." This well equipped facility with capable staff has provided world-class R&D services to both food and non-food customers over the past twenty years. Funding for this facility comes from a combination of fee-for-service revenues and provincial and federal support.[95]

Saskatchewan Agrivision Corporation, Inc. (SAC Inc.) - This organization's State of the Industry Fact Sheet describes SAC Inc. as: "a coalition of farm, rural and business leaders working as a catalyst to proactively develop a vision for increased agri-value processing leading to increased farm gate income and rural revitalization." This publication also states: "By 2010, Saskatchewan's output of agricultural bio-based products will make up at least 25% of the farm gate revenues and 25% of the processing sector's value added."[96]

4.4.2.4 Canadian Universities and Colleges[97]

Most of the leading colleges and universities in Canada with agricultural or engineering programs have the potential to contribute to the research effort underpinning a bioproducts industry in Canada. Several universities, including: Moncton, Sherbrooke, Guelph, Manitoba, Saskatchewan, Alberta and UBC have extensive experience in a wide range of agricultural disciplines. Others including McGill, Ottawa, Queen's, Toronto, McMaster, Waterloo, Saskatchewan and Alberta have significant experience in engineering sciences of importance to the development of biopolymers which might compete with petrochemical based products. Still others have strong medical, environmental, fisheries or forestry programs which could provide valuable expertise. Even universities without strengths in these applied disciplines may have the potential to contribute to this industry through expertise in basic and applied microbiology, physics or chemistry, or in any of a number of business disciplines. Specific examples of contributions which universities can make will be seen throughout Section 6 of this report where the selected bioproduct opportunities are discussed.

Universities which have become involved in bioproducts covered in this report include: McGill (biopolymers), Sherbrooke (biofuels, etc.), Toronto (misc.), McMaster (biopolymers), Guelph (misc), Waterloo (biopolymers), Saskatchewan (biofuels, biocomposites) and Alberta (bioplastics, biofuels).

Another new initiative in its formative stages is the Green Chemistry Network supported by BIOCAP and spearheaded by Professor Bill Chan of McGill University. A submission was

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[94] http://www.greenfuels.org/assn.html

[95] http://www.pos.ca/

[96] http://www.agrivision.sk.ca

[97] Please note, this is not intended to be a comprehensive listing of Canadian academic bioproducts capabilities, but merely an introduction to some of the leading institutions.

presented to the Federal Government in February 2003 in support of the group's effort to secure funding under the "Networks of Centre of Excellence" program. The submission will be for $24 million over a 4½ year period and will involve an estimated 40 university researchers. An additional $5 million is anticipated to be raised from the private sector through contract research.[98]

4.4.2.5 Trade Associations

As mentioned in Section 4.2.3, in the US, the national and state soybean and corn producers' associations play a very active role in both supporting and directing research focussed on expanding markets for their respective crops. In recent years an expanding amount of these budgets have been directed toward the development of industrial products containing components derived from their respective crop. This type of support is present in Canada, but on a considerably smaller scale. Some of the associations involved to date in supporting non-food/non-feed research and development with a portion of their research budget include:

- Canadian Soybean Export Association
- Ontario Soybean Growers
- Canola Council of Canada
- Canadian Canola Growers Association
- Manitoba Canola Growers Association
- Saskatchewan Canola Development Commission
- Alberta Canola Producers Commission
- Flax Council of Canada
- Saskatchewan Flax Development Commission
- Ontario Corn Producers' Association

Other producer groups such as: The Western Canadian Wheat Growers Association, The Saskatchewan Pulse Growers, and The Western Barley Growers Association have supported research, but at a modest level. In the case of the wheat and barley industries, significant research occurs through the research budget of the Canadian Wheat Board, and The Western Grain Research Foundation.

Several provinces/regions have also formed an industrial advocacy group which support biotechnology research. Examples of these organizations include: BioAlberta, BioAtlantech, BioQuebec, and BioOntario. Similarly, several industrial manufacturing sectors have established associations, but for the most part, these too serve more as industry lobby groups with little of no budget for research.

[98]Bill Chan (McGill University) – Personal communication.

Section 5: The Canadian Bioproducts Environment

5.1 Introduction

The Canadian bioproducts environment is becoming increasingly active to say the least. Virtually all government departments at all levels, most educational institutions, and most companies working with organic materials have at least a passing interest and in most cases serious interest in this emerging field. The federal government in particular has given high priority to bioproducts. The steering committee struck to investigate and provide leadership is comprised of representatives from eleven different departments and agencies, each seeing their role as being important, if not pivotal, to the future development of the industry.

From the private sector's perspective, interest is also high, but somewhat guarded in view of what appears to be a somewhat clouded regulatory and international trade environment. Much of the interest as well as the apprehension revolves around research. The very significant advances in technology have not only opened up new business opportunities, but have at the same time illuminated the important environmental issues which can be questioned with virtually all industrial products and human activity.

5.2 Multi-faceted Nature of the Industry

It could be argued that the development of a bioproducts industry involves more scientific disciplines than any other field of study. Scientists involved in each of the basic sciences such as physics, chemistry, biology and microbiology, are not only involved in a passive, or supportive way, but through active participation in the development of this intriguing yet complex industry. Similarly, researchers and development specialists in many applied fields including engineering, agriculture, forestry, fisheries, food science, material science, medical sciences and environmental science all have significant contributions to make to the development of products and processes which are not only environmentally sustainable, but also acceptable to investors.

Overlying the multi-faceted nature of the industry itself is the need for coordination and collaboration at the political level if individual and collective achievement is to occur. Environmental problems are generally not confined to a single jurisdiction, but are shared among all regions and all nations. Similarly, solutions to these problems almost always lie in large measure in joint effort among participants working in a spirit of cooperation.

5.3 Enabling Technologies

Computer Innovations - There are numerous examples of using the power of modern computers to enable activities to take place much faster, with far greater accuracy and with much less effort than before. Rapid developments in both computer hardware and software are changing the limits of scientific analysis daily. An example of the use of computers is through the analysis of the greenhouse gas effects of various methods to produce biofuels. Changes in technology allow for "what if' scenarios to be run much more quickly than even months ago.

Biotechnology - This truly exciting set of technologies has opened up fields such as genomics and proteomics and provides countless opportunities both in terms of new product and process development and understanding and dealing with environmental issues. The controversial area has been the use of biotechnology to produce transgenic crops. However, the use of rDNA techniques can play an important role in changing microorganisms to do such tasks as:

- produce enzymes to hydrolyze cellulose and hemicellulose to simple sugars, and
- genetically engineer microorganisms to ferment five carbon sugars as well as six carbon sugars such as glucose.

An example of this is the development by Nancy Ho and her colleagues at Purdue University of genetically engineered *Saccharomyces* yeast, modified so that it could convert xylose to ethanol, as well as convert glucose to ethanol (Ho et al.,1999).[99] The article outlines how modern techniques in biotechnology enabled the scientists to identify genes coding for different metabolic pathways and then modify the genetic systems to enable the yeast to ferment xylose to ethanol. Furthermore, new yeasts were developed which contained multiple copies of certain xylose metabolizing genes. This improved the stability of the transgenic yeasts, enabling continuous fermentations to be considered.

This type of GM yeast would be contained in a factory, rather than grown in a field. Several commentators on biotechnology believe this type of transgenic product would be expected to be less controversial than transgenic crops.

It should also be noted that many activities in biotechnology do not involve transgenic organisms. Ingeldew's studies of yeast metabolism and very high gravity fermentation to produce ethanol from starch are examples of excellent work in biotechnology which do not involve transgenic materials.[100] This topic is discussed in greater detail in section 6.2.2. of this report.

Advances in gasification technology and the development of improved metallic catalysts - The pages of the first five Biomass Conferences of the Americas give many examples of the great improvements in gasification technology that have been developed. This has been coupled with improved methods for gas clean-up and methods for selectively producing products such as ethanol from synthesis gas. Donald Klass believes that gasification and metallic synthesis routes to ethanol may be inherently less expensive than fermentation routes.[101] Thus gasification of biomass, followed by metallic catalyst conversion to ethanol, may be able to produce ethanol less expensively than fermentation routes.

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[99]Ho, N.W.Y., Chen, Z., Brainard, A.P. and Sedlak, M. 1999. Successful design and development of genetically engineered *Saccharomyces* yeast for effective cofermentation of glucose and xylose from cellulosic biomass to ethanol. Advances in Biochem. Eng./Biotech. 65: 163-192.

[100]Ingeldew, M. University of Saskatchewan, 2003 - Personal communication.

[101]Klass, D.L. 1998. Biomass for Renewable Energy, Fuels, and Chemicals, Academic Press, Toronto, Canada.

Pretreatment and fractionation of biomass into different components - Advances in these areas may make it possible to separate biomass into components that enable biorefineries to become more practical. For example, the FIRST process (i.e. feedstock impregnation rapid steam treatment) may be a technology to separate lignocellulosic biomass into different components more successfully than previous methods. This process is discussed in depth in section 6.2.4.3.

Methods for separating sugars into pure components, developed by national research laboratories in the US, may enable specific sugars to become platform chemicals for development of various bioproducts. Other evolving technologies such as membrane separation now allow for the relatively efficient recovery of pure components from mixture of chemical substances.

5.4 The Biorefinery Concept

The biorefinery concept was first proposed by Professor Lars Munck of the University of Copenhagen. The process in its simplest terms involves the feeding of bio-based materials into one end of a process and drawing off a range of intermediate or end products at the other end of the production line. Although this method of production is the backbone of the petrochemical industry, the application of the concept is not quite that simple for plant and animal materials. The complex molecular structure, coupled with the heterogeneity found in most materials, necessitates a step by step approach designed specifically for each of the various starting materials. In addition, the highest economic returns from the processing of bio-based materials often comes from the recovery of components in their native state using physical or chemical separation methods which do not disrupt the chemical structure of the target material(s).

Indeed, the biorefinery concept, if viewed as the processing of a biomaterial with the aim of recovery and sale of all of the products, is not a new concept. For more than a century the more progressive food companies have following this approach. The hog processing plants of the 1950's learned to use "everything but the squeal". What is new, and clearly worth pursuing, is the recovery of fractions from the raw material which can subsequently be purified and converted biologically, chemically and/or physically into end products with significantly higher value than the raw material.

In their ongoing effort to stimulate use of this biorefinery approach, the US Department of Energy (DOE) Biomass Program has awarded about $75 million to six major cost-share agreements for integrated biomass research and development. Broin and Associates, Cargill, Cargill Dow LLC, Dupont, High Plains Corporation, and the National Corn Growers Association head the multiple-organization teams for the six projects. DOE's National Renewable Energy Laboratory (NREL) and Pacific Northwest National Laboratory (PNNL) will participate in five of the six projects.[102]

[102] www.ott.doe.gov/rbep/

5.5 Human Resources Infrastructure

Canada's human resources infrastructure pertaining to the bioproducts field could be described as having great potential, but not a particularly strong past, or current, record. Strengths in agricultural production, food processing, fisheries technologies and wood processing provide an important base for an industrial bioproducts industry, but are not in themselves sufficient to resolve many of the problems facing the fledgling bioproducts industry. Similarly, engineering capabilities, particularly those relating to the chemical and petrochemical processing industries, are valuable, but generally fall short in dealing with plant and animal materials. Canada's very significant focus and growing expertise in biotechnology relating to plant and animal genetics is similarly a valuable asset, and may play a major role in the development of some valuable new raw materials, but this still represents only one of many required components.

Where there appears to be significant opportunity to build our capabilities is in the several fields where overlapping technologies occur. To be successful in this ever-changing physical and business environment, Canadian companies will need the synergistic input which can only come from collaborative effort when people share their collective expertise in solving the many bioproduct puzzles facing the product development team. Universities and colleges can play a key role in assuring the ongoing supply of scientists and engineers with strong basic understanding of the chemistry, biology and physics upon which the applied technologies are founded. The vital interdisciplinary skills often require years of experience to develop. In the case of bioproducts, the development of these new interdisciplinary skills will require sustained effort and investment on the part of both the public and the private sector. These human resources are not ones which can be easily put in place overnight.

Also of critical importance will be the degree to which Canadian scientists and developers can link with their counterparts in the US and the EU where considerably more funding is available and greater expertise on the development of bioproducts resides. The global nature of many of the environmental aspects of this industry help to pave the way for this collaboration and to overcome some of the intellectual properties issues which often reduce or eliminate benefits which can accrue from collaboration.

Cautious but significant expenditures in bench and pilot scale equipment designed specifically for carrying out the new processing technologies will also be required to selectively upgrade some of Canada's existing facilities. However, those involved in research funding and equipment purchase decisions must not overlook the option of leasing or renting specialized equipment as an option. In many cases, the operational expertise residing in the staff at the vendor's pilot/demonstration facility, coupled with the savings on capital expenditures far outweighs the rental costs. The bioproducts field is fast moving and therefore rife for the potential of equipment becoming technologically obsolete within months, or a few years.

5.6 Ethical Issues

In addition to assessing the important issues relating to supply of raw materials for purposes of sustaining a viable bio-based industrial economy (see the following section), ethical issues regarding the use of food materials for non-food uses must not be overlooked. Whereas this issue has received considerable negative comment in the past, current trends suggest that world production of food products will continue to outstrip consumption for the foreseeable future. In fact, responsible use of bioresources will not only lead to a lessening of man's "footprint" on the environment, but eventually to an environmentally, socially and economically sustainable use of our valuable renewable resources. There is a strong belief that the concurrent processing of biomaterials for both food and non-food markets will lead to increased opportunities and rewards for the entire supply chain. Ultimately, if/when demand begins to exceed supply, the consumer will make the appropriate choices with their buying decisions. The quality of management with regard to environmental issues and the range of short term verses long term costs and benefits will also rest with the public through their choices of elected representatives.

Section 6: Assessment of Key Bioproducts Opportunities

6.1 Biofuels – Material Balance Overview

In assessing the opportunities of any venture, it is essential to consider the long term supply and sustainability of the raw material(s) involved. It is indeed true that many exciting new industrial products can be produced from plant and animal sources, but with what consequences? What impact (other than higher raw material prices) would a thriving bioproducts industry have on the food and feed industries? What effect would it have on soil, water and air quality if biomaterials are moved from the existing life cycle environment to another environment? These questions are important ones to pose. Equally important, they are questions for which industry must find correct answers. As the leading candidate for use of large quantities of biomass, the biofuels sector has been wrestling with these questions in recent years. The following attempts to bring some perspective to this issue.

Table 1 shows the total amounts of grains produced in 2000 in Canada. These amounts are compared with the estimated amounts of black liquor produced by pulp mills and the amounts of fuel wood consumed by industry and by residences (the amounts of these forest resources were derived from data provided by Jaques et al. (1997)[103]).These resources are compared with the amounts of gasoline and diesel fuel consumed in Canada in the year 2000.

In the period from 1990 to 2000:

- gasoline consumption rose 13%, from 33.9 billion L to 38.3 billion L,
- diesel fuel consumption rose 39%, from 16.7 billion L to 23.2 billion L.

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[103]Jaques, A., Nietzert, F. and Boileau, P. 1997. Trends in Canada's Greenhouse Gas Emissions 1990-1995. Environment Canada, Ottawa, ON, Catalogue No. En49-5/5-8E. See also Jaques, A.P. 1992. Canada's Greenhouse Gas Emissions: Estimates for 1990. Environment Canada, Ottawa, ON. Report EPS 5/AP/4.

Table 1 is somewhat misleading since the fraction of some materials which can be converted into biofuels varies. For example, 1000 kg of wheat grain would produce about 300 kg of fuel ethanol, while 1000 kg of canola seed would yield about 420 kg of biodiesel from the oil fraction and 1000 kg of soybeans would yield about 200 kg of biodiesel from the oil fraction.

It is evident from Table 1 that considerable improvements in fuel efficiency of motor vehicles would be needed if liquid fuels produced from some portion of agricultural and forestry bioresources were to make a major contribution to the total liquid fuels requirements of the Canadian economy in the future.

Table 1. Amounts of selected bioresources in Canada in 2000.

Resource	Amounts (in millions of tonnes)
Wheat	26.8
Barley	13.5
Corn grain	6.8
Canola	7.1
Soybeans	2.7
Gasoline, final demand	28.8
Diesel fuel, final demand	19.5
Black liquor solids from pulp production	24.4
Industrial fuel wood consumption	10.5
Residential fuel wood consumption	14.1

Gasoline, diesel fuel, black liquor solids and industrial fuel wood consumption for 2000 were obtained from Statistics Canada Catalogue 57-003, Quarterly Report of Energy Supply and Demand. Residential fuel wood consumption data were for 1995 and were obtained from Environment Canada Report En49-5/55-8E, Trends in Canada's Greenhouse Gas Emissions (1990-1995). Crop production data for 2000 were obtained from Statistics Canada Catalogue 22-002, Field Crop Reporting Series, Production of Principal Crops.

Some further resources are potentially available from agriculture in the form of crop residues surplus to soil protection and animal feed and bedding requirements. In eastern Canada, it has been estimated by Helwig et al. (2002)[104] that one million t of cereal straws and three million of corn stover are available for possible industrial uses, if adequate prices are paid.

[104]Helwig, T., Jannasch, R., Samson, R., DeMaio, A. and Caumartin, D. 2002. Agricultural Biomass Inventories and Conversion Systems for Energy Production in Eastern Canada. Report to Natural Resources Canada, Ottawa, Ontario. Available from REAP-Canada, Ste. Anne de Bellevue, QC H9X 3V9.

In Western Canada, Stumborg (2002)[105] has estimated that the amounts of cereal straws, cereal chaff and flax straw available for industrial applications is about two million tonnes. This is the amount available surplus to soil protection and animal feed requirements. It assumes that straw is removed from a particular field only one year in four and only one farmer in four sells straw for ethanol production. Wheat production has gone down in western Canada in the last five years suggesting that the estimate of two million tonnes available may be too high.

It is also possible that industrial hay crops might be produced in the future. Switchgrass is being examined in the US for biofuels applications. Woody biomass, grown as part of agroforestry activities, might also be an agricultural bioresource in the future.

Methane is another potential biofuel. Helwig et al. (2002)[106] calculated that the gross energy potential from the production of biogas from livestock manure in eastern Canada is 16 PJ (16×10^{15} joules). However, the economics of this technology looked discouraging even for large farms or feedlots. Landfills across Canada emit large amounts of methane due to anaerobic decomposition of biomaterials such as waste paper and food and garden wastes. Capture of this landfill methane looks attractive and is being developed further. The methane would be used as a fuel in nearby power stations. Substantial amounts of greenhouse gas emissions could be saved.

Ruminant livestock emit large amounts of methane (eructation) during the course of digestion. This is a significant source of greenhouse gas emissions in the Canadian economy. Recently it has been discovered that addition of vegetable oils to the diet of ruminant animals reduces methane eructation and also increases the amounts of conjugated linoleic acid in the meat and milk (Mir et al., 2000).[107] This would constitute another route to reducing methane emissions.

These are the resources potentially available for various bioproduct applications. The following sections of this report examine how the agricultural bioresources might be used to provide biofuels and bioproducts for the Canadian economy. This section of the report also estimates the reduction in greenhouse gas emissions that might be achieved by wide-spread utilization of these bioproducts in the Canadian economy.

6.1.1 Crop Breeding Issues

Dr. Martin Reaney, Agriculture and Agri-Food Research Centre in Saskatoon, has suggested that crop breeding could start considering bioproduct applications as part of the selection process

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[105] Stumborg, M. 2002. Potential for Biofuel Development. Proceedings AgFibre Conference, Winnipeg, MB. Available from the author at SPARC, Agriculture and Agri-Food Canada Research Centre, Swift Current, SK. S9H 3X2

[106] Helwig, T., Jannasch, R., Samson, R., DeMaio, A. and Caumartin, D. 2002. Agricultural Biomass Inventories and Conversion Systems for Energy Production in Eastern Canada. Report to Natural Resources Canada, Ottawa, Ontario. Available from REAP-Canada, Ste. Anne de Bellevue, QC H9X 3V9.

[107] Mir, Z., Rushfeldt, M.L., Mir, P.S., Paterson, L.J. and Weselake, R.J. 2000. Effect of dietary supplementation with either conjugated linoleic acid (CLA) or linoleic acid rich oil on the CLA content of lamb tissue. Small Anim. Res. 36: 25-31.

(personal communication to E. Coxworth, February, 2003). His comments are paraphrased as follows:

Crop breeders have never attempted to breed for life cycle assessment goals. Could breeders alter the ratio of N, P or S, our major inputs into crop production? The answer is yes. The tools are all in place to identify crops that extract less N, P and S while maintaining productivity. Recommendations on these varieties could commence by the fall of 2003.

Example 1:
High oil content canola varieties (low N, P and S) would need to be favoured by the marketplace, the farmer, and/or government decree to maximize the benefit. Breeders would easily select to improve the crop according to the new goals.

Farmers would lower inputs. Processors would have a higher value grain. Emissions would be reduced. Total production of seed would drop slightly while the total value of the industry would increase. This would happen for all crops so modified.

Example 2:
Pesticide resistant crops (e.g., canola) have persistent management benefits. These benefits improve carbon sequestration and reduce fuel inputs. These crops were not present in 1990 and were not used in previous life cycle analyses conducted in Australia and Europe.

Example 3:
High yielding hybrid canola varieties were introduced over the last eight years. They have the potential impact of significantly changing the ratio of input per acre to output. The life cycle analysis is likely to be positive.

6.1.2 Biofuel Additives and Fuel Cost Reduction

Reaney (M. Reaney, personal communication to E. Coxworth, February, 2003) has emphasized that the bioproduct industry should be conducting collaborative research with the petroleum industry so that synergies between bioprocessing and petroleum industry processing might be realized. Reaney suggested four examples:

Example 1:
Small amounts of biodiesel and vegetable oils act as effective lubricity additives to diesel fuel. From years of testing, it was clear to Reaney that there was no material offering comparable functionality being used in Canadian diesel fuels.

Example 2:
It is probable that cetane enhancers may be developed from bioresources that when added to diesel fuel may improve fuel combustion substantially. It is also possible that enhancing cetane by the addition of biosourced materials could substantially reduce diesel fuel production losses.

Example 3:
Technology for adding alcohols and water to diesel fuel is being developed which would significantly reduce NOx emissions. The technology requires the addition of substantial amounts of detergent to the fuel. Research to produce biosource detergents could be important in maximizing the environmental benefits of this technology.

Example 4:
Ethanol improves fuel octane levels. A petroleum refiner might utilize ethanol in this application to decrease refining costs (and input energy) in raising fuel octane of the final retail gasoline. (Editors' note: One refiner in Ontario is already doing this).

6.2 Ethanol

6.2.1 Sector Overview

According to the Canadian Renewable Fuels Association (web site: www.greenfuels.org), the ethanol industry in Canada produced 238 million litres of ethanol. Some 26 million litres from that total probably needs to be removed since API Grain Processors in Red Deer, Alberta, recently went into receivership.[108] Thus, the present production of ethanol in Canada is 212 million litres per year. Most production in eastern Canada is based on corn grain, with the exception of Tembec in Quebec, where production is based on fermentation of pulping liquors. A number of new plants or plant expansions are being planned or are underway. In eastern Canada, if all the new facilities are eventually built, some 441 million litres of new ethanol would be produced, most based on fermentation of corn grain. In Saskatchewan, the government has announced plans for three ethanol plants of 80 million litres capacity each (Briere, 2002).[109] If all three plants are built, Saskatchewan ethanol production would be 240 million litres per year. Total Canadian ethanol production would then be 893 million litres per year.

All three plants in Saskatchewan are intended to be based on wheat, probably Canadian Prairie Spring (CPS) type. Given fluctuations in grain supply and price, some critics have suggested that some, or all, plants might use corn grain imported from the US, at least during certain years when the price of local wheat was too high. The high price of wheat in 2002, driven in part by drought and other adverse weather in western Canada and elsewhere, was cited as part of the reason for the failure of API Grain Processors. Prices in 2002 for wheat were $225-$230 per tonne. In 2001, average price for the wheat used was $151. Farmers would have made more money from wheat production, however, in 2002.

The Saskatchewan ethanol production plans hope for an expansion in the livestock industry in association with the development of the ethanol industry. The increase in livestock would consume the dried distillers grains and solubles (DDGS) produced as a co-product by the ethanol plants.

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[108]Cowley, P. 2002. Losses force Alta. Ethanol plant into receivership. Western Producer, December 12, p.75.

[109]Briere, K. 2002. Ethanol. Western Producer, November 21, pp. 76-78.

However, expansion of the cattle industry could lead to an increase in greenhouse gas emissions, due to an increase in methane and nitrous oxide emissions from the cattle and their manure. This will be discussed later under gaps in research.

6.2.2 Key Opportunities

Since ethanol production from lignocellulose resources is still an experimental process, the main opportunity for ethanol production in the near future lies with ethanol produced from grain. Two innovations would aid the success of this approach:

- Very high gravity fermentation can yield ethanol concentrations in the fermentation broth of 18% or more (Ingledew, 2002).[110] This reduces the energy costs of the process and increases the productivity of the plant (more ethanol per day from the same equipment).
- Preprocessing barley, rye and triticale to remove a fibre fraction improved the economics and productivity of these cereals for ethanol production (Sosulski et al., 1997).[111] Removing the fibre fraction increased the starch content of the remaining fibre-reduced fraction used for fermentation. Ethanol productivity (litres of ethanol per day per unit volume of fermentation reactor) would be increased compared to using whole cereals. The distillers solids and solubles from the fibre-reduced cereal fraction fermented would then be combined with the fibre fraction as a feed for livestock. This biorefining approach also improved the ability to use these cheaper grains for ethanol production in periods when wheat prices were too high for cost-effective use of wheat as a raw material for ethanol production.

In the longer term, ethanol production from lignocellulosic raw materials will be needed if this biofuel is to make a major contribution to total transportation fuel supplies. A greenhouse gas analysis of the Iogen process to make ethanol from cereal straw determined that ethanol produced from lignocellulosic raw materials would reduce greenhouse gas emissions, compared to gasoline, more than ethanol produced from grains. The lignin byproduct from the ethanol production would be used as fuel for the ethanol process. Since this lignin is a renewable fuel, the total fossil fuel-derived carbon dioxide emissions from the process would be very low. Stumborg (2002)[112] determined that, for every million litres of ethanol produced:

- use of cereal residues as the feedstock would reduce GHG emissions (compared to gasoline) by 2.25 million t of CO_2 equivalents,
- use of cereal grain as the feedstock would reduce GHG emissions by 1.47 million t of CO_2 equivalents.

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[110]Ingledew, W.M. 2002. Very high gravity ethanol fermentation: yield and productivity are the keys to success. ABIC 2002 Conference, Saskatoon, Sask. Available from AgWest Biotech, Saskatoon, SK S7N 3R2, E-mail agwest@agwest.sk.ca.

[111]Sosulski, K., Wang, S., Ingledew, W.M., Sosulski, F.W. and Tang, J. 1997. Preprocessed barley, rye, and triticale as a feedstock for an integrated fuel ethanol-feedlot plant. Appl. Biochem. Biotech. 63-65: 59-70.

[112]Stumborg, M. 2002. Potential for Biofuel Development. Proceedings of the AgFibre Conference, Winnipeg, MB. Available from the author at SPARC, Agriculture and Agri-Food Canada Research Centre, Swift Current, SK S9H 3X2.

A number of different routes to ethanol from lignocellulose are under active investigation. In Canada, Iogen has a pilot plant being used for scale-up studies aimed at commercial production. Iogen has stated that it expects the first commercial plant based on lignocellulosic raw materials to begin construction in 2004 (Wilson, 2002).[113]

Another new route to employing crop residues to produce energy may compete for the straw resource. A Manitoba company, Vidir Machines, has built and tested a combined gasification/combustion system to provide heat for poultry and hog barns, greenhouses and industrial buildings (Siemens, 2002).[114] The process involves technology developed by Natural Resources Canada. The automated gasification/combustion process employs big round bales of straw which are shredded before entering the gasification unit. The first poultry barn operator to test the technology expects to save more than 50% of his present heating costs, and recover the investment cost in less than five years. This technology will be discussed in more detail in section 6.4: Methane and other gasification routes to bioenergy.

6.2.3 Potential Impact on GHG Emissions

Stumborg (2002)[115] has recently estimated the potential from grains and crop residues in Canada. His calculations assumed that ethanol production from crop residues was developed technically and economically to be competitive with (or better than) ethanol production from grains. Stumborg's data is presented in Table 2.

Table 2. Ethanol Potential and GHG Savings Using Canadian Cereal Crops

Raw material	EtOH production potential (millions of litres)	GHG savings per year (million tons $C0_2$)
Cereal grains	1182	1.74
Grain corn	536	0.79
Cereal residues	600	1.35
Corn stover	175	0.36
Totals	2793	4.24

To put this in perspective, the potential GHG emissions from the Canadian economy in 2010, unless large improvements in energy efficiency were introduced, would be 763 million tonnes per year of carbon dioxide equivalents, about 200 million tonnes above the Kyoto target of 565 million tonnes

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[113]Wilson, B. 2002. Ethanol straw plants still on the drawing board. Western Producer, September 5, p. 76.

[114]Siemens, H. 2002. Straw heat saves big bucks for farmer. Manitoba Co-operator, December 5, p.33.

[115]Stumborg, M. 2002. Potential for Biofuel Development. Proceedings of the AgFibre Conference, Winnipeg, MB. Available from the author at SPARC, Agriculture and Agri-Food Canada, Swift Current. SK. S9H 3X2

of carbon dioxide equivalents (Stumborg, 2002).[116]

Stumborg's calculations of GHG reductions were based on two very detailed analyses of the energy costs and greenhouse gas emission reduction effects of production of ethanol from corn grain in southern Ontario (Levelton et al., 1999)[117] and ethanol produced from lignocellulosic feedstocks (Levelton and $(S\&T)^2$, 2000).[118]

Energy cost of ethanol production from corn grain, including the energy credit for saving energy in the gasoline production refinery when ethanol is used to provide octane value.
Levelton et al. (1999)[119] noted that: "ethanol not only replaces gasoline volume but it also adds octane to the gasoline pool. To take advantage of this octane a refinery has several options:

- Remove and sell other high octane material such as the aromatics benzene, toluene and xylene,
- Reduce the operating severity of the reformer, which is usually the refinery's lowest cost source of incremental octane,
- Increase gasoline production,
- Some combination of the above.

All of these options should result in lower energy consumption and essentially provide an energy credit to the ethanol."

Levelton et al. (1999)[120] modelled lower reformer severity. They calculated an energy credit of 0.164 MJ/L for a 10% ethanol blend, or a credit of 1.64 MJ/L of ethanol used.

This credit was taken into account when calculating the total energy costs and benefits when ethanol was produced from corn grain in Ontario and used in a 10% blend in gasoline. All costs of corn production and processing into ethanol and dried distillers grains and solubles were taken into account, including the ethanol credit for saving energy in the refinery. Levelton et al., (1999)[121] calculated that the ratio of energy output to input ranged from 1.50:1 to 1.83:1 depending on the end use of the ethanol.

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[116] Ibid, idem.

[117] Levelton Engineering Ltd., $(S\&T)^2$ and J.E. Associates. 1999. Assessment of Net Emissions of Greenhouse Gases from Ethanol-Gasoline Blends in Southern Ontario. Report to Policy Branch, Agriculture and Agri-Food Canada, Ottawa, ON K1A 0C5.

[118] Levelton Engineering Ltd. and $(S\&T)^2$. 2000. Assessment of the Net Emissions of Greenhouse Gases from Ethanol-Blended Gasolines in Canada: Lignocellulosic Feedstocks. Report to Policy Branch, Agriculture and Agri-Food Canada, Ottawa, ON K1A 0C5. Report R-2000-2.

[119] Ibid, idem.

[120] Ibid, idem.

[121] Ibid, idem.

The only energy input not included in Levelton et al. (1999)[122] analysis is the energy required to produce and repair farm machinery and the steel and concrete used to make the ethanol refinery. DeLucchi (1993)[123] has argued that these energy costs should be included in the energy analysis of agriculture raw materials and their processing. These are not expected to be large items, since the efficiency of producing steel and concrete has improved considerably in the last several decades since some of the original energy analyses of ethanol production from corn grain were conducted.

Stumborg (2002)[124] has calculated that ethanol produced from corn grain reduces greenhouse gas emissions by 1.47 kg/L of ethanol, when used in a 10% blend in gasoline. This calculation takes into account the energy savings and GHG reduction in the refinery when ethanol is used to provide octane benefits to the gasoline/ethanol blend.

Table 3 summarizes the findings of Levelton et al. (1999)[125] with regard to ethanol produced from corn grain in Ontario. Table 3 also shows that improvements in the efficiency of producing ethanol, and in the average fuel efficiency of the car and truck fleet is expected by 2010. Both these effects reduce the grams of carbon dioxide equivalents emitted by vehicles travelling one kilometre.

A litre of ethanol has about two thirds the combustion energy of gasoline. Thus a 10% ethanol-gasoline blend will have less energy that a litre of gasoline and will drive a vehicle slightly less far. A 10% ethanol blend has a 1% better energy specific fuel efficiency which partly compensates for the lower energy content. When all the energy and greenhouse gas effects are taken into account, a vehicle using a 10% ethanol blend emits about 3.9% less total greenhouse gases than a vehicle using gasoline as a fuel. By 2010, it is expected that a vehicle fuelled by a 10% ethanol blend will emit about 4.6% less greenhouse gases per kilometre driven, than a vehicle using gasoline only.

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[122]Ibid, idem.

[123]DeLucchi, M.A. 1993. Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity. Appendixes K and P. ANL/ESD/TM-22, Vol. 2. Argonne National Laboratory, Argonne, Illinois 60439.

[124]Stumborg, M. 2002. Potential for Biofuel Development. Proceedings AgFibre Conference, Winnipeg, MB. Available from the author at SPARC, Agriculture and Agri-Food Canada Research Centre, Swift Current, SK S9H 3X2.

[125]Levelton Engineering Ltd., (S&T)^2 and J.E. Associates. 1999. Assessment of Net Emissions of Greenhouse Gases from Ethanol-Gasoline Blends in Southern Ontario. Report to Policy Branch, Agriculture and Agri-Food Canada, Ottawa, ON K1A 0C5.

Table 3. Emissions of greenhouse gases (grams of carbon dioxide equivalents per kilometre driven) from a vehicle employing a 10% ethanol blend compared to conventional gasoline. Effects for 2000 and estimated for 2010. Derived from Levelton et al. (1999).

Year	Gasoline	10% ethanol blend
2000	317.1 (100%)	304.9 (96.2%)
2010	298.3 (94%)	284.5 (89.7%)

( ) = percent of gasoline in 2000.

Integration of employment of fuel ethanol with improvements in fuel efficiency of vehicles. Potential reductions in GHG emissions. One recent study of methods by which Canada could reach the Kyoto target in 2012 of GHG emissions six percent below 1990 levels concluded that major improvements in fuel efficiency of vehicles had the potential to achieve this goal for the transportation sector, if combined with modest employment of ethanol and biodiesel as renewable fuels (Torrie et al., 2002).[126] Known technologies for renewable fuels and for improvements in vehicle fuel efficiency were used to estimate the potential to reduce GHG emissions from the transportation sector. Torrie et al. (2002) concluded that:

- Ethanol production, mainly from grain, was targeted to be 1.3 billion L in 2012, used mainly in the personal transportation sector,
- Biodiesel production was calculated to be 420 million L by 2012, used mainly in the freight transportation sector,
- The main fuels used for transportation in 2012 were still gasoline and diesel fuel,
- Substantial improvements in fuel efficiency of cars and trucks by technically feasible methods, including introduction of gasoline-electric and diesel-electric hybrid vehicles, were coupled with this modest employment of ethanol and biodiesel renewable fuels,
- Combination of these technologies was estimated to reduce:
  - personal transportation GHG emissions from 119 million t of CO_2 equivalents in 2004 to 73 million t in 2012,
  - freight transportation GHG emissions from 60 million t of CO_2 equivalents in 2004 to 48 million t in 2012.

General Motors plans to offer a variety of gasoline-electric and diesel-electric hybrid vehicles over the next four years.[127] General Motors conducted a very detailed analysis of various advanced fuels and vehicle engine + drive systems to determine their potential to reduce GHG emissions (General Motors, 2001).[128] This study was conducted in collaboration with Argonne National Laboratory, BP, Exxon Mobil and Shell. The study concluded that diesel-electric hybrids and gasoline-electric

[126]Torrie, R., Parfett, R. and Steenhof, P. 2002. Kyoto and Beyond. Torrie Smith and Associates, Ottawa, ON K1N 7B7. Available from www.torriesmith.com.

[127]Saskatoon Star Phoenix. 2003. January 6th, p. A10.

[128]General Motors. 2001. Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems - North American Analysis. See the web site: www.gm.com.

hybrids had the most potential to reduce GHG emissions in the short to medium term. Hydrogen fuel-cell powered systems had similar reductions in GHG emissions, assuming the hydrogen was derived from natural gas. Ethanol derived from lignocellulose had the most potential to reduce GHG emissions, amongst renewable fuels, provided the technology could be made cost competitive, and provided the resource base was large enough to permit wide-spread use in the transportation system.

6.2.4 Current Research

6.2.4.1 Research on crop production and harvesting systems

Current research is divided into studies leading to ethanol from grain and studies directed at ethanol production from lignocellulosic raw materials such as crop residues. To aid in analysing the ethanol production systems, the different stages in production, from crop production through biofuel production to final emissions from the tailpipe of the vehicle will be followed. Gaps in research identified by the people we talked to, plus analysis of the literature, will be discussed at each stage of the production and utilization chain.

Crops and cropping systems: Some crops in the future may be designed to have properties suitable for bioproduct application, according to discussions with senior Agriculture and Agri-Food Canada staff. For example, some cereal crops might be designed in the future to produce larger amounts of starch, including selection to produce certain kinds of starch more suited for industrial applications. Oats are being studied for genetic improvement "for value-added traits, disease resistance, wide adaptation, and nutraceutical, pharmaceutical and industrial uses." Industrial applications could include ethanol, bioplastics, fibre-board, pulp and paper (Bailey, 2002).[129]

Patrick Girouard of Iogen (Girouard, 2003)[130] has indicated that "the main area that requires more R&D in our case is research on dedicated grass along with extension with farmers. Full development of a cellulose ethanol industry will require use of dedicated grasses at some point within the next ten years. Research should go beyond maximizing biomass yield and seek to optimize feedstock composition for specific conversion processes".

Iogen has found that the composition of the lignocellulosic feedstock can be selected to improve the ability of enzymes to hydrolyze pretreated biomass to produce fermentable sugars (U.S. Patent to Iogen, 2000, Foody et al., 2000).[131] Iogen found that feedstocks with a ratio of arabinoxylan to total nonstarch polysaccharides (AX/NSP) of greater than about 0.39 were superior substrates for enzymatic hydrolysis, after reacting (e.g., with high pressure steam) at conditions that disrupted the fibre structure and hydrolyzed a portion of the cellulose and hemicellulose. Substrates with this high

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[129]Bailey, D. 2002. Genetic improvement of oats for value-added traits, disease resistance, wide adaptation, and nutraceutical, pharmaceutical and industrial uses. ICAR Project: 88880341.

[130]Girouard, P. 2003. Personal communication to T. McEwen, Jan. 6th, 2003 via E-mail.

[131]Foody, B., Tolan, J.S., Bernstein, J.D. and Foody, P. 2000. Pretreatment process for conversion of cellulose to ethanol. U.S. Patent 6,090,595.

a ratio of AX/NSP enabled production of more glucose with less cellulase enzyme than any other procedure. Preferred feedstocks included oat hulls and corn cobs. Foody et al. (2000) also suggested that one might *breed* biomass feedstocks, e.g., forage grasses, to possess higher ratios of AX/NSP to better suit the production of ethanol by enzymatic hydrolysis of lignocellulosic feedstocks.

Research gap " Investigations are needed to determine if the arabinoxylan/nonstarch polysaccharide ratio can be increased in industrial grasses, such as switchgrass in eastern Canada, to better match the requirements of the ethanol industry. What would be the effect on ruminant animal feed value, since livestock feed would also be a possible use of such forage grasses?

Ron Kehrig, Bioproducts Saskatchewan, suggested that sorghum and millet should be examined for dual grain + straw ethanol production, somewhat similar to corn grain + stover utilization for ethanol production being studied in the US (Hettenhaus, 2002).[132]

Cropping systems can have a large effect on the energy and economic costs of production. For example, spring wheat crops grown after alfalfa in the rotation had much lower energy costs of production than spring wheat grown after a cereal or non-legume oilseed (Entz et al., 1995).[133] No nitrogen fertilizer was required for spring wheat grown for two years after alfalfa in the rotation (Manitoba conditions), greatly reducing the energy costs of wheat production. This would be expected to reduce the energy costs of ethanol produced from wheat grown in such a cropping system.

A reviewer (M. Reaney) has suggested that alfalfa be considered for a bioenergy crop itself since it has very low energy costs of production. Alfalfa had about 1/6th the energy costs of production of wheat grain (Entz et al., 1995).

Zero tillage systems are well known to increase soil organic matter. In addition, studies in Saskatchewan found that zero tillage production systems reduced the crop yield losses during drought conditions compared to conventional tillage crop production systems (Zentner et al., 1999).[134] This advantage could be important for increasing crop supplies for industrial applications, as well as reducing income losses for the farmer.

Nitrous oxide emissions from crop production systems: Nitrous oxide (N_2O) is a serious

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[132]Hettenhaus, J. 2002. Talking about corn stover with Jim Hettenhaus. The Carbohydrate Economy 4(2): 1, 8-13.

[133]Entz, M.H., Henry, S., Bamford, K.C., Schoofs, A. and Ominski, P.D. 1995. Carbon released by manufactured inputs in prairie agriculture: impact of forage crops and tillage systems. Chapter 5 of volume 2 of Coxworth et al., 1995. Study of the Effects of Cropping and Tillage Systems on the Carbon Dioxide Released by Manufactured Inputs to Western Canadian Agriculture: Identification of Methods to Reduce Carbon Dioxide Emissions. Report to H.H. Janzen, Agriculture and Agri-Food Canada, Lethbridge, AB.

[134]Zentner, R.P., Lafond, G.P., Derksen, D.A., Wall, D.D., Geremia, R. and Blomert, B.J. 1999. The influence of conservation tillage on economic returns and riskiness of cropping systems in the thin Black soil zone. Proceedings Soils & Crops '99, Feb. 25-26, Saskatoon, SK, pp. 98-108. Extension Division, Univ. of Sask., Saskatoon, SK S7N 5C8.

greenhouse gas with a global warming potential 310 times that of carbon dioxide. It is emitted from soils as a result of soil microorganisms action on nitrogen compounds in the soil. These nitrogen compounds arise from the application of nitrogen fertilizers, addition of manures, production of legumes and decomposition of crop residues. Nitrous oxide emissions constitute a significant fraction of the total greenhouse gas emissions attributed to ethanol production from corn grain (Levelton et al., 1999).[135] Nitrous oxide is to be distinguished from nitric oxide (NO) and nitrogen dioxide (NO_2) which are produced by combustion of fuels, and are serious factors in air pollution in the lower atmosphere, but are not considered to be serious long-lived greenhouse gases, as is nitrous oxide.

A three year study in western Canada, led by Reynald Lemke, Semiarid Prairie Agriculture Research Centre (SPARC), Agriculture and Agri-Food Canada (AAFC), Swift Current, Saskatchewan, is nearing completion (fall of 2003). Four sites in different parts of Saskatchewan produced three crops (spring wheat, canola and flax) over three years. Different weather conditions were experienced at these sites over the three years, from excessive moisture to severe drought. Different methods of applying nitrogen fertilizer and two different nitrogen fertilizers (anhydrous ammonia and urea) were employed. Other related experiments by Lemke found that annual nitrous oxide emissions were less with zero tillage than with conventional tillage (Pratt, 2002).[136]

Research gap " Lemke's study on nitrous oxide should enable the calculations of the complete greenhouse gas emissions from the spring wheat to ethanol production chain. These studies could now include:

- nitrous oxide emissions from spring wheat under different levels of nitrogen fertilizer, method of application of fertilizer, and different types of N fertilizer,
- effects of drought and other weather conditions on crop yields, nitrous oxide emission per unit of grain produced and energy costs of crop production,
- effects of tillage systems on nitrous oxide emissions from spring wheat production,
- effects of tillage systems on carbon sequestration and its relationship to nitrous oxide emissions,
- the ripple effects of these GHG gas emissions and sequestration effects on ethanol production from spring wheat,
- the economic effects of these different crop production systems.

Claudia Wagner-Riddle at the University of Guelph in Ontario is conducting similar studies on nitrous oxide emissions from a corn-wheat-soybean rotation conducted under contrasting management conditions (Wagner-Riddle, 2002).[137] The results from these studies at Guelph will be very useful in determining the total GHG emissions from ethanol production from corn grain and

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[135]Levelton Engineering Ltd., (S&T)[2] and J.E. & Associates. 1999. Assessment of the Net Emissions of Greenhouse Gases from Ethanol-Gasoline Blends in Southern Ontario. Report to Policy Branch, Agriculture and Agri-Food Canada, Ottawa, ON K1A 0C5.

[136]Pratt, S. 2002. Pulse crops defended against pollution charge. Western Producer, December 19, p. 19.

[137]Wagner-Riddle, C. 2002. Developing Canadian human resources for field evaluation of management practices for reduction of nitrous oxide emissions. ICAR Project: 33330737.

biodiesel production from soybeans.

It may be possible to use the "virtual farm" computer technology program developed by Agriculture and Agri-Food Canada to calculate the total greenhouse gas emissions effects of these crop productions systems (Janzen, 2003).[138]

Supplies of feed grains for ethanol processing: A controversy has arisen over the supplies of feed grain for an expansion of the ethanol industry in western Canada. Kraft and Rude have argued that recent expansions in the livestock industry in Alberta and Manitoba have made them feed-deficit provinces that depend for much of their feed grains on Saskatchewan (Kraft and Rude, 2002).[139] There is only a surplus of 670,000 tonnes of feed grain in the prairie region in a normal year. Much of this will be used for ethanol production by Saskatchewan, if that province expands its ethanol industry as planned. Kraft and Rude argued that Manitoba would increasingly be required to import corn grain from the USA to meet their feed grain needs.

Research gap " Studies appear to be needed to examine the feed grain situation in western Canada and to determine how future expansion in the livestock industry and in the ethanol industry might affect supplies of feed grain and other feed ingredients. Ethanol production from feed grains produces dried distillers grains and solubles (DDGS) as a co-product. How might this material be most effectively used as a feed component for livestock? What would be the net economic effects of these changes?

A reviewer has questioned using present grain production as a guide for potential production and markets in the future. For example, if declines in red meat consumption in North America continue into the future, demands for feed grains could decline, possibly to be replaced with markets for industrial crops with different starch and protein levels. There would then be a research gap to design crops for these new industrial markets.

Increases in livestock production and increases in ethanol production: Net effects on greenhouse gases emissions: The Saskatchewan government hopes that expansion in the ethanol industry would cause an expansion in the livestock industry (Briere, 2002).[140] However, increases in livestock production tend to increase greenhouse gas emissions. Kulshreshtha and Junkins (2000)[141] determined that the expected increase in Saskatchewan livestock production would lead to a substantial increase in greenhouse gas emissions. This was offset by projected increases in carbon sequestration in soils caused by reductions in the amount of summerfallow and the adoption

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[138]Janzen, H. 2003. Quoted by Wilson, B. Software tracks environmental damage. Western Producer, January 2, 2003, p. 55.

[139]Kraft, D.F. and Rude, J.I. 2002. Feed grains and Ethanol Processing in Manitoba. Available at www.umanitoba.ca/afs/agric_economics/staff/kraft.html. Also derived from personal communication with D. Kraft.

[140]Briere, K. 2002. Ethanol. Western Producer, December 12, p. 75.

[141]Kulshreshtha, S. and Junkins, B. 2002. Options for mitigation of greenhouse gas emissions from agriculture: an economic perspective for Saskatchewan farmers. Proceedings Soils & Crops 2000, Univ. of Sask., Saskatoon, SK, Feb. 24-25, pp. 413-420. Extension Division, Univ. of Sask., Saskatoon, SK S7N 5C8.

of zero tillage.

Research gap " Further calculations are needed to determine the effects of the expansion in the ethanol production industry, coupled with the planned expansion in the livestock industry, on the net emissions of GHGs from the Saskatchewan agricultural economy.

New and improved crop harvest and storage systems. Benefits for bioproducts development and benefits to farmers: Research is being conducted on harvesting systems with the goals of trying to improve farmers' net income as well as providing feedstocks for bioproduct applications, including biofuels. For example, studies are being conducted at Indian Head, Saskatchewan on use of a header-stripper system for fast harvest of grain and chaff. All the straw is left standing in the field by this system. It can be harvested at a later date. Grain can be harvested very quickly by this system, an important beneficial factor for farmers if weather conditions are poor during harvest time. At the same location, chaff collection is being conducted in conjunction with conventional combine harvest. Both systems show some advantages over conventional grain harvest (Lafond, 2002).[142]

The chaff harvest system mimics the McLeod Harvest System, a new harvest system recently developed in Manitoba. The new system has been economically analysed by Prentice et al. (1999)[143] at the University of Manitoba. In this system, a field unit threshes the crop and collects a mixture of the grain, chaff and weed seeds in a large tank. This mixture is transferred to a truck with a large truck box. The grain and chaff mixture is transported to the farmyard where an automated yard unit separates the grain and cleans it. The chaff and weed seeds mixture is blown through a fan and pipe system to a large pile for storage, prior to use as cattle feed or transport to a processing plant. The action of the fan increases the density of the chaff mixture considerably, allowing transport to a processing centre if needed off the farm. Considerable savings in weed control costs were measured in field experiments. The chaff and weed seed mixture also often contained small crop seeds or broken seed which increased the feed value. <u>The total economic benefits were calculated to exceed $30/acre,</u> a very considerable increase in farm net income. Chaff collected from canola and flaxseed harvest contained considerable amounts of vegetable oil which would be expected to suppress methane eructation and increase conjugated linoleic acid in the meat and milk. Prentice and his co-workers concluded that: "...the McLeod Harvest System could be the most important innovation to prairie agriculture since the breeding of canola". Chaff can be converted into ethanol with about the same yields as straw (Craig and Kernan, 1989)[144] and has been included in the estimates of potential

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[142] Lafond, G. 2002. New harvest systems being studied at the Agriculture and Agri-Food Canada research farm at Indian Head, Sask. Personal communication to E. Coxworth.

[143] Prentice, B.E., Stewart, S. and Wang, Z. 1999. An Economic Assessment of the McLeod Harvest System. Available from the Dept. of Agricultural Economics, Univ. of Manitoba, Winnipeg, MB R3T 2N2.

[144] Craig, W. and Kernan, J. 1989. Examination of the Technical and Economic Feasibility of Producing Liquid Fuel Extenders and Additives from Cereal Chaff. Saskatchewan Research Council Publication R-811-1-E-89. Saskatchewan Research Council, 15 Innovation Blvd., Saskatoon, SK S7N 2X8.

ethanol production in Canada calculated by Stumborg (2002).[145]

Straw collection and storage alternatives are also being evaluated (Lyschynski et al., 2001).[146] These systems would lead to use of straw as a raw material for biofuel or bioproduct applications (Stumborg, 2002).[147]

Corn stover harvest present different challenges to straw and chaff harvest from small grains. In the bioplastics section of this report (see section 6.5.5), Biomass Agri-Products and its partners are developing a new system for harvest of corn grain and stover in one pass. Storage methods for the stover are also being investigated in this study.

Various studies on methods to collect and store corn stover were to have been reported at the Fifth Biomass Conference of the Americas in September, 2001. Although the conference was cancelled, abstracts of papers are available at www.fsec.ucf.edu/bioam. or www.nrel.gov/bioam. These American studies may be of relevance to collection of corn stover in Ontario and Quebec.

6.2.4.2 Production of ethanol and co-products from grains

Fermentation of grains to ethanol. Biorefinery approaches: The three products from fermentation of cereal grains are ethanol, carbon dioxide (produced in roughly equal amounts to ethanol as a result of the fermentation of the starch) and solid and liquid residues from the grain, containing the grain protein and the grain fibre, plus small amounts of other non-fermented grain ingredients. In most grain fermentation plants, the solid and liquid residues are combined and dried to produce an animal feed material called dried distillers grains and solubles (DDGS). The selling price of this material is not enough to enable the ethanol to be sold at a price competitive with gasoline as a fuel. Thus, various government incentives are needed to enable ethanol to be sold as a fuel. There is thus a need to reduce the costs of the process and to find higher value markets for the co-products from grain fermentation.

Recent research developments on fermentation of grains to produce ethanol have been described in section 6.2.2: Key opportunities. Very high gravity fermentation of grains is now being adopted by the American ethanol industry, according to Ingledew (2002)[148], and is leading to reductions in costs

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[145] Stumborg, M. 2002. Potential for Biofuel Development. Proceedings AgFibre Conference, Winnipeg, MB. Available from the author at SPARC, Agriculture and Agri-Food Canada Research Centre, Swift Current, SK S9H 3X2.

[146] Lyschynski, D., Hill, L. and Boyden, A. 2001. Wheat straw availability and quality changes during harvest, collection and storage. Abstracts of the 5th Biomass Conference of the Americas. Available from the web site: www.fsec.ucf.edu/bioam.

[147] Stumborg, M. 2002. Potential for Biofuel Development. Proceedings AgFibre Conference, Winnipeg, MB. Available from the author at SPARC, Agriculture and Agri-Food Canada Research Centre, Swift Current, SK S9H 3X2.

[148] Ingledew, W.M. 2002. Very high gravity fermentation: yield and productivity are the keys to success. ABIC Conference, Saskatoon, SK. Available from AgWest Biotech, Saskatoon, SK S7N 3R2.

and improvements in productivity.

Another method to reduce costs has been to produce other products, such as wheat bran, for sale into various food and other markets. The Minnedosa plant of Husky developed a product called Fibrotein, which contains the bran and protein fraction from wheat. This product was isolated before the starch component goes into the fermentation vessel to produce ethanol. Sales of the Fibrotein into human food markets helped produce revenue and reduced the fraction of the processing costs borne by the ethanol production. While Mohawk sold this product into the food industry for a time, it is no longer manufactured.

Sosulski and Sosulski (1994)[149] calculated that removing a wheat bran fraction for sale into the human food market, prior to fermenting the starch-increased residue for ethanol, would increase profits considerably.

A process was developed in the late 1980's by AAFC and POS scientists for dehulling oats using ethanol. Separation of dehulled oats then led to various food and cosmetic products. Some of the starch could be fermented to produce fuel ethanol.

The Pound-Maker ethanol plant in Saskatchewan feeds the wet distillers grains (DG) and distillers solubles (DS) to cattle in a feedlot beside the ethanol plant. All costs of drying these products are avoided. However, the size of the ethanol plant is small (less than 15 million L capacity). Brad Wildeman of Pound-Maker has questioned the economics in western Canada of drying the DG and DS to produce DDGS for sale off site (Briere, 2002).[150] This is the common practice at most grain ethanol plants in North America. He believes the DDGS product would be too costly to compete with barley in feedlot rations in western Canada.

Research gap " An economic analysis may be needed to determine the relative economics of small ethanol plants situated beside a modest size feedlot, and feeding wet DG and wet DS directly, compared with a large ethanol plant, with economies of scale, but drying all DDGS for sale off site. This study might need to also calculate the best markets for DDGS in the prairie region.

Research gap " The API wheat grain biorefinery at Red Deer, Alberta, has gone into receivership (Cowley, 2002).[151] The plant produced wheat flour, wheat gluten, livestock feed and ethanol (Maynard, 1999).[152] What were the reasons for the plant's failure? A major increase in wheat prices was cited as one reason. How could such biorefineries avoid such problems in the future?

American studies are looking at a biorefinery concept based on the mill feed byproducts from

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[149]Sosulski, K. and Sosulski, F. 1994. Wheat as a feedstock for fuel ethanol. Appl. Biochem. Biotech. 45/46; 169-180.

[150]Briere, K. 2002. Ethanol. Western Producer, November 21, pp. 76-78.

[151]Cowley, P. 2002. Losses force Alta. Ethanol plant into receivership. Western Producer, December 12, p.75.

[152]Maynard, A. 1999. Processing plant turns grain into gold. Western Producer, June 3, p.17.

conventional wheat grain milling (Elliott et al., 2001).[153] However, starch is being considered for processing into products other than ethanol, such as polyols or lactic acid. It is also possible to use ethanol as a platform chemical for the production of more valuable bioproducts.

Other products from processing of corn grain are being evaluated by MBI International in Michigan (Ponnampalam, 2001).[154] A degerminating process would be integrated with production of corn oil, corn fiber oil, xylitol and arabinose as well as ethanol. The carbon dioxide released from the fermentation of the corn starch would be used to produce succinic acid.

The United States Department of Agriculture lab in California has developed a process to isolate wheat gluten from wheat flour by extraction with ethanol, rather than water (the traditional processing method)(Robertson, 1998).[155] The new process is claimed to be much less polluting and produce a better quality wheat gluten.

Sequestration of carbon dioxide in oilfields also recovers more oil at the same time as carbon dioxide is taken out of the air: The third product from grain fermentation is carbon dioxide. A potential market is as an agent to enhance oil recovery from old oil fields. In this process, carbon dioxide, usually captured from the combustion of fossil fuels, e.g., from a coal burning power station, is pumped underground into the oil bearing formation of an oil field where it displaces oil from the formation and enables greater efficiencies in the oil recovery process. The carbon dioxide stays underground and therefore is removed from the GHG scenario. In theory, carbon dioxide from grain fermentation could also be used for this purpose.

Such a carbon dioxide sequestration/utilization project is being conducted at Weyburn in southern Saskatchewan. The carbon dioxide for this $1.1 billion enhanced oil recovery project is obtained by a pipeline from North Dakota where it is produced as a byproduct from coal gasification (Business Unlimited, 2002).[156] Some 14 million tonnes of CO_2 are to be sequestered in the oilfield at the same time as more oil is recovered. This sequestering of carbon dioxide is equivalent to taking 40% of the vehicles in Saskatchewan off the road for a period of 15 years, the length of time of the enhanced oil recovery program. If pipelines are built in western Canada to move carbon dioxide captured from fossil fuel burning plants to oilfields for enhanced recovery, it may be possible for ethanol plants in suitable locations to sell their carbon dioxide for this new market. Because the CO_2 is removed from the atmosphere, the net greenhouse gas emissions from such ethanol plants would be greatly reduced.

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[153] Elliott et al. 2001. Abstract from the 5th Biomass Conference of the Americas. Available from www.nrel.gov/bioam.

[154] Ponnampalam, E. 2001. Integrating emerging technologies with biomass refining. Abstract from the 5th Biomas Conference of the Americas. Available from www.nrel.gov/bioam.

[155] Robertson, G.H. 1998. New process improves wheat flour separation. Agricultural Research, February issue, p. 17.

[156] Business Unlimited. 2002. Breathing new life into the Weyburn oilpatch. Business Unlimited magazine, December issue, p. 5. Greenhouse Issues, September, 2002. Discusses the concept in general and plans for the North Sea oil fields carbon dioxide sequestration-enhanced oil recovery program (www.iea.org.uk).

The IPCC (Intergovernmental Panel on Climate Change) is planning to prepare a formal report on capture and storage of carbon dioxide (www.ieagreen.org.uk). This report will discuss issues such as environmental impacts and risks, costs, carbon dioxide sources, transport and geographical distribution of storage possibilities.

6.2.4.3 Production of ethanol from lignocellulosic feedstocks

Fermentation processes: This has been a very active research and development area in North America. A variety of processes are being studied with several at the stage of pilot plant development, including the Iogen process under development in Ontario.

The drive to produce ethanol from lignocellulosic sources came for several reasons. Only a limited amount of ethanol could be produced from grains before competition for the resource for food and feed and other markets would limit further expansion. Furthermore, the total amount of grain produced in the US, for example, could only provide a small amount of the ethanol needed to replace all the gasoline used in the US. Ingledew (2002)[157] has calculated the potential for the corn grain situation:

- North American consumption of gasoline = 450 billion L,
- ethanol needed to supply 10% supplement to gasoline = 45 billion L,
- assume 387 L ethanol/t of corn grain,
- grain required for ethanol production would be 116 million t,
- total corn production is 250 million t,
- therefore, 46% of the total corn production would be needed just to supply 10% of the gasoline demand.

The total amount of crop residues available for industrial uses, such as ethanol production, were estimated to be very large. Klass (1998)[158] calculated that the total amount of crop residues potentially available in the US was about 257 million t, similar in size to the North American corn grain production. Lynd et al. (1991)[159] calculated that some 324 to 396 million acres of land might be available in the US to grow biomass (trees, forage grasses) for conversion into ethanol. This amount of land was estimated to be capable of producing from 12.4 to 26.5 EJ (exajoules or 10^{18} joules) of biomass, roughly 0.65 to 1.39 billion tonnes.

According to Klass (1998), major problems are associated with the production of fermentation ethanol from these materials, such as the difficulty of hydrolyzing cellulose to maximize glucose yields and the inability of conventional ethanogenic yeast to ferment pentose sugars that make up a large portion of the hemicellulose polymers in lignocellulosic biomass. Lignocellulosic materials

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[157]Ingledew, W.M. 2002. Very high gravity fermentation: yield and productivity are the keys to success. ABIC Conference, Saskatoon, SK. Available from AgWest Biotech, Saskatoon, SK S7N 3R2.

[158]Klass, D.L. 1998. Biomass for Renewable Energy, Fuels, and Chemicals. Academic Press, Toronto, Canada.

[159]Lynd, L.R., Cushman, J.H., Nichols, R.J. and Wyman, C.E. 1991. Fuel ethanol from cellulosic biomass. Science. 251: 1318-1323.

are complex associations of cellulose (a polymer made up of repeating glucose units), hemicellulose (a polymer mix made up of various six carbon and five carbon sugars, such as xylose) and lignin. Various processes have been developed to:

- render the lignocellulosic materials more reactive (steam treatment with or without acids, ammonia fibre explosion, supercritical water, supercritical carbon dioxide, etc.),
- employ acids or cellulase enzymes to hydrolyze (saccharify) the cellulose and hemicellulose to simple sugars,
- design fermenting microorganisms to produce ethanol from both six carbon and five carbon sugars,
- develop techniques to both enzymatically hydrolyze materials and ferment the resulting sugars to ethanol (simultaneous saccharification and fermentation (SSF)).

A number of these steam treatment and acid hydrolysis methods have been developed. One problem has been the ease with which hemicellulose sugars degrade to furfural and other toxic substances. These can hinder the ethanol fermentation and reduce the yields of hemicellulose sugars for conversion into ethanol.

A number of these new processes for production of ethanol from lignocellulosic biomass have been reviewed by McCloy and O'Connor (1998).[160] This study examined the engineering and economic possibilities of these processes to produce ethanol from forest residues in British Columbia.

An advanced technology to hydrolyze lignocellulose materials to simple sugars in almost quantitative yields was developed by Dr. L. Paszner at the University of British Columbia. The ACOL process (Acid Catalyzed Organosolv Saccharification Process) uses aqueous acetone as the reaction medium (Klass, 1998).[161] Acetone plays a critical role in forming short term compounds with the sugars and preventing their decomposition into materials such as furfural. Complete recovery of simple sugars and lignin was achieved in less than five minutes at temperatures of 165-230 degrees C. The acetone is recovered for reuse in the process.

The Arkenol process uses concentrated sulfuric acid in a two stage process to hydrolyze the hemicellulose to simple sugars in the first stage and then hydrolyze the cellulose to glucose in the second, higher temperature stage (Dow, 1998).[162] The insoluble lignins are separated from the sugar-sulfuric acid solution. Sulfuric acid is next separated from the sugars by ion exchange chromatography. The sulfuric acid is recirculated. The sugars are fermented to ethanol using yeasts specifically cultured by Arkenol to convert both six-carbon and five-carbon sugars to ethanol.

BC International has developed a process based on dilute acid hydrolysis of lignocellulosic materials

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[160]McCloy, B.W. and O'Connor, D.V. 1998. Wood-Ethanol: A BC Opportunity. Report to BC Ministry of Environment, Lands and Parks, Victoria, BC V8W 9M1.

[161]Klass, D.L. 1998. Biomass for Renewable Energy, Fuels, and Chemicals. Academic Press, Toronto, Canada.

[162]Dow, D. 1998. The Arkenol biomass to ethanol process. Workshop on Bioconversion of Wood Residues to Ethanol: A BC Opportunity? May 20-21, Vancouver, BC. Available from David Gregg, Chair of Forest Products Biotechnology, University of British Columbia, Vancouver, BC.

(Wyman, 1998).[163] The sugars are fermented by a bacterium genetically engineered to ferment both six and five-carbon sugars:

- based on several bacteria that digest sugars, such as *E coli* and *Klebsiella oxytoca,*
- inserted genes from *Zymomonas mobilis* that allowed these new hosts to produce ethanol,
- shut off genes that produce other products from the host organism, such as organic acids.

A pilot plant in Louisiana is testing this new technology.

Another approach has been developed by the National Renewable Energy Laboratory in Colorado (Klass, 1998).[164] *Zymomonas mobilis* was metabolically engineered to ferment xylose (the main five carbon sugar in many materials) and later also to ferment arabinose, the other main five-carbon sugar.

Nancy Ho and her colleagues at Purdue University have genetically engineered *Saccharomyces* yeasts to be able to ferment five-carbon sugars (Ho et al., 1999).[165] The modified organism can coferment both glucose and xylose present in the medium simultaneously to ethanol. Super stable lines were developed which make possible continuous fermentation.

Another approach to ethanol production from lignocellulosic substrates has been developed by Iogen. The process has been described by Levelton and $(S\&T)^2$ (2000).[166] Material is pre-treated by a modified steam explosion step. Enzymes produced by a microorganism such as *Trichoderma* are added which hydrolyze the cellulose and hemicellulose to simple sugars in solution. Filtration removes the lignin. The lignin is dried and used to generate electricity and steam to run the processing operations. Some electricity may be left over for sale off-site. The sugar solution is fermented to yield ethanol. This process has very low fossil fuel requirements, since the combustion of the lignin byproduct provides all the process steam and electricity requirements of the process. This process thus also has very low greenhouse gas emissions, considerably lower than those from ethanol produced from grain.

Costs of ethanol produced from lignocellulosic materials: A recent analysis of the NREL process calculated that plants using this technology would produce ethanol at a cost of $0.40 (US)/L,

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[163]Wyman, C. 1998. BC International biomass to ethanol strategy. Workshop on Bioconversion of Wood Residues to Ethanol: A BC Opportunity? Available from David Gregg, Chair of Forest Products Biotechnology, University of British Columbia, BC.

[164]Klass, D.L. 1998. Biomass for Renewable Energy, Fuels, and Chemicals. Academic Press, Toronto, Canada.

[165]Ho, N.W.Y., Chen, Z., Brainard, A. P. and Sedlak, M. 1999. Successful design and development of genetically engineered *Saccharomyces* yeasts for effective cofermentation of glucose and xylose from cellulosic biomass to fuel ethanol. Advances in Biochemical Engineering/Biotechnology. 65: 163-192.

[166]Levelton Engineering Ltd. and $(S\&T)^2$. 2000. Assessment of the Net Emissions of Greenhouse Gases from Ethanol-Blended Gasolines in Canada: Lignocellulosic Feedstocks. Report to Policy Branch, Agriculture and Agri-Food Canada, Ottawa, ON K1A 0C5. Report R-2000-2.

considerably more than ethanol produced from corn grain ($0.24 (US)/L (McAloon et al., 2000).[167] This process uses mild acid hydrolysis to solubilize the hemicelluloses. Cellulase enzymes are used to hydrolyze the cellulose to glucose. A genetically engineered microorganism is used to ferment the sugars to ethanol. The capital costs of the lignocellulosic process were much higher than the cost of the grain process. This reflected the greater complexity of this process.

Biorefinery approaches: The cost analysis of the NREL process demonstrated that there was a need to develop other products besides ethanol from lignocellulosic materials to help reduce costs.

The University of Utah developed a process to manufacture methoxybenzenes from lignin by a combination of base-catalyzed depolymerization, hydrotreatment and etherification (Shabtai et al., 2001).[168] These methoxybenzenes were found to have very high octane ratings, making them suitable as octane enhancers for gasoline. Thus this use could provide a large market for these lignin products to match the large ethanol market.

Enerkem Technologies of Montreal reported on processes to generate bioenergy and co-products from plants processing about 100,000 tonnes per year (Chornet et al., 2001).[169] This amount of material would be more available locally than the requirements of a large ethanol from lignocellulose plant, which might require 400,000 tonnes per year or more of raw material. A pretreatment of feedstock impregnation and rapid steam treatment (FIRST) was used to allow fractionation of raw materials. Using this fractionation process, a variety of products were produced from bark-rich residues from forestry operations, sugar beet pulp, corn stover, and urban wood. They stressed that a priori knowledge of markets for these products was essential for successful development of such biorefineries.

There is growing interest in methods to produce cheap simple sugars from lignocellulosic biomass. These sugars could then be used for ethanol production or for various industrial products. NREL has developed simple percolation methods, using very dilute sulfuric acid (less than 0.1%), to obtain high yields of sugars (Elander et al., 2001).[170] Sophisticated separation techniques are being developed to obtain pure sugars, such as xylose, to be used for the production of industrial

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[167]McAloon, A., Taylor, F., Yee, W., Ibsen, K. and Wooley, R. 2000. Determining the Cost of Producing Ethanol from Corn Starch and Lignocellulosic Feedstocks. National Renewable Energy Laboratory Report NREL/TP-580-28893. NREL, Golden, CO 80401-3393.

[168]Shabtai, J., Zmierczak, W.W., Johnson, D.K. and Chornet, E. 2001. Lignin conversion to partially oxygenated biogasolines and alkoxyaromatic gasoline blending components. Abstract from the 5th Biomass Conference of the Americas. See www.nrel.gov/bioam/.

[169]Chornet, E., D'Amour, R., Chornet, V., and Abatzoglou, N. 2001. Refining low grade non-homogeneous biomass feedstocks; bioenergy and a co-product strategy. Abstract of the 5th Biomass Conference of the Americas. See www.nrel.gov/bioam/.

[170]Elander, R.T., Nagle, N.J. and Torget, R.W. 2001. Thermochemical depolymerization of biomass carbohydrates. Abstract of the 5th Biomass Conference of the Americas. See www.nrel.gov/bioam/.

bioproducts (Hess et al., 2001)[171], (Neeves et al., 2001).[172] This has led to the development of a biorefinery planning model (Jechura et al., 2001).[173]

Research gap " There would seem to be a place for studies by the Green Chemistry Network in Canada to determine regional opportunities and restraints and raw material resources for such biorefineries. The experience in Quebec (Chornet, 2001)[174] could be used as a model for regional studies in other parts of the country.

Stumborg (personal communication to E. Coxworth, 2003) suggests that a sugar based platform for the production of acids, plastics and synthetic fibres may be the most profitable use of biomass in the long term, rather than conversion of the sugars into ethanol.

Gasification routes to ethanol: Several people have suggested inclusion of a discussion of gasification routes to ethanol. In this approach, biomass is gasified to produce a mixture of carbon monoxide and hydrogen. After cleanup of the gas stream, the mixture can be reacted in the presence of suitable metallic catalysts to produce ethanol (Klass, 1998).[175] Klass was of the opinion that this approach had the potential to produce ethanol more cheaply than ethanol produced by fermentation. Pearson (2001)[176] described such a process recently. Pearson's process uses steam reforming rather than partial oxygen reforming. This eliminates the need for an oxygen plant and greatly reduces capital cost of the process. This should allow for smaller sized processing facilities. A pilot plant to test this process has been built in Mississippi.

In Canada, Ethopower, a small company in Kelowna, BC, which is developing gasification technology for forest industry residues in BC, has teamed up with the Chemical Engineering Department, UBC, to test whether ethanol can be produced from the synthesis gas produced by Ethopower (Ed Hogan, NRCCan, personal communication to E. Coxworth, 2003).

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[171]Hess, J.R., Kearney, M., Kochergin, V., Peterson, E.S. and Foust, T.D. 2001. Industrial membrane filtration and fractal separation systems for separating monomers from heterogeneous plant material. Abstract of the 5th Biomass Conference of the Americas. See www.nrel.gov/bioam/.

[172]Neeves, K.B., Elander, R.T., Jechura, J.L. and McMillan, J.D. 2001. Expanding the biomass sugars platform: An investigation of sugar separation and purification techniques in the context of an integrated biomass processing refinery. Abstract of the 5th Biomass Conference of the Americas. See www.nrel.gov/bioam/.

[173]Jechura, J.L., Ibsen, K.N., McMillan, J.D. and Neeves, K.B. 2001. Encouraging the development of biorefineries - development of qualitative and quantitative planning models. Abstract of the 5th Biomass Conference of the Americas. See www.nrel.gov/bioam/.

[174]Chornet, E., D'Amour, R., Chornet, V., and Abatzoglou, N. 2001. Refining low grade non-homogeneous biomass feedstocks: bioenergy and a co-product strategy. Abstract of the 5th Biomass Conference of the Americas. See www.nrel.gov/bioam/.

[175]Klass, D.L. 1998. Biomass for Renewable Energy, Fuels, and Chemicals. Academic Press, Toronto, Canada.

[176]Pearson, S.R. 2001. The manufacture of synthesis gas and ethanol from biomass using the Pearson thermo-chemical steam reforming and catalytic conversion process. Abstract of the 5th Biomass Conference of the Americas. See www.nrel.gov/bioam/.

Gasification routes to ethanol are also being evaluated in Saskatchewan, testing various forest residues and straw as raw materials. A memorandum of understanding on this topic has been signed between the Town of Nipawin and various research and development organizations, including the Saskatchewan Research Council (Michalyca, 2002)[177], (Ranganathan, 2003).[178]

A related Swedish gasification-alcohol synthesis process has been described by Lindblom and Berglin (2001).[179] A detailed description of the process has been recently published by Berglin et al. (2002).[180] Black liquor is the main waste product from Kraft pulping of wood. In a conventional pulp mill, the black liquor is concentrated and then burned to produce process steam, leaving a residue which contains the sodium sulfide and sodium hydroxide ready for recycling as the pulping chemicals. 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. In the proposed process, concentrated black liquor would be gasified to produce a synthesis gas. After clean-up this gas would be reacted in the presence of metallic catalysts to produce methanol. Substantial amounts of bark would be burned in a separate boiler to provide power and steam for the new process. The calculations indicated that a 1000 tonne per day pulp mill (350,000 tonnes of pulp per year) would be able to produce 210,840 tonnes of methanol per year (about 266 million litres per year). The plant would earn about $27.8 million per year more. Pulping chemicals would be recycled as in the old process.

It would be interesting to determine whether such a plant could produce ethanol if the catalyst were changed to one similar to the one developed by Pearson (2001).[181] Ethanol production and consumption is already a large industry in North America, and there may be more demand and sales potential for ethanol rather than methanol.

The potential amounts of methanol produced by the Lindblom and Berglin process, from one pulp mill, is similar to the amounts of ethanol that Canada is producing from all sources at the present time. Canada has a large black liquor resource of about 24 million tonnes of dry matter (see Table 1 in section 6.1 Biofuels-Materials Balance Overview). The conclusion is that gasification of black liquor, followed by alcohol synthesis, using metallic catalysts, might have the potential to produce very large amounts of alcohols for the Canadian economy. If the catalyst in the Swedish system could be changed so that ethanol was obtained, instead of methanol, very large amounts of ethanol,

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[177]Michalyca, S. 2002. Nipawin to develop biomass ethanol. News release, September 19, (contact S. Michalyca at (306) 862-9866).

[178]Ranganathan, R. 2003. Saskatchewan Research Council (306) 933-8185. Personal communication to E. Coxworth, January 10th, 2003.

[179]Lindblom, M. and Berglin, N. 2001. Efficient production of methanol from biomass via black liquor gasification. Abstract of the 5th Biomass conference of the Americas. See www.nrel.gov/bioam/.

[180]Berglin, N., Lindblom, M. and Ekbom, T. 2002. Efficient production of methanol from biomass via black liquor gasification. 2002. TAPPI Fall Conference and Trade Fair. Available from Mats Lindblom, E mail: mats.lindblom@chemrec.se.

[181]Pearson, S.R. 2001. The manufacture of synthesis gas and ethanol from biomass using the Pearson thermo-chemical steam reforming and catalytic conversion process. Abstract 5th Biomass Conference of the Americas. See www.nrel.gov/bioam/.

in theory, could be produced. 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.

Large amounts of bark and wood residues are available in British Columbia (some three million tonnes per year, according to McCloy and O'Connor, 1998).[182] This might be another resource for possible conversion into alcohol via the gasification route.

This technology, if successfully developed, might produce enough ethanol that other, more conventional ethanol producers, might be able to focus more on higher value bioproducts, which would likely improve the economics of these operations. In a sense, this has already been observed by Chornet et al. (2001)[183] in Quebec. Their studies indicate that there is more potential for profits in development of processes for higher value bioproducts than ethanol.

Research gap " The Green Chemistry Network being developed in Canada might want to examine the new Swedish process for gasification of black liquor and catalytic conversion into alcohol. Does it have potential for Canada? Can the process be changed to produce ethanol instead of methanol, if desired? The bioenergy subgroup, led by Professor Chornet, within the Green Chemistry Network, is planning to investigate gasification of biomass topics (personal communication from Ajay Dalai, Chem. Eng. Dept., Univ. of Sask.). The information about the gasification to alcohol studies in Sweden by Lindblom and Berglin (2001) has been passed on to Professor Dalai.

The Hydrogen Economy and Biomass: Biomass can be converted into hydrogen by gasification processes (Reddy et al., 1997).[184] Hydrogen could then be used as a fuel for a vehicle powered by a fuel cell. Reddy et al. (1997)[185] calculated that about twice as much transportation energy (GJ/ha/year) could be achieved by gasification of wood to hydrogen, as could be achieved by enzymatic hydrolysis of wood to ethanol. 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. When these two effects were combined, conversion of wood to hydrogen and its use in a fuel cell powered vehicle, gave 4.3 times the transportation services of ethanol produced from wood by enzymatic hydrolysis of wood, and used in an internal combustion engine.

The cost and technology for storage of hydrogen has been an important issue, particularly for hydrogen applications in transport. Recently, Cho and colleagues in Korea found that conducting

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[182]McCloy, B.W. and O'Connor, D.V. 1998. Wood-Ethanol: A BC Opportunity. Report to BC Ministry of Environment, Lands and Parks, Victoria, BC V8W 9M1.

[183]Chornet, E., D'Amour, R., Chornet, V. and Abatzoglou, N. 2001. Refining low grade non-homogeneous biomass feedstocks: bioenergy and a co-product strategy. Abstract of the 5th Biomass Conference of the Americas. See www.nrel.gov/bioam/.

[184]Reddy, A.K.N., Williams, R.H. and Johansson, T.B. 1997. Energy After Rio: Prospects and Challenges. United Nations Development program, New York, NY, USA 10017, see pages 92-99.

[185]Ibid.

polymers, such as polyaniline and polypyrrole, treated with hydrochloric acid, had a storage capacity, under pressure, of eight percent hydrogen by weight (Cho et al., 2002).[186] The industry goal for practical storage of hydrogen is 6.5%. There still remains the important issue of whether the hydrogen can be easily released from the polymers. We speculate that it might be possible to synthesize conducting polymers, such as polypyrrole, from bio-based feedstocks.

Ethanol can be converted to hydrogen in a partial oxidation reformer mounted in a vehicle. The hydrogen could then be used in a fuel cell. The Renewable Fuels Association in the USA believes that ethanol is the preferred fuel/hydrogen carrier to use in reformer-fuel cell combinations in vehicles (Bentley and Derby, 2002).[187] New catalysts for conversion of ethanol into hydrogen are being investigated by Ajay Dalai of the Chem. Eng. Dept, Univ. of Sask. (Ed Hogan, NRCCan, personal communication to E. Coxworth, 2002).

The US Department of Energy has announced that hydrogen will be the vehicle fuel of the future under the goals of the new R&D program announced in January of 2002 (C&EN, 2002).[188]

Stumborg (personnal communication to E. Coxworth, 2003) suggested that other uses for renewable hydrogen (such as from gasification of biomass) may be able to replace hydrogen derived from natural gas to manufacture ammonium fertilizer or to serve as a hydrogenation and hydrotreating chemical in the production of gasoline and diesel fuel.

6.2.5 R & D Analysis

6.2.5.1 Canadian strengths

The proceedings of the 1997 Ethanol Research and Development Workshop (available from M. Stumborg, Semiarid Prairie Agriculture Research Centre, Agriculture and Agri-Food Canada, Swift Current, Saskatchewan) enumerates many of the groups and individuals conducting research on ethanol in Canada at that time. Some of the groups active at that time and what they were investigating are listed as follows:

- University of Calgary (M.M. Maloney) and the Lethbridge Research Centre of AAFC - (K.J. Cheng and K.A. Beauchemin) - insertion of fungal enzyme capabilities in transgenic canola to produce cellulase enzymes in canola seed,
- Lethbridge Research Centre of AAFC (K.J. Cheng) - evaluating rumen microorganisms for their ability to convert cellulosic biomass to ethanol,
- University of Laval (G. Tircotte and K. Belkacemi) and the AAFC Research Centre in Ste. Foy (P. Savoie) - investigating the ammonia fibre explosion method to pretreat forages to

[186]Cho, S.J. et al. 2002. Quoted by Service, R.F. Conducting polymers pack the hydrogen. Science. 297: 1796.

[187]Bentley, J. and Derby, R. 2002. Ethanol & Fuel Cells: Converging Paths of Opportunity, Renewable Fuels Association, www.ethanolRFA.org. See also CFEVR, December, 2002, pp. 65-66.

[188]C&EN. 2002. DOE shifts gears in auto R&D program to hydrogen. Chemical and Engineering News (C&EN), January 14, p.18.

obtain ethanol from the fibrous fraction,

- Sherbrooke University (E. Chornet) and Kemestrie, Inc. (P. Jollez and P. Laborde) - steam explosion techniques to produce ethanol and other products from cereal straw and forages, development of a regional scale biorefinery concept,
- Queen's University (A. Daugulis)- development of extractive fermentation for production of ethanol from starch sources,
- Iogen Corporation (B. Foody) - development of pretreatment methods for lignocellulosic biomass, development of methods to produce cellulase and related enzymes for hydrolysis of cellulose and hemicellulose,
- Faculty of Forestry, University of British Columbia (J.N. Saddler and D.J. Gregg) - steam explosion pretreatment and assessment of various enzymes for obtaining ethanol from softwood residues,
- Tembec Inc., Chemistry Division (D.R. Cameron and R.A.C. Benson) - study of xylose fermentation to produce ethanol,
- Prairie Agriculture Machinery Institute, Humboldt, Sask. (P.Leduc) - methods for whole crop harvest for ethanol production,
- Resource Efficient Agricultural Production (REAP), Ste. Anne de Bellevue, Quebec (R. Samson) - comparison of short rotation forestry with switchgrass as a raw material for ethanol production,
- University of Saskatchewan, Applied Microbiology and Food Science Department (W.M. Ingledew) - very high gravity fermentation technology to produce ethanol from starch.

Many of these groups continue to be active in ethanol research at the present time. Iogen has gone on to become one of the leading companies in the development of technology to produce ethanol from lignocellulosic materials. Both Petro Canada and Shell have invested in Iogen.

The Paszner process for fast hydrolysis of lignocellulosic materials in the presence of acetone continues to be of interest. It was developed by Dr. Paszner at the University of British Columbia.

Gasification and alcohol synthesis from synthesis gas appears to be within the realm of interest of the Green Chemistry Network. The Chemical Engineering Departments of the universities of Saskatchewan, British Columbia and Sherbrooke have interests in this general area. Ethopower in Kelowna, BC, is developing the technology for gasification of forestry biomass, of which there is a lot in BC. They will be working with UBC on production of ethanol from synthesis gas. The Saskatchewan Research Council is also investigating ethanol production from gasification of wood and bark residues and cereal straws (contact D. Soveran, K. Hutchence and R. Ranganathan).

CANMET Technology Centre, NRCCan, and the Catalysis Division of the Canadian Society for Chemistry are starting points for discussion of the field of metallic catalysts and their capabilities.

6.2.5.2 and 6.2.5.3 R & D Challenges and Gaps in Research

The many research opportunities and challenges have been described during the course of discussion of different issues in section 6.2.4: Current Research.

6.2.5.4 Themes for Future Research

Three very different approaches to production of fuel ethanol have been described. All have advantages and disadvantages which could be factors in future research. Most of the ethanol produced in North America uses corn grain as the raw material. The costs of producing ethanol are being reduced by adoption of technology such as very high gravity fermentation. The byproduct of DDGS (dried distillers grains and solubles) is used as a feed for livestock. Ethanol produced by this route is more expensive on an equivalent energy basis than gasoline. This approach (ethanol from corn grain) still needs some form of federal and provincial tax incentives to be competitive with conventional gasoline. Higher values are needed for the co-products produced if ethanol prices are to be reduced. Many studies are attempting to find new, higher value uses for the co-products to help reduce ethanol prices.

If significant production of ethanol from wheat or feed grains is to occur in western Canada, several research issues need to be addressed. The first issue is related to the supply and price of raw materials, as affected by competing uses and by adverse weather, such as drought. The second issue is related to the analysis of the complete energy and greenhouse gas emissions for ethanol produced from feed wheat or other low cost grains in western Canada. A study similar to the study already done for corn grain in eastern Canada is needed. This new study should include the energy costs and greenhouse gas emissions from the machinery used in crop and ethanol production so that a complete picture is obtained.

There are limits to how much ethanol could be produced by this route (fermentation of grain) without seriously interfering with other uses and markets for grains, including new industrial products based on cereal starch as the raw material. Thus there is considerable interest in developing methods to produce ethanol from lignocellulosic raw materials.

Two different routes are being studied. The first employs fermentation of the simple sugars obtained by chemical or enzymatic hydrolysis of cellulose and hemicellulose, the main carbohydrates present in lignocellulosics. A variety of different options are being studied, and are at different stages along the way to commercial production. Valuable co-products are needed if ethanol produced by this route is to become commercially competitive with gasoline. Research is continuing on developing new co-products.

In the second route to ethanol production from lignocellulosics, gasification of biomass is being studied. Gasification technologies, coupled with the employment of metallic catalysts, for the synthesis of ethanol look more promising than previously, due to advances in gasification technology, improved methods for gas clean-up and better and more selective metallic catalysts. Gasification methods for biomass also could lead into hydrogen production, which may be very important in the future. Gasification methods can use raw materials such as black liquor solids from wood pulping, or bark, which are not suitable for fermentation route approaches.

Biorefinery approaches to developing products from biomass still look promising. However, other products, with higher economic value, may be of more appeal than ethanol. Thus ethanol might become a byproduct. The potential production of ethanol from black liquor solids is an application of this approach, in that pulp is the main product. The pulp and paper industry in Canada is so large that production of alcohols from black liquor solids could develop into a major source of ethanol production, provided that suitable methods of production can be developed.

The use of supercritical solvents for the reaction of biomass materials to produce new products is still in the early stages of development but continues to look interesting.

6.2.5.5 Specific Recommendations

Integration of development of ethanol production in Canada needs to be coupled with improvement in the fuel efficiency of the whole transportation sector. Recent developments indicate that companies such as General Motors are starting to think along the same lines.

6.3 Biodiesel

6.3.1 Sector Overview

A recent review has covered much information, relevant to this present report, on the greenhouse gas emissions, air pollution reduction potential and economics of biodiesel. This recent (September, 2002) publication reviewed the greenhouse gas emissions, energy costs, exhaust emissions and economics of biodiesel produced in Canada (Levelton and $(S\&T)^2$).[189] This study examined four sources of raw materials for biodiesel production: canola, soybean, animal fats and recycled frying oils. In addition, Reaney (2002)[190] has recently reviewed the potential for biodiesel production and use in Canada.

Interest in the production and use of biodiesel has been driven by a number of factors:

- use of a renewable fuel for diesel engines and a fuel produced by agriculture,
- a method to assist farmers with new markets for canola oil (Europe),
- reductions in greenhouse gas emissions, relative to diesel fuel,
- reductions in air pollutants,
- an agent to improve the lubricity of diesel fuel.

Biodiesel tends to reduce particulates in the exhaust of diesel engines (Levelton and $(S\&T)^2$, 2002).[191] Particulates (soot aerosols, black carbon) have been implicated as potential carcinogens and as major causes of deaths associated with air pollution. Most recently, black carbon has been

[189]Levelton Engineering Ltd. and $(S\&T)^2$. 2002. Assessment of Biodiesel and Ethanol Diesel Blends, Greenhouse Gas Emissions, Exhaust Emissions, and Policy Issues. Report to Natural Resources Canada, Ottawa, ON K1A 0E4.

[190]Reaney, M. 2002. Success stories in the biodiesel business. ABIC Conference, Saskatoon, SK., September 17. Available from AgWest Biotech, Saskatoon, SK. Also personal communication with M. Reaney at the Saskatoon Research Centre of Agriculture and Agri-Food Canada.

[191]Levelton Engineering Ltd. and $(S\&T)^2$. 2002. Assessment of Biodiesel and Ethanol Diesel blends, Greenhouse Gas Emissions, and Policy Issues. Report to Natural Resources Canada, Ottawa, ON K1A 0E4.

suggested to be a serious factor in global warming (Menon et al., 2002; Chamiedes and Bergin, 2002; Jacobson, 2002).[192] Thus methods, such as use of biodiesel, which reduce black carbon emissions from diesel engines would have a double benefit: reduction in air pollution and reduction in global warming potential.

According to Levelton and $(S\&T)^2$ (2002)[193], the Environment Protection Agency in the US found that a 20% blend of biodiesel in regular diesel fuel reduced air pollutants as follows:

- carbon monoxide by 10%,
- particulate matter by 15%,
- total hydrocarbons by 10%,
- sulfate emissions by 20%,
- nitrogen oxides were increased by 2%.

In Canada, diesel fuel consumption has risen much faster than gasoline consumption. Between 1990 and 2000:

- gasoline consumption rose from 33.9 billion L to 38.3 billion L, an increase of 13%,
- diesel fuel consumption rose from 16.7 billion L to 23.2 billion L, an increase of 39%.

The statistics for gasoline and diesel fuel consumption were obtained from Statistics Canada Catalogue 57-003 for the relevant years.

Thus there is an increasing need to find renewable fuel additives to diesel fuel, and/or find other methods to improve fuel efficiency and reduce total diesel fuel consumption.

World production of biodiesel: Biodiesel is a commercial fuel in Europe, with current consumption considerably more than one million tonnes (over one billion litres). It is widely used in Germany, Austria and France (Levelton and $(S\&T)^2$, 2002p. 66).[194] Smaller amounts are produced in the United States (about 83,000 tonnes or 92 million L). Very small amounts are being produced in Canada, mostly for bus trials in Montreal and Saskatoon. One company, Milligan Biotech, of Foam Lake, Saskatchewan, is starting to sell a fuel lubricity additive made from a blend of materials which includes canola biodiesel. The product is added to commercial diesel fuel to reduce engine wear and improve fuel efficiency (Reaney, 2002).[195]

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[192]Menon, S., Hansen, J., Nazarenko, L. and Luo, Y. 2002. Climate effects of black carbon aerosols in China and India. Science 297: 2250-2253; Chamiedes, W.L. and Bergin, M. 2002. Soot takes center stage. Science 297; 2214-2215: Jacobson, M. 2002. Quoted by Jones, N. Diesel's dirty surprise. New Scientist, 2 November, p. 9.

[193]Levelton Engineering Ltd. and $(S\&T)^2$. 2002. Assessment of Biodiesel and Ethanol Diesel Blends, Greehouse Gas Emissions, and Policy Issues. Report to Natural Resources Canada, Ottawa, ON K1A 0E4.

[194]Levelton Engineering Ltd. and $(S\&T)^2$. 2002. Assessment of Biodiesel and Ethanol Diesel Blends, Greenhouse Gas Emissions, Exhaust Emissions, and Policy Issues. Report to Natural Resources Canada, Ottawa, ON K1A 0E4. See page 66.

[195]Reaney, M. 2002. Success stories in the biodiesel business. ABIC Conference, Saskatoon, SK. Available from AgWest Biotech, Saskatoon, SK.

Canadian diesel fuel has much poorer lubricity than diesel fuels from other countries (B. Hertz, quoted by Reaney, 2002). This has increased interest in the use of biodiesel as a lubricity agent to improve the performance of Canadian diesel fuel.

6.3.2 Key Opportunities

Lubricity improvement agents added to Canadian diesel fuel: The fuel efficiency of commercial Canadian diesel fuel, purchased at the pump, was found by Hertz (2001)[196] to be improved by an average of 5.8% when 0.5% canola biodiesel was added. The engine wear was reduced by 51%. These results were obtained in four highway and city trials using a VW New Beetle TDI diesel-powered automobile. Thus the canola biodiesel was valuable for its ability to improve fuel efficiency and reduce engine wear, more than its value as a renewable fuel. This considerably improves the economics of using canola biodiesel (Hertz et al., 2001).[197]

Use of cheap animal fats as raw materials: Biodiesel produced from animal fats and greases and recovered cooking oils was found to have a cost of production of 36 cents per litre, considerably less than the cost of biodiesel produced from canola oil or soybean oil of about 63 cents per litre (Levelton and $(S\&T)^2$, 2002).[198] A reviewer noted that there has been recently a sharp spike in the price of vegetable oils and animal fats due to short supply. Long term prices may be different. It is unclear at the present time how much of the Canadian production of animal fats and greases and waste fats (e.g., from recovered oil used for frying foods) might be diverted from present animal feed markets, but the total could be considerable. Concern about disease transmission through animal waste product markets has resulted in a drop in demand for some products, which has lowered the market value of these materials.

Niche markets related to ease of biodegradability and reduced air pollution: Biodiesel is much more easily biodegraded in aquatic environments than conventional diesel fuel. This could increase the demand for such fuels in marine environments (Raneses et al., 1999).[199] Other niche markets for biodiesel could be underground mines (because of reduction in air pollutants) and federal vehicle fleets. These three markets were estimated to create a demand for 379 million L in the US.

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[196]Hertz, B. 2001. Extending diesel fuel engine life with canola fuel additives. Crop Production Week Seminar, Saskatoon, Sask., January 10th. Available from B. Hertz., Mechanical Engineering Department, Univ. of Sask., Saskatoon, SK.

[197]Hertz, B., Button, R., Coxworth, E. and Gray, R. 2001. Biodiesel fuel additives/lubricants to improve diesel fuel use efficiency and reduce engine wear. Prairie Sustainable Agriculture and Rural Development Project (Prairie SARD), University of Saskatchewan, Saskatoon, Sask. Available from E. Coxworth, Saskatoon, SK S7H 0J3.

[198]Levelton Engineering Ltd. and $(S\&T)^2$. 2002. Assessment of Biodiesel and Ethanol Diesel Blends, Greenhouse Gas Emissions, Exhaust Emissions, and Policy Issues. Report to Natural Resources Canada, Ottawa, ON K1A 0E4.

[199]Raneses, A.R., Glaser, L.K., Price, J.M. and Duffield, J.A. 1999. Potential biodiesel markets and their economic effects on the agricultural sector of the United States. Industrial Crops and Products. 9: 151-162.

New technology to produce biodiesel: David Boocock and co-workers at the University of Toronto developed a new method to produce biodiesel which greatly reduces the time of reaction and can handle materials with considerable amounts of free fatty acids (e.g., animal fats and greases, recycled waste oils from food production) (Levelton and $(S\&T)^2$, 2002). A company (BIOX) has been formed to develop this new technology.

6.3.3 Potential Impact on GHG Emissions

Levelton and $(S\&T)^2$ (2002)[200] calculated the total greenhouse gas emissions from field to fuel for biodiesel manufactured from canola oil, soybean oil, animal fats and recycled cooking oils. The results were compared to conventional diesel fuel (Table 4).

The calculations included factors such as nitrous oxide emissions from soils, which were the largest single factor in the total GHG emissions from the production of canola and soybean biodiesel. The calculations also include credits for all co-products such as canola meal, soybean meal, animal meat meal and glycerol.

A reviewer has questioned the low greenhouse gas emissions from animal fat and from recycled cooking oil, and has suggested that the complete greenhouse gas analysis of these materials should include some fraction of the greenhouse gas emissions from the production of the animal (in the case of animal fats) and some fraction of the emissions from the production of the original cooking oil.

Table 4. Total greenhouse gas emissions from the manufacture of biodiesel from various sources, compared to diesel fuel.

Fuel source	Greenhouse gas emissions in percent of diesel fuel, equiv. energy basis. ( ) = kg eCO_2/L
Diesel fuel	100.0 (3.12)
Canola biodiesel	36.3 (1.25)
Soybean biodiesel	36.9 (1.27)
Animal fat biodiesel	8.3 (0.29)
Cooking oil biodiesel	24.5 (0.71)

Biodiesel has 90.6 % of the energy of diesel fuel (L/L).

[200]Levelton Engineering Ltd. and $(S\&T)^2$. 2002. Assessment of Biodiesel and Ethanol Diesel Blends, Greenhouse Gas Emissions, Exhaust Emissions, and Policy Issues. Report to Natural Resources Canada, Ottawa, ON K1A 0E4.

These are the GHG emissions which would apply if biodiesel were to be used as a renewable fuel. If canola were to be used primarily as a lubricity improvement agent, different calculations would be required. For an initial assessment, Hertz et al. (2001)[201] assumed:

- addition of 0.5% canola biodiesel to conventional diesel fuel,
- a fuel efficiency improvement of 4%,
- fuel savings of 27 kg CO_2 equivalents/L of fuel for a large truck,
- application to all diesel fuel used for transportation in Canada in 1999 (22,171 billion L).

Total greenhouse gas emissions savings were calculated to be 2.86 million tonnes of CO_2 equivalents based on a total fuel savings of 4.1% compared to the situation without biodiesel addition. The *profit* from these savings in GHG emissions was estimated to be \$279/tonne of CO_2 equivalents saved.

6.3.4 Current Research and Gaps in Research

The approach used by Levelton and (S&T)^2 (2002)[202] was to examine each stage in the production cycle from crop production through to biodiesel production and use in vehicles.

6.3.4.1 Oilseed crop production

Total production of canola and soybeans is shown in Table 5 for 2000, 2001 and 2002. This table also shows potential total oil production and compares this with total final demand for diesel fuel in 2000. It is important to note that the actual production of vegetable oil in Canada is considerably less than the potential shown in Table 5, since much of the canola crop is exported as raw unprocessed seed.

It is clear that the present diesel fuel demand far outstrips the ability of some fraction of current vegetable oil production, or potential production, to provide diesel engine fuel requirements. Thus biodiesel produced from these raw materials, plus some fraction of animal fat production, would need to be targeted at niche markets or targeted at meeting lubricity requirements of the diesel fuel market.

[201]Hertz, B. Button, R., Coxworth, E. and Gray, R. 2001. Biodiesel fuel additives/lubricants to improve diesel fuel use efficiency and reduce engine wear. Prairie Sustainable Agriculture Development Project (Prairie SARD), University of Saskatchewan, Saskatoon, SK. Available from E. Coxworth, Saskatoon, SK S7H 0J3.

[202]Levelton Engineering Ltd. and (S&T)^2. 2002. Assessment of Biodiesel and Ethanol Diesel Blends, Greenhouse Gas Emissions, Exhaust Emissions, and Policy Issues. Report to Natural Resources Canada, Ottawa, ON K1A 0E4.

Table 5. Production of main oilseeds and potential vegetable oil production in Canada for three years. Comparison with demand for diesel fuel. Production in millions of tonnes.

Crop or Fuel	2000 seed	2000 oil		2001 seed	2001 oil		2002 seed	2002 oil
Canola	7.1	2.8		4.9	2		3.6	1.4
Soybean	2.7	0.5		1.6	0.3		2.3	0.4
Total oil potential	NA	3.3		NA	2.3		NA	1.8
Diesel fuel	NA	19.5		NA	NA		NA	NA
Veg. oil (% of diesel)	NA	17%		NA	NA		NA	NA

NA = not applicable

Agroforestry approaches to oilseed production - Reaney (personal communication to E. Coxworth, November, 2002 and February, 2003) has suggested that chokecherries, a common wild fruit production shrub on the prairies, may have a surprisingly high seed oil production and fermentable carbohydrate production. Chokecherries have been reported to give yields of fruit as high as 15 t/ha (fresh basis). The fruit could be processed to yield 1800 kg carbohydrate for fermentation to ethanol. The carbohydrates are glucose, fructose and sorbitol. The sorbitol can be converted to glucose by use of a single enzyme. For comparison, a typical wheat crop of 2,800 kg/ha would yield 1,960 kg of carbohydrate in the form of starch suitable for fermentation to ethanol. The seed contained in the fruit could be a source of vegetable oil. The seed yield is 2,250 kg. Based on 30% oil, the oil yield would be 675 kg/ha. A typical canola crop (1,300 kg/ha) would yield 546 kg of oil per hectare.

Reaney stressed that chokecherries are at a very early stage of development as an industrial crop but clearly they (and likely other hardy perennial and woody species) should be studied and developed further. The initial results suggest that hardy northern perennial species have the potential to outperform annual crops now under cultivation.

Chokecherries can be used as a shelterbelt species to protect fields against the effects of drought and high winds. The Shelterbelt Centre of PFRA at Indian Head, Saskatchewan is investigating methods to select for high berry production. The Horticulture Department of the University of Saskatchewan has a long-standing program of development of fruit production, including chokecherries. Stumborg (personal communication to E. Coxworth, March, 2003) noted that there may be interesting nutraceuticals (e.g. flavonoids) in chokecherries.

Research gap " Further investigate chokecherry fruit production and seed processing methods with regard to the potential role of chokecherries in oilseed production. Check for other perennial crop species with potential as vegetable oil crops.

Mitigation of drought effects on oilseed production - The effects of drought on canola production were particularly evident in 2002 (see Table 5). Reaney (2002)[203] suggested that *Brassica carinata* is a new species for production of canola-type oilseed that shows great potential in terms of greater drought resistance than conventional canola species.

In addition, cropping system experiments at Indian Head, Saskatchewan, found that use of zero till for flaxseed production considerably reduced the yield loss during drought years compared to production employing conventional tillage crop production (Zentner et al., 1999).[204]

Research gap " Several *Brassica* species are being developed which are reported to be more heat and drought tolerant than conventional canola. It would be interesting to compare yields under drought conditions of these crops, with or without a zero tillage crop production system, to conventional canola.

6.3.4.2 Nitrous oxide emissions from crop production

Nitrous oxide emissions from soils were found to be the largest single source of greenhouse gas emissions from the production of canola biodiesel and soybean biodiesel (Levelton and $(S\&T)^2$).[205] Experiments are underway in Saskatchewan (Lemke et al. at SPARC, AAFC, Swift Current, Saskatchewan) to measure nitrous oxide emissions from canola, and at Guelph, Ontario (Claudia Wagner-Riddle, University of Guelph) to measure nitrous oxide emissions from soybean production. Both research groups are examining various methods to manage crop production to reduce nitrous oxide emissions. The Saskatchewan studies experienced everything from drought to excessive moisture during the three years of studies at four sites. Thus these results will give information about nitrous oxide emissions per tonne of canola under a variety of growing conditions and methods of crop production.

Research gap " As the above results are obtained, it should be possible to determine the effects of various crop management methods, and weather effects, on nitrous oxide emissions from canola and from soybeans. These results could then be used to determine the overall effects on greenhouse gas emissions from production of canola biodiesel and soybean biodiesel. Levelton and $(S\&T)^2$ (2002)[206] have employed a computer program (GHGenius) to determine the effects of changes in nitrous oxide emissions on total GHG emissions from biodiesel production from oilseeds.

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[203]Reaney, M. 2002. Success stories in the biodiesel business. ABIC Conference, Saskatoon, SK. Available from AgWest Biotech, Saskatoon, SK.

[204]Zentner, R.P., Lafond, G.P., Derksen, D.A., Wall, D.D., Geremia, R. and Blomert, B.J. 1999. The influence of conservation tillage on economic returns and riskiness of cropping systems in the thin Black soil zone. Proceedings Soil & Crops '99, Feb. 25-26, Saskatoon, SK, pp. 98-108. Extension Division, Univ. of Sask., Saskatoon, SK S7N 5C8.

[205]Levelton Engineering Ltd. and $(S\&T)^2$. 2002. Assessment of Biodiesel and Ethanol Diesel Blends, Greenhouse Gas Emissions, Exhaust Emissions, and Policy Issues. Report to Natural Resources Canada, Ottawa, ON K1A 0E4.

[206]Levelton Engineering Ltd. and $(S\&T)^2$. 2002. Assessment of Biodiesel and Ethanol Diesel Blends, Greenhouse Gas Emissions, Exhaust Emissions, and Policy Issues. Report to Natural Resources Canada, Ottawa, ON K1A 0E4.

6.3.4.3 Innovations to improve economic returns to farmers

Dale Murray of Oakville, Manitoba, has found a method to grow canola that has improved his net returns by \$40/ac (\$99/ha)(Bourdeau'Hui, 2002).[207] Murray has tested growing canola on 22" rows (56 cm rows). The canola plants branch out over the growing season to fill the spaces between the rows. However, there is much more air movement between the rows as the plants grow, which greatly reduces the need for fungicide to control diseases. If conditions are right, Murray may be able to avoid fungicide use. In addition, in some years, herbicide use can be cut also. Other savings are in seed costs and seed treatment costs. Some extra fuel and labor may be needed some years.

One reviewer questioned whether canola would have enough significant compensatory growth to yield as much in wide-row spacing as in conventional row spacing. The Murray's have three years yield data which should aid in evaluating this radical approach to canola production.

Research gap " The net income increase potential is so large with this innovative way to grow canola, that it may be worthwhile to conduct replicated trials at several locations to determine the potential to use this innovation in growing canola.

The McLeod Harvest system has been tried with canola and with flaxseed. This new approach to harvesting crops collects seed, chaff and weed seeds together (see the ethanol section, 6.2 for more details). The feed value of the millings (the mixture of chaff, broken crop seed and weed seeds) from both canola and flaxseed was quite high. Both millings contained 6 to 7% oil (Racz and Christensen, 1999).[208] This may be of value in reducing methane eructation in animals using this feed. This will be discussed in section 6.4.

6.3.4.4 Biotechnology applications to the development of oilseed crops

A recent issue of the PBI Bulletin describes research on designing canola and soybeans to have fatty acid compositions more suited to various industrial applications (PBI Bulletin, 2002).[209] While some of these transformations were designed for higher value applications than fuel, there may be applications to biodiesel as well. Canola oil with lower contents of double or triple unsaturated fatty acids (high oleic acid varieties) would be expected to be less likely to be unstable (autoxidize) in the presence of air during long storage. This would likely also be the case with biodiesel made from such high oleic acid types.

A reviewer has suggested that high molecular weight oils, e.g. containing long chain fatty acids (> C18), require less methanol, per unit of oil, to produce the methyl esters. This could improve the economics and life cycle effects of biodiesel.

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[207] Bourdeau'Hui, C. 2002. Row-crop canola looks OK. Grainews, October issue, p. 40.

[208] Racz, V.J. and Christensen, D.A. 1999. Nutritive value and utility of grain milling byproduct from the McLeod Harvest System. Dept. of Anim. and Poultry Sci., Univ. of Sask., Saskatoon, SK.

[209] PBI Bulletin. 2002. Issue 1. Diversification of Canadian oilseeds. Part 1: Adding value to the oil. Plant Biotechnology Institute, NRCC, Saskatoon, SK S7N 0W9.

Higher oil content oil seeds are also possible via conventional as well as transgenic methods. Methods are also being developed to improve the feed value of the oilseed meal left after the oil is extracted. Selvaraj (2002)[210] is developing methods to reduce the levels of sinapine in canola. Sinapine is a phenolic compound that reduces palatability and digestion by animals. Selvaraj has succeeded in reducing levels to less than 20% of the original content by use of transgenic methods. This is expected to increase the economic value of the meal and market potential. Georges (2002)[211] has found methods to reduce phytate content in canola, using both transgenic and mutagenic methods. The phytate levels in conventional canola seed meal has limited its value for certain protein markets, such as aquaculture. Lower levels of phytate would open up several feed markets for more use of canola meal and perhaps greater economic value.

6.3.4.5 Oilseed processing into oil and meal

Biotechnology methods to improve the feed value of the meal (see preceding section) represent methods to improve the economic value of the meal which do not require new investment on the part of the oilseed operation. Reaney (1994)[212] has described methods to improve the oilseed extraction process by such methods as front end dehulling, use of hydrocyclones and aqueous processing. Reaney (personal communication, February, 2003) has reported that oilseed processing using solvent extraction consumes significant amounts of energy. Processes which simply crush the seed use substantially less energy while producing a meal with an oil content between 4 and 9%. This high oil-content meal might be used in ruminant animal diets to enhance conjugated linoleic acid (CLA) in meat and meal, while reducing methane eructation.

In Alberta, Temelli (2002) is examining extraction, fractionation and reactions of lipids using supercritical carbon dioxide.[213]

Professor H.L. Classen, Animal and Poultry Science Department, University of Saskatchewan, has developed a method to extract a protein concentrate from canola meal (personal communication to E. Coxworth, May 26th, 2003). A company, MCN, has been formed to commercially develop the process. The process is at the pilot plant stage of development. One of the potential markets for the protein concentrate is aquaculture.

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[210] Selvaraj, G. 2002. Adding value to canola by reducing sinapine in the meal. PBI Bulletin issue 2. pp. 2-3. Plant Biotechnology Institute, NRCC, Saskatoon, SK S7N 0W9.

[211] Georges, F. 2002. Improving canola-development of low phytate canola. PBI Bulletin issue 2. pp. 3-4. Plant Biotechnology Institute, NRCC, Saskatoon, SK S7N 0W9.

[212] Reaney, M. 1994. The future of biooils. Biooils Symposium, Saskatoon, SK., March 3-4. Saskatchewan Canola Development Commission, Saskatoon, SK.

[213] Temelli, F. 2002. Extraction, fractionation and reactions of lipids using supercritical CO_2. ICAR Project: 22221217.

6.3.4.6 Production of biodiesel

There are three basic routes to biodiesel production:

- Base catalyst transesterification of a vegetable oil or animal fat with methanol,
- Directed acid catalyzed esterification of the oil with methanol,
- Conversion of the oil to fatty acids, and then to methyl esters with acid catalysts.

The products from these reactions are the methyl esters of the fatty acids originally present in the fat or oil and glycerine. Markets and new uses for the glycerine are described in the platform chemical section of this report (section 6.9).

Details of one of the main processing routes to biodiesel (the Lurgi process) are described in Levelton and $(S\&T)^2$ (2002).[214] An example of a new process, the BIOX process, was recently discovered by David Boocock at the University of Toronto (Boocock et al, 1996; Boocock et al., 1998).[215] In this innovation, an inert solvent, such as tetrahydrofuran, is used that generates an oil-rich single phase containing the oil, methanol and the catalyst. The previous Lurgi process involves two immiscible phases which slowly react together to form the methyl esters. In the Boocock process, reaction is complete in ten minutes, compared to several hours reaction time in previous processes. The acid catalyzed process, needed for oils containing significant amounts of free fatty acids, is complete in minutes instead of hours by previous processes. The new process lends itself to continuous process methods, and this is being developed by the BIOX Corporation near Toronto.

The inert solvent in the BIOX process is recovered by distillation and this increases the energy costs for the BIOX process compared to the Lurgi process.

Reaney (2002)[216] has discovered that the recycled alkali transesterification catalyst (containing crude glycerol and alkali) from producing biodiesel can be reacted with a linoleate rich triglyceride to conjugate the linoleic acid double bonds. The product is a conjugated linoleic acid (CLA) which other studies has shown to be a very desirable nutraceutical. This new process makes CLA and biodiesel affordable. The process is being developed by Bioriginal Food and Science Corporation in Saskatoon, Sask.

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[214] Levelton Engineering Ltd. and $(S\&T)^2$. 2002. Assessment of Biodiesel and Ethanol Diesel Blends, Greenhouse Gas Emissions, Exhaust Emissions, and Policy Issues. Report to Natural Resources Canada, Ottawa, ON K1A 0E4.

[215] Boocock, D.G.B., Konar, S.K., Mao, V. and Sidi, H. 1996. Fast one-phase oil-rich processes for the preparation of vegetable oil methyl esters. Biomass and Bioenergy 11: 43-50; Boocock, D.G.B., Konar, S.K., Mao, V., Lee, C. and Buligan, S. 1998. Fast formation of high-purity methyl esters from vegetable oils. JAOCS 75: 1167-1172.

[216] Reaney, M.J.T. 2002. Method for commercial preparation of conjugated linoleic acid using recycled alkali transesterification catalyst. US Patent 6,409,649. See also US Patents 6,414,171 and 6,420,577.

6.3.4.7 Application of biodiesel as a fuel or lubricity improvement agent for diesel fuel

Two very different applications are possible for biodiesel:

- As a renewable fuel added in some significant proportion, frequently 20% in summer, 5% in winter, to diesel fuel. The objective is to reduce air pollutants and to reduce greenhouse gas emissions.
- As a lubricity improvement agent added to diesel fuel at less than 2%.

Canadian petroleum diesel fuel was found to have much poorer lubricity than diesel fuels from other countries (Hertz, 2001)[217], (Reaney, 2002)[218] based on a world-wide survey of winter diesel fuel quality conducted by Paramins Fuel Additives, Exxon Chemicals Limited, Abingdon, Oxfordshire, UK, for the years 1997-1999. Tests in Saskatchewan with addition of low levels of various biodiesel materials found that canola biodiesel improved lubricity more than biodiesel made from other oils such as linseed, sunflower or rapeseed (Munson et al., 1999).[219] Vehicle trials were conducted with a VW New Beetle TDI diesel-powered vehicle. Canola biodiesel was added at a 0.5% level to commercial diesel fuel purchased at the pump. Fuel efficiency was improved by 5.8% and engine wear was reduced by 51%.

The total amount of biodiesel estimated to be required to effect these potential fuel efficiency improvements to the entire diesel vehicle fleet in Canada was quite small, some 115 million litres, or about 3% of total canola and soybean theoretical oil production in 2000. This would still leave considerable amounts of biodiesel for use in various niche markets.

Research gap " Further vehicle trials are needed with a large truck, in both urban and highway driving conditions, to confirm that these fuel savings and reductions in engine wear can be achieved in large vehicles. Trials are also needed using low sulfur diesel fuel, due to come into use in 2005. Laboratory trials have found that one percent addition of canola biodiesel will meet the lubricity needs of Canadian low sulfur diesel fuel (R. Button, Saskatchewan Canola Development Commission, personal communication to E. Coxworth, 2002). Further information is also needed on methods being developed by various oil companies to add derivatives to low sulfur diesel fuel to meet the lubricity and other performance requirements.

Stumborg (personal communication to E. Coxworth, 2003) cautioned that fuel savings achieved with addition of biodiesel to diesel fuel used in a TDI small automobile may be more than that seen in a modern large truck with a Detroit or Cummins electronically controlled unit injector engine. Trials with trucks should employ both summer and winter diesel fuel.

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[217]Hertz, B. 2001. Extending diesel fuel engine wear life with canola fuel additives. Crop Production Week Seminar, Saskatoon, SK., January 10th. Available from B. Hertz, Mechanical Engineering Department, University of Saskatchewan, Saskatoon, SK.

[218]Reaney, M. 2002. Success stories in the biodiesel business. ABIC Conference, Saskatoon, SK. Available from AgWest Biotech, Saskatoon, SK.

[219]Munson, J.W., Hertz, P.B., Dalai, A.K. and Reaney, M.J. 1999. Lubricity survey of low-level biodiesel fuel additives using the Munson ROCLE bench test. SAE technical paper 1999-01-3590.

Reaney (personal comments to E. Coxworth, 2003) has stated that the best approach might be to use various bioproducts to help optimize diesel fuel performance. Thus some conventional lubricity additives might be added, plus canola biodiesel, to optimize engine performance and fuel efficiency. A variety of other bioproducts might also be employed to enhance such fuel properties as cetane nimner, freezing point depression and oxygen content. Other bioproducts might be used as detergents, antifreeze deicers, crystallization inhibitors, antioxidants and compounds to reduce NOx emissions. Also worth trying would be the "super cetane" obtained by hydrotreating poor quality vegetable oils or tall oil, a byproduct of the pulping of pine and Douglas fir. The hydrocarbons obtained by this process have very high cetane numbers (Stumborg comments to E. Coxworth, 2003)

6.3.4.8 Integration of biodiesel use with a shift to more fuel-efficient diesel vehicles

Reaney (personal communication to E. Coxworth, 2002) emphasized that simple management of bus and truck fleets can often reduce fuel consumption by 5 to 10%. Such low cost methods to save fuel and money might provide the capital needed to invest in other, more expensive, methods to reduce fuel consumption and reduce air pollution.

For an example of new technology methods, there has been a considerable increase in the development of diesel-electric and gasoline-electric hybrid vehicles. Diesel-electric hybrid buses are starting to be sold in the USA. In this new type of engine system, a diesel engine is coupled with a large battery system. A generator driven by the combustion engine charges the battery pack. Electric motors in the wheels provides all the power in a series design. In a parallel design system, the combustion engine both drives the wheels and charges the battery pack (see www.allisontransmission.com). The battery pack provides extra power during acceleration. During braking, the battery pack is recharged by using the electric motors in the wheels as generators.

Such hybrid engine systems have been found to dramatically reduce air pollution in urban stop and go drive situations. Bus trials in Brazil measured a 90% drop in particulate matter, a decrease in carbon monoxide of 60-70%, and a reduction in nitrogen oxides of 25-30% (Clean Fuels and Electric Vehicles Report (CFEVR), 2002a).[220] Trials in Oregon with hybrid diesel-electric buses recorded a 60% improvement in fuel efficiency (CFEVR, 2002b).[221] Employment of diesel-electric hybrid systems coupled with low sulfur diesel fuel provided a great reduction in particulate matter, since an exhaust treatment system could be employed to trap and destroy particulate matter (CFEVR, 2000).[222] Emissions as low as natural gas powered buses could be achieved. The life cycle costs of diesel-electric buses were more expensive than conventional buses, but less expensive than

[220]Clean Fuels and Electric Vehicles Report (CFEVR). 2002a. Four hybrid bus designs tested in Brazil. June issue, pp. 112-114.

[221]Clean Fuels and Electric Vehicles Report (CFEVR). 2002b. Two hybrid buses in Portland first in northwest U.S. June issue, pp. 117-118.

[222]Clean Fuels and Electric Vehicles Report (CFEVR). 2000. Diesel hybrid buses match natural gas emissions, says NAVC study. June issue, pp. 110-112.

natural gas powered buses (CFEVR, 2002c).[223] The main extra expense of the hybrid system was the batteries. Improvements in cold weather performance of batteries, plus a reduction in costs, are being investigated.

Canadian technology by Azure Dynamics is being used in demonstration trials with a Canada Post delivery truck (see www.azuredynamics.com).

The employment of gasoline-electric and diesel-electric hybrid vehicles was an important component of a plan to reduce Canada's GHG emissions from transportation by 2012 (below the Kyoto target) (Torrie et al., 2002).[224]

Research gap " Test the integration of biodiesel with the diesel-electric hybrid vehicle system to determine whether further improvements in fuel efficiency, reductions in air pollutants, and a further reduction in GHG emissions can be achieved. Check whether similar studies have been done in other countries.

6.3.5 R & D Analysis

6.3.5.1 Canadian Strengths

1. Canada has developed an effective team to conduct greenhouse gas, energy and economic analyses of renewable fuels (Levelton and (S&T)^2) in the Vancouver area of BC. The Vancouver area is also the home of several hybrid motor design companies (Azure Dynamics, Railpower). Ballard fuel cells will also be most likely placed as part of hybrid vehicle systems.

2. The Montreal area of Quebec is developing experience in producing biodiesel from animal fats and low value soybean oil. Rothsay/Laurenco, a Maple Leaf Foods subsidiary located in Ville Sainte-Catherine, specializes in the recycling of agro-industry wastes. It will supply the biodiesel which will be used in performance trials in the bus fleet (Montreal).

3. The Saskatoon area of Saskatchewan has a cluster of groups and individuals experienced in:
   – Oilseed crop development (AAFC Research Centre and the University of Saskatchewan),
   – Oilseed processing by the POS Pilot Plant Corporation,
   – Oilseed processing into biodiesel (AAFC Research Centre, the University of Saskatchewan and the Bioprocessing Centre, Innovation Place),
   – Lubricity effects of biodiesel and vegetable oils in diesel engines (Mechanical Engineering Department, University of Saskatchewan),
   – Biotechnology methods to design and improve oilseed crops are being developed by the

[223]Clean Fuels and Electric Vehicles Report (CFEVR). 2002c. Heavy hybrid buses cheaper than natural gas, costlier than diesel. September issue, pp. 109-112.

[224]Torrie, R., Parfett, R. and Steenhof, P. 2002. Kyoto and Beyond: the Low Emission Path to Innovation and Efficiency. Available from Torrie Smith and Associates, Ottawa, Ontario (www.torriesmith.com).

Plant Biotechnology Institute of NRCC,
- Commodity group support is being led by the Saskatchewan Canola Development Commission,
- One company, Bioriginal Food and Science Corporation, is coupling biodiesel manufacture with the synthesis of conjugated linoleic acid (a desirable nutraceutical) using glycerol (a byproduct of biodiesel production) as the solvent for the process,
- Another small company, Milligan Biotech, in Foam Lake, Saskatchewan, is producing canola biodiesel for application as a lubricity improvement agent in diesel fuel.

4. In Ontario, the University of Toronto and BIOX are developing new technology for fast production of biodiesel from animal fats and waste cooking oils.

5. In Ontario, The Ontario Soybean Growers' Marketing Board has supported a number of studies on application of soy biodiesel in various special niche markets, such as underground mines (Bee, 1998).[225]

6. Nitrous oxide studies are being conducted by the Semiarid Prairie Agricultural Research Centre (SPARC), AAFC, Swift Current, Saskatchewan, in collaboration with other AAFC research stations, the University of Saskatchewan, and the Prairie Agriculture Machinery Institute. In eastern Canada, the University of Guelph in Ontario is conducting experiments to determine management methods to reduce nitrous oxide emissions from production of soybeans, corn and wheat.

6.3.5.2 and 6.3.5.3 R & D Challenges and Gaps in Research

These topics have been discussed in the course of describing current research (6.3.4). Numerous examples were found of gaps in present research which could lead to better products and greater application in the Canadian economy. There did not appear to be specific structural bottlenecks which would inhibit future development.

6.3.5.4 Themes for Future Research

There is a need to work closely with the liquid fuel industry and bus and truck fleets in the future to ensure successful application of biodiesel technology into widespread use. At the same time as this integration is going on, research and development studies could start filling in the gaps in R&D identified in section 6.3.4.

General themes in R&D centre around:
- further development of the crops, including better drought resistance in western Canada,
- obtaining information on nitrous oxide emissions and methods to reduce them,
- working with farmers to improve farm net income from oilseed production,
- obtaining further information on low level use of biodiesel to improve fuel efficiency and

[225] Bee, K. 1998. Biodiesel update. Presented to the Canadian Renewable Fuels Association Annual Meeting, June 11th.

reduce engine wear,
- using the information from these R&D results to develop the biodiesel industry,
- obtaining information on integration of biodiesel into advanced engine systems, such as diesel-electric hybrids.

6.3.5.5 Specific Recommendations

Two very different applications for biodiesel appear to exist:
- use as a renewable fuel in niche markets,
- general use as an agent to improve the lubricity of diesel fuel to improve fuel efficiency and reduce engine wear.

Research studies should be directed at both these types of markets to determine the most promising application strategies for each market type.

Canadian diesel fuel may be a special case, particularly after low sulfur diesel is introduced, where collaboration with the liquid fuel industry could be very helpful, both to help solve potential problems in that industry and help improve the profitability of the trucking industry in the country.

The development of new drive systems for diesel vehicles, particularly diesel-electric hybrids drive systems, needs to be watched closely. Integration of biodiesel with such new drive systems, with their much greater fuel efficiency, would enable the biodiesel component of the fuel to provide more transport services for the same amount of biodiesel consumed.

6.4 Methane and Other Gasification Routes to Biofuels

6.4.1 Sector Overview

This section discusses several different approaches to providing gaseous biofuels from agricultural raw materials. The best known of these biofuels is biogas (a mixture of methane with lesser amounts of carbon dioxide and trace amounts of other gases), produced by anaerobic digestion of animal manures or other wet organic wastes, such as sewage. There have been many studies on methods to produce biogas from digestion of animal manures. Capital costs and performance in cold weather are problems still under investigation. Biogas is routinely produced at a number of sewage treatment plants across Canada.

Methane cannot only be a gaseous fuel, but, if it is allowed to escape into the atmosphere, can also be a potent GHG, with 21 times the global warming potential of carbon dioxide. Landfill sites are some of the principal sources of methane emissions in Canada due to anaerobic decomposition of organic wastes. There are a number of opportunities to capture methane gas from landfill sites and use it for heat or electricity production. This capture and utilization of methane, otherwise escaping from landfill sites, turns a problem into an asset.

The development of more biodegradable plastics could lead to more evolution of methane, if these biodegradable plastics end up in landfills. More capture of methane gas from landfill sites could become an important part of the strategy for development of these new bioproducts to avoid a high GHG emissions penalty.

Methane is evolved by the digestion processes of ruminant animals (enteric fermentation) and is vented into the atmosphere (eructation). This eructation process in ruminant animals is one of the principal sources of GHG emissions from the agricultural sector of the Canadian economy. A number of studies are trying to find cost effective and stable methods to reduce methane eructation from ruminant animals and which methods do not reduce the productivity or profitability of the animal and do not harm their health. One such method to be discussed also increases the nutraceutical content of the meat and milk of the ruminant animals.

Other gaseous fuels can also be produced from agricultural raw materials, such as straw, by controlled partial oxidation or steam oxidation. The gas mixture is principally composed of carbon monoxide and hydrogen. Routes to produce ethanol from this synthesis gas are discussed in the ethanol sector of this report (6.2). It is possible to use this gas to produce heat for buildings also. In one process called close coupled gasification/combustion, the gaseous fuel mixture, produced by controlled oxidation at a fairly modest combustion temperature, is immediately captured and burned in a second, higher temperature combustion unit to produce heat for use in a barn or small business. Total fuel efficiency is reported to be high and emissions of air pollutants low. One example of this system, being developed in Manitoba, is discussed in this report.

6.4.2 Key Opportunities

Capture of methane gas from landfill sites and its use to provide fuel to power stations or other markets for the fuel is already being done at a number of sites. A major program to capture methane from a number of additional landfill sites across Canada has just been announced by a Canadian energy company. There appears to be the potential for substantial reductions in GHG emissions by this activity.

There are a number of studies in many countries examining methods to produce methane biogas from livestock manure. Capital costs and operating problems in cold weather have inhibited much application of this technology on Canadian farms. One promising operation has been started at a Hutterite colony in Alberta.

Another approach to livestock manure treatment may have as great an application potential. In this process, developed by System Ecotechnologies Inc. in Saskatoon, SK., hog manure slurry is treated sequentially with two simple, non-toxic inorganic chemicals, to precipitate solids. Ammonia can then be recovered from the clear liquid and used as a fertilizer. The treated water is then recycled to the barn for recovering more hog manure. While this method does not recover biogas by anaerobic treatment, the overall manure treatment costs are competitive with the conventional lagoon storage systems for hog manure treatment. Since no lagoon is involved, methane emissions are expected to be much lower in the new system.

Feeding vegetable oils, such as canola oil, to ruminant animals has been shown to reduce methane eructation and increase the levels of conjugated linoleic acid (CLA), a desirable nutraceutical in the meat and milk. Studies on feeding vegetable oils to ruminant animals are being conducted at the Lethbridge Research Centre of AAFC. This technology may be one method to reduce methane eructation from ruminant animals at the same time as the health benefits of the meat and milk are increased. Other methods to improve the productivity of ruminant animals may have greater general applicability but do not potentially improve the economic and health value of the meat or milk produced by the animal.

Changes in the rumen microflora, by deliberate inoculation with selected digestion system microorganisms, have been found in studies in the UK to reduce methane eructation (Nelson et al., 2000).[226] This method has been calculated to provide a strategy to greatly reduce methane emissions from the European livestock industry, if it were to be widely adopted.

Close coupled gasification/combustion systems may offer bioenergy applications for farms and small industrial situations.

6.4.3 Potential Impact on GHG Emissions

6.4.3.1 Landfill methane capture opportunity

Methane is an active greenhouse gas with a global warming potential (GWP) some 21 times the GWP of carbon dioxide. It is evolved in considerable amounts from landfill sites across Canada from anaerobic decomposition of biomaterials such as waste food, waste paper and garden wastes. Methods are available to capture this landfill methane and, if a power station or other source of demand is nearby, burn it to generate heat or generate electricity.

One criticism of the development of biodegradable bioproducts is that such materials would easily generate methane in landfills. If the methane was not captured and converted into heat or electricity, this methane evolution would generate substantial amounts of GHG emissions attributed to the bioproduct. In comparison, non-biodegradable plastics, such as polyethylene, would not biodegrade in landfills and might therefore have a lower lifecycle GHG emission potential than biodegradable plastics. Thus capture of methane from landfill sites would be an important part of the development strategy for biodegradable products that could end up in landfill sites.

With regard to the capture of landfill methane gas and the GHG emissions reduction benefits, a recent study for Environment Canada by Conestoga-Rovers & Associates and The Delphi Group (2000)[227] concluded that:

- landfills offer the opportunity to reduce methane emissions, expressed as carbon dioxide

[226]Nelson, N., Valdes, C., Hillman, K., McEwan, N.R., Wallace, R.J., and Newbold, C.J. 2000. Effect of a methane oxidizing bacterium isolated from the gut of piglets on methane production in Rusitec. Reproduction Nutrition Development. 40 (2): 212.

[227]Conestoga-Rovers & Associates and The Delphi Group. 2000. Identification of Potential Landfill Sites for Additional Gas Recovery and Utilization in Canada. Available from Environment Canada, Hull, QC K1A 0H3.

equivalents (eCO_2), by 141 million tonnes over the period 2000-2020, or about 7 million tonnes per year, and
- only about 25% of landfill gas is captured/flared or utilized at the present time, leaving large opportunities for further capture and utilization.

Suncor (McArthur and Salaff, 2000)[228] has recently announced that it has signed a five-year agreement with Conestoga-Rovers to capture landfill methane to generate electricity.

A study in New York City (Powell, 2002)[229] found that organic matter waste has risen per unit of garbage between 1920 and 1990, increasing the potential for GHG emissions (mostly methane) considerably. If there is a trend to greater production of biodegradable packaging the potential for greater methane emissions could increase. Thus the development of biodegradable biomaterials will need to be coupled with greater capture of landfill methane. Composting of recycled/waste biomaterials could also decrease the potential for GHG emissions.

6.4.3.2 Reduction of methane emissions (biogas) from livestock manure

There has long been an interest in recovering methane fuel (biogas) by anaerobic digestion of livestock manure. Cost-effective methods in Canada for farm-scale production has not been easy to find. A recent review of prospects for recovery of methane by digestion of manure in eastern Canada concluded that, although the potential was quite high, the capital costs were so high that application on average sized farms was unlikely (Helwig et al., 2002).[230] Helwig et al., (2002) concluded that 16 million GJ (16 PJ) of bioenergy could in theory be produced from manure biogas in eastern Canada, which could reduce GHG emissions by about 1.2 million tonnes of carbon dioxide equivalents (eCO_2), assuming biogas replaced heating oil.

An integrated system to produce heat, electricity and recycled water by anaerobic digestion of animal manures has recently been constructed at a Hutterite colony in Alberta (MacArthur, 2003).[231] This system was based on European technology and has been adapted for application in western Canada by BioGem Power Systems. BioGem bought the North American rights for the technology from a European company that already has 130 biogas plants in operation around the world. The biogas produced by anaerobic digestion is cleaned to remove hydrogen sulfide and then is used as the fuel in a piston engine. The engine drives a generator to produce electricity. Waste heat from the motor is captured to provide heat for poultry and hog barns. The electricity generated is sold at a premium for peaking power into the Alberta grid. Recycled water is an important part of the system. Drought in the last several years in Alberta has increased the importance of manure treatment

[228] McArthur, S. and Salaff, S. 2000. Suncor enters landfill gas business. IPPSO Facto 14: 28.

[229] Powell, K. 2002. Trash trends. Nature 419: 891.

[230] Helwig, T., Jannasch, R., Samson, R., DeMaio, A. and Caumartin, D. 2002. Agricultural Biomass Residue Inventories and Conversion Systems for Energy Production in Eastern Canada. Report to Natural Resources Canada, Ste. Anne de Bellevue, QC H9X 3V9.

[231] MacArthur, M. 2003. Farm lights up on manure. Manure as power source saves money. Western Producer, January 16, pp. 1, 10.

systems that recycle and clean water, allowing it to be reused for livestock.

The system installed at the Iron Creek Hutterite colony near Viking, Alberta has:

- eliminated the $100,000 manure injection cost,
- eliminated the colony's $250,000 electricity bill,
- reduced the $60,000 water bill,
- cut the heating bill for the colony in half,
- earned $110,000 selling peaking power to the electricity power grid,
- been expected to recover the $2 million cost in about eight years.

The water purification system (delivering about 5 gallons/minute) is not yet working to capacity. When it is operating at full capacity, it will deliver about 20 to 25 gallons per minute, about four times as much as at present, and about as much as a prairie farm well. Water recycling may be one of the most important benefits of the manure treatment system.

It may be too early in the testing of this manure treatment system in western Canada to calculate the GHG emissions reduction potential of the BioGem technology, but preliminary estimates would be of interest.

Many bioproduct manufacturing processes may generate waste waters with considerable biological oxygen demand (BOD) potential. Ethanol production from cellulosic feedstocks via fermentation routes is an example of a process that would generate considerable amounts of waste water requiring treatment (Wilkie et al., 2000).[232] Anaerobic digestion may be needed to reduce this BOD potential to acceptable levels. Such digestion processes would generate methane which could be used as a fuel for some of the energy requirements of the original bioproduct manufacturing process.

6.4.3.3 Suppression of methane eructation by ruminant animals

A recent review of methods to reduce methane emissions from ruminant animals (Mathison et al., 1998)[233] concluded that:

- the most practical way to reduce methane emissions per unit of product is to increase productivity level,
- future research should examine the development of new products for reducing protozoal numbers in the rumen,
- examine the use of bacteriocins or other compounds which specifically target methaneogenic bacteria,
- while dietary lipid (e.g. canola oil) at the 4% level can reduce methane emissions by 33%, the extra cost of these ration ingredients does not make them viable for reducing methane emissions.

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[232]Wilkie, A.C., Riedesel, K.J. and Owens, J.M. 2000. Stillage characteristics and anaerobic treatment of ethanol stillage from conventional and cellulosic feedstocks. Biomass Bioenergy. 19: 63-102.

[233]Mathison, G.W., Okine, E.K., McAllister, T.A., Dong, Y., Galbraith, J. and Dmytruk, O.I.N. 1998. Reducing methane emissions from ruminant animals. J. Appl. Anim. Res. 14: 1-28.

Methane is evolved from the digestion processes of ruminant animals. This methane evolution is a significant source of greenhouse gases into the Canadian economy. In 1995, Jaques et al. (1997)[234] estimated that methane eructation (from enteric fermentation by ruminant animals) evolved about 720 thousand tonnes of methane or 15 million tonnes of eCO_2.

Feeding vegetable oils to ruminant animals increases CLA, a desirable nutraceutical.
Various methods are being developed to reduce this methane evolution (Janzen et al., 1998).[235] One method of interest as a potential bioproduct strategy involves feeding vegetable oils to ruminant animals, which suppresses methane eructation at the same time that the meat and milk of the animals contains more conjugated linoleic acid, a desirable nutraceutical (Ivan et al., 2001).[236] This greater nutritional value may help offset the extra costs of including the vegetable oils in the diet. It may be too early to estimate the methane reduction potential of this method.

However, it could be a large market for vegetable oils, if the extra cost can be justified on the basis of the extra food and nutraceutical value of the product.

Changing bacteria in the rumen to reduce methane eructation.
Studies at the Rowett Institute in Scotland found that introducing specific bacteria into the diet of sheep reduced their methane eructation by 17% (Coghlan, 2000).[237] If this technology was widely applied in Europe, it was estimated that a reduction in total methane emissions from the economy of 4 to 5% could be achieved. The specific methane oxidizing bacterium was isolated from the gut of piglets (Nelson et al., 2000).[238]

Other Gasification Processes from Biomass.
Close coupled gasification/combustion processes (CCGC) appear to offer considerable promise for generation of heat energy from biomass materials such as straw. A company in Manitoba (Vidir Machines) has employed technology developed by NRCCan and designed and built a system for heating applications for poultry barns, hog barns, and small industrial establishments (Siemens, 2002; Fallding, 2002).[239] Recent technological developments appear to have reduced concerns about methods to handle the ash from such materials. In addition, this new technology can achieve an

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[234] Jaques, A., Neitzert, F. and Boileau, P. 1997. Trends in Canada's Greenhouse Gas Emissions. Environment Canada, Ottawa, ON K1A 0H3.

[235] Janzen, H.H., Desjardins, R.L., Asselin, J.M.R. and Grace, B. 1998. The Health of Our Air. Publication 1981/E, Agriculture and Agri-Food Canada, Ottawa, ON K1A 0C5.

[236] Ivan, M., Mir, P.S., Koenig, K.M., Rode, L.M., Neill, T. and Mir, Z. 2001. Effects of dietary sunflower oil on rumen protozoa population and tissue concentration of conjugated linoleic acid in sheep. Small Ruminant Research. 41: 215-227.

[237] Coghlan, A. 2000. Why a change of diet is good for the environment. New Scientist, 15 April, p.6.

[238] Nelson, N., Valdes, J.P., Hillman, K., McEwan, N.R., Wallace, R.J. and Newbold, C.J. 2000. Effect of a methane oxidizing bacterium isolated from the gut of piglets on methane production in Rusitec. Reproduction Nutrition Development 40 (2): 212.

[239] Siemens, H. 2002. Straw heat saves big bucks for farmer. The Manitoba Co-operator, December 5, p. 33; Fallding, H. 2002. Manitoba chickens bask in heat from straw, Saskatoon. Star Phoenix, Dec. 3, p.C4.

impressive combustion efficiency (of the order of 85%). Air pollution problems are also greatly reduced with this new technology. The owner of the first poultry barn to install this straw close coupled gasification/combustion system has estimated that the new system will reduce his barn heating costs from a range of $50,000 to $60,000 to about $20,000 per year. The investment costs are expected to be paid off in less than 5 years.

The close coupled gasification/combustion system can also use wood waste or municipal garbage as the fuel. Both these raw materials are being considered by other groups interested in the Vidir technology.

6.4.4 Current Research (Includes Gaps in Research)

6.4.4.1 Landfill gas capture
Landfill methane capture has been a commercial process for some time. Concerns about greenhouse gas emissions have increased interest in further development of this process, leading to greater industrial activity.

6.4.4.2 Biogas production on farms
Cost effective methods to enable biogas production on farms is still under investigation. Masse and Croteau (1998)[240] in Quebec are studying sequencing batch bioreactor systems which can operate at lower temperatures than mesophylic or thermophylic systems. Helwig et al. (2002)[241] described a number of anaerobic digestion systems tested in Canada. One system in Ontario used anaerobic digestion to treat waste water from a pet food production plant. The key to successful operation was to insulate the building very well to maintain the temperature in the biodigester without excessive heat loss or the requirement for large amounts of the methane produced being required to be burned to keep the digester operating in cold weather.

The BioGem manure treatment system recently installed on a Hutterite colony in Alberta (McArthur, 2003)[242] warrants further investigation. It has been running long enough so that evaluation of the performance of the system, in terms of GHG emissions reduction, could be determined.

Research gap " Determine the GHG emissions reduction potential of the BioGem system in operation in Alberta.

Other processes than anaerobic digestion may offer potential to treat animal manures and reduce GHG emissions. For example, a simple system for liquid hog manure treatment has been developed

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[240]Masse, D. and Croteau, F. 1998. New technology of manure treatment. Page 57 of the Health of Our Air. Publication 1981/E, Agriculture and Agri-Food Canada, Ottawa, ON K1A 0C5.

[241]Helwig, T., Jannasch, R., Samson, R., DeMaio, A. and Caumartin, D. 2002. Agricultural Biomass Residue Inventories and Conversion Systems for Energy Production in Eastern Canada. Report to Natural Resources Canada, Ottawa, ON. Available from REAP-Canada, Ste. Anne de Bellevue, QC H9X 3V9.

[242]MacArthur, M. 2003. Farm light up on manure. Manure as power saves money. Western Producer, January 16, pp. 1, 10.

by Lakshman of System Ecotechnologies in Saskatoon (White, 2002; Ewins, 2000).[243] Hog manure slurry is treated in sequence with two inorganic, non-toxic chemicals. These create reactions that separate the solids from the liquids, eliminate the odours, and concentrate most of the nutrients in the solids. Ammonia is captured from the liquid phase and stored as aqueous ammonia. The water phase (ammonia removed) can then be recycled to the barns for use as wash water. The sulfur-rich solids can be used as a fertilizer. The aqueous ammonia solution can also be used as a fertilizer. Present costs of this process are about $3 per pig marketed, slightly less than the $3.60 spent per pig on lagoon storage and spreading the lagoon solution as fertilizer. This new type of manure treatment would be expected to substantially reduce methane emissions since no lagoon storage systems are involved.

Solid manure treatment systems are also being adopted by some hog operations. In the Pure Lean Hogs system, pigs are bedded in wood chips (Gompf, 2001).[244] The wood chips are periodically removed and composted. The compost is sold commercially in various retail outlets. Odors from this type of hog barn are reported to be much less than from conventional hog operations with slatted floors and slurry systems for removing manure.

At the University of Guelph, Claudia Wagner-Riddle and colleagues (2001)[245] are studying methane and nitrous oxide emissions from various methods of storing manure and the levels of methane and nitrous oxide in confinement facilities. The study is developing analytical tools to evaluate the most cost effective solutions to reduce greenhouse gas emissions.

Research gap " Can the analytical tools developed in the University of Guelph study be used to evaluate the reduction in nitrous oxide and methane from new systems such as described previously and determine the overall economics?

Some processes for anaerobic digestion may be more suited for waste water treatment from wet bioproduct manufacturing processes than for farm manure treatment. Waste water treatment could be an important cost in some processes.

6.4.4.3 Production of methane by digestion processes in ruminant animals

Jamie Newbold and fellow workers at the Rowett Research Institute in Scotland have found that introducing specific bacteria into rumen fluid caused a reduction in the evolution of methane from the rumen fluid (Coghlan, 2002).[246] More of the carbon was evolved as carbon dioxide, whose global warming potential (GWP) is considerably less than methane. The best bacteria found, *Brevibacillus parabrevis*, converted half the methane in rumen fluid to carbon dioxide. Newbold also added these specific bacteria to the diets of sheep. Methane production went down by 17%. If this technique

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[243] White, E. 2002. Manure cleaner impresses farmers. Western Producer, June 13, p. 32; Ewins, A. 2000. Pilot plant will test smell remover system. Western Producer, September 28, p. 62.

[244] Gompf, L. 2001. These pigs don't stink. Grainews, November issue, pp. 1,5.

[245] Wagner-Riddle, C. 2001. Improved greenhouse gas emission estimates from manure storage systems. ICAR Project: 33330738.

[246] Coghlan, A. 2002. Why a change of diet is good for the environment. New Scientist, 15 April, p. 6.

became widespread, Newbold calculated that Europe's methane emissions would be reduced by about 4 to 5%, more than half the target of 8%.

Research gap " This interesting approach to suppressing methane evolution may need evaluation in Canada. What would be the cost of the process? Would it only apply to animals in confinement or could it also be applied to animals on pasture?

6.4.4.4 Combined gasification/combustion systems
This new system for providing space heat looks particularly interesting for application in small to medium sized confined animal operations, greenhouse operations, rural and small town industrial buildings and groups of residences close enough together that space heat energy could be distributed between buildings. It does not appear to require any financial support programs other than some up-front capital support from NRCCan for introduction of the technology (Fallding, 2002).[247] The technology could compete for straw, wood waste and municipal solid waste with other bioproduct and biofuel processes.

Research gap " Determine where this new technology might find application across Canada. How is the financial attractiveness of this process affected by the price of natural gas and other fuels? How much of the straw and other agricultural raw material resource could be consumed by wide-spread adoption of this technology? Could this technology be applied to provide heat energy for various bioproduct manufacture processes?

Note that this gasification technology is the little brother of large-scale gasification technologies being considered for production of alcohols from waste biomass (see section 6.2 on ethanol).

6.4.5 R & D Analysis

6.4.5.1 Canadian Strengths

The University of Guelph in Ontario and Agriculture and Agri-Food Canada in Ottawa have developed expertise in the measurement of greenhouse gas emissions from livestock and in development of management systems to reduce greenhouse gas emissions from livestock and their manures. The Lethbridge Research Centre of AAFC, as well as other AAFC research centres and stations and the University of Alberta have conducted studies on greenhouse gas emissions from livestock. The Lethbridge Centre has been conducting research on the feeding of vegetable oils to ruminant livestock, including the effects on production of conjugated linoleic acid and the suppression of methane evolution from the rumen.

Biogas production by anaerobic digestion of animal manures has been studied by Masse and colleagues at Agriculture and Agri-Food Canada Research Branch in Quebec. The description of the BioGem operation in Alberta suggest that it may have some similarities to the batch sequencing

[247]Fallding, H. 2002. Manitoba chickens bask in heat from straw. Saskatoon Star Phoenix, Dec. 3, p. C4. See also Siemens, H. 2002. Straw heat saves big bucks for farmer. Manitoba Co-operator, Dec. 5, p. 33.

reactor being studied in Quebec.

Close coupled gasification/combustion systems starting to be applied commercially were developed by NRCan.

6.4.5.2 Gaps in Research

These have been discussed in 6.4.4: Current Research.

6.4.5.3 Themes for Future Research

Manure treatment systems continue to offer economic and technical challenges. The BioGem system in operation in Alberta needs further study to determine whether it is a success story of anaerobic treatment to produce biogas, and if so, why? The reasons may be economic and market, as much as technology.

Methods to reduce methane eructation from ruminant animals seems likely to continue to be a challenge, although there are new leads that look promising.

Further study of close coupled gasification/combustion systems seems warranted to determine where it would be most commercially attractive and how wide-spread the applications might be. It may be feasible on a relatively modest scale, which would be interesting for applications in barns and small businesses.

6.4.6 Recommendations

The anaerobic biogas system (BioGem) in operation in Alberta is worthy of further study to determine the possibility of application elsewhere in Canada.

The increased production of CLA in meat and milk by feeding vegetable oils to ruminant animals merits further investigation to determine the economics, market potential and the amount of vegetable oils that might be required if the method became commercially used in significant amounts.

New methods to restrict methane emissions from ruminant animals, such as feeding specific bacteria to convert methane into carbon dioxide before release from the animal, will continue to be investigated.

6.4.7 Success stories

Further evaluation of the Vidir gasification/combustion system may indicate that it is a success story. Initial reports sound promising.

The new-to-Canada anaerobic digestion system in operation in Alberta (BioGem), and similar systems, merit further investigation.

6.5 Bioplastics

6.5.1 Sector Overview

> **CONCERTED ACTION IS NEEDED TO DEVELOP HIGH VOLUME BIOPLASTIC APPLICATIONS.**

Bioplastics is a major product focus in both Europe and the US. Significant R&D has taken place over the last 10 years on both continents, and new products are now reaching the commercialization stage. Canada has several small start up companies that are targeting their technologies and products to small niche markets. In order for Canada to obtain meaningful greenhouse gas reductions from bioplastics, a concerted action will be required to develop high volume industrial bioplastic applications.

6.5.2 Key Opportunities

> **PRICE AND PERFORMANCE ARE IMPORTANT DRIVERS IN NORTH AMERICA**

Biodegradable plastics are gaining market momentum in Europe as a result of government regulations promoting the composting of biodegradable materials. The EU market for bioplastics in 2000 was 10,000 tonnes (40% of world market) and it is expected to grow to 60,000 tonnes by 2005. The main product markets are food packaging, compost bags, paper coatings, dishes and cutlery.[248] Other commercial applications for starch biopolymers include loosefill packaging; sheets, shaped and blocked packaging for electronics; injection moulding; films and fillers; and children's toys.[249] Long term market opportunities for bioplastics in the EU are estimated to be about 300,000 tonnes by 2010.[250]

US markets are also expanding, but they are being driven by more traditional economic drivers like price and performance. Cargill Dow Polymers has built a 140,000 tonnes/year polylactic acid (PLA) plant in Blair, Nebraska that will be used to provide raw materials for food packaging (e.g. bio-oriented films, and thermoformed trays and lids), fibre applications (apparel, industrial fibres, non-wovens) and fibre-fill (comforters, pillows)[251]. DuPont has built a new factory in Kinston, North

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[248]Warmington, A. Biodegradables Takes Off. European Plastics News. January, 2002. Reported on the IENICA web site, http://www.ienica.net/usefulreports.htm.

[249]Presentation by Ludovic Raynaud, National Starch and Chemical Biopolymers: Packaging - A New Generation, March 29-30, 2001.

[250]Johnson, D. July, 2000. Renewable Raw Materials - A way to reduce greenhouse gas emissions for EU industry. EU Commission, DG Entreprise/E.1.

[251]Cargill Dow is also exploring product development in other emerging areas including: injection stretch blow moulded bottles; food service and packaging foam; and emulsions (paper and board coatings and pigments, paints, binders for nonwoven fabrics, binders for building products, and adhesives).

Carolina that will produce Sorona, which is a copolymer made from 1,3 propanediol (made from corn starch) and teraphthalic acid (made from petrochemicals). Sorona is also targeted at fibre applications.

In general, there are two main sources of commercially available biodegradable plastics:

- starch-based materials (either unmodified, or modified and complexed with other polymers); and
- polylatic acid (PLA), where starch is first fermented to lactic acid and then polymerized into PLA.

Polyhydroxy alkanoates (PHA)[252], proteins[253], and cellulose derivatives represent only a minor fraction of the current market (although this could change as a result of new R&D).[254]

6.5.3 Potential Impact on GHG Emissions

As a rule of thumb, starch-based plastics can save between 0.8 - 3.2 tonnes of CO_2 per tonne compared to one tonne of fossil fuel-derived plastic. The range reflects the share of petroleum-based co-polymers used in the plastic. The life-cycle GHG savings (in CO_2 equivalents) for oilseed based plastic alternatives has been estimated to be 1.5 ton per ton of polyol made from rapeseed oil.[255]

However, a number of experts do not see bioplastics as having a significant impact on greenhouse gas reduction during this decade because of its relatively small market size. In order to expand beyond current niche markets that are focussed on biodegradability, R&D efforts will have to focus on reducing the price/performance gap with petrochemicals.[256] The DuPont and Cargill Dow research efforts, which are aimed at replacing major fibres like PET, represent the type of direction we must pursue to significantly impact CO_2 emission reductions.

In order to increase the GHG benefits of bioplastics, CO_2 savings must also be captured downstream at the end of a product's life cycle. For example, there is a need to examine CO_2 savings from energy generation and advanced product recycling.[257] One of the advantages of bio-based, biodegradable plastics is that they can be recovered and used as a soil amendment at the end of their life. This

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[252]PHA can either be produced by bacteria, using a fermentation process, or grown and stored within GMO plants acting as a plant factory. See R.A. Weusthuis et al. Potential of PHA Based Packaging Materials for the Food Industry. The Food BioPack Conference. August 2000.

[253]Proteins can be either vegetable-based (e.g. corn zein, wheat gluten, soy protein, etc.) or animal-based (e.g. milk proteins, collagen, gelatin, keratin, etc.). See S. Guilbert. Potential of protein Based Biomaterials for the Food Industry. The Food BioPack Conference. August 2000.

[254]Bastioli, C. August 2000. Global Status of the Production of Bio-based Packaging Materials. The Food BioPack Conference.

[255]Johnson D. Renewable Raw Materials - A way to reduce greenhouse gas emissions for EU industry. EU Commission, DG Entreprise/E.1. July, 2000, p. 16.

[256]Ibid.

[257]Ibid.

assumes there is adequate product labeling (to differentiate biodegradable from non-biodegradable plastics) that a waste separation and composting infrastructure is in place, and that compost standards and a testing regime have been developed to ensure compost quality. These are all additional areas requiring further research. In particular, there is a need to study the eco-toxicity from potential accumulation of contaminants in the soil, and various chemical reactions among biodegradable products.[258]

Research is also necessary to ensure that bio-based plastics do, in fact, reduce more CO_2 emissions and other pollutants over their life cycle than conventional plastics. A fairly recent Scientific American article claims, for example, that PHA grown in plant-based factories may actually be more energy intensive and emit greater CO_2 emissions than conventional plastics. PLA based plastics, on the other hand, may have marginally better CO_2 impacts than petrochemically-derived plastics.[259]

Some bioprocessing techniques, which reduce the number of manufacturing steps in a chemical conversion process, may reduce both capital and energy requirements and provide more meaningful CO_2 reduction potential.[260]

6.5.4 Major Players

Some of the important EU manufacturers of bioplastics include Novamont (Italy), Natura Verpakung (Germany), Rodenburg Biopolymers (Netherlands), ICI/National Starch and Chemical Company (UK), AVEBE (The Netherlands) and BASF (Germany).

Some of the major EU centres for coordinating R&D include:

- PHA - ATO Agrotechnological Research Institute (Netherlands)
- PLAs - Galactic (Belgium)
- Starch Proteins - INRA-LBTB Lab Protein Biochemistry & Technology (France)
- Thermoplastic Starches - ATO Agrotechnological Research Institute (Netherlands)
- 1,3-Propanediol - GBF Gessellschaft fur Biotechnologische Forschung mbH (Germany)

Some key US companies include: Cargill Dow Polymers, Dupont, Genencor International, Eastman Chemicals, Metabolix, Proctor & Gamble, DuPont Soy Polymers, and ECM BioFilms (which has developed an additive that renders conventional plastics like polyethylene and polypropylene biodegradable).

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[258] J. Fritz, J., Link, U., and Braun, R. Environmental Impacts of Bio-based/Biodegradable Packaging. The Food BioPack Conference. Copenhagen, Denmark. August 27-29, 2000.

[259] Gerngross, Tillman U. and Slater, Steven C. How green are green plastics? Scientific American. August, 2000.

[260] An example is DuPont's production of nylon 6 12. The diacid in PA 6 12 is dodecanedioic acid (DDDA) which conventionally is made in four steps — butadiene is converted to cyclododecatriene, then to cyclododocane, then to cyclodecyl alcohol or ketone, and finally to DDDA. DuPont has engineered a biocatalyst which makes DDDA from dodecane in one step. When this bioprocessing technology is applied industrially, it is estimated that it could cut capital investment in half and reduce manufacturing costs by two-thirds. DuPont and Genencor have also produced a microorganism that can convert glucose directly into 1,3-propanediol in one step.

US centres of university or government expertise include:

- Eastern Regional Research Center (USDA)
- Western Regional Research Center (USDA)
- Idaho National Engineering and Environmental Laboratory (US DOE)
- The Biodegradable Polymer Research Center, University of Massachusetts at Lowell
- The Starch Institute for Non-Traditional Applications for Starch (SINAS) at Michigan State University and,
- The Center for Crops Utilization Research, Plant Sciences Institute, Iowa State University.

6.5.5 Current Research

In general, EU and US R&D has focussed on increasing the availability of cheap raw materials, reducing production costs, and refining production and manufacturing processes to meet industry and market needs.

Both starch and protein-based plastics are hydrophilic (i.e. easily absorbs moisture). Starch-based thermoplastics also suffer from low impact strength. Current research is focussed on finding new packaging concepts/processes that overcome these problems. Starch-polyester blends is one method of introducing water resistance. BAK (Bayer-Germany) and Eastar (Eastman-USA) have both been successfully blended with starch to improve water sensitivity. Many other approaches to creating moisture resistant starch plastics are being researched and are discussed in the sections below.

At present, polylactic acid is made from lactic acid, which is derived from the fermentation of starch crops like corn or wheat. Less expensive feedstocks that do not compete with food uses are needed for the PLA plastics industry to be sustainable over the longer term. These new feedstocks could include lignocellulosics like wheat straw and corn stover, which can be converted into a sugar platform for lactic acid production. Other examples are provided in the sections to follow.

Increased production of biodiesel and growth in the oleochemical industry has resulted in a surplus glycerol world market and declining prices. One of the products that can be made from the microbial conversion of surplus glycerol is 1,3-propanediol - which can be used to produce natural plastics that are light-insensitive and more biodegradable than synthetic polymers. Propanediol is a useful component in polyethers, polyesters, and polyurethanes. It can also be used as a solvent and a chemical intermediate for various other compounds. Early R&D efforts in the EU focussed on reducing the costs of converting glycerol to propanediol by optimizing culture conditions, improving process performance, and influencing metabolic pathways to create improved microbial strains.[261] More recently, DuPont and Genencor International in the US have produced a microorganism that can convert glucose to propanediol in one step, thereby greatly increasing the productivity of the conversion process.

A number of bacteria species produce a plastic material (PHA) within their cells. These bacteria can

[261]See EU Air Programme Summary - AIR2-CT93-0825. Production of 1,3-Propanediol From Glycerol Surpluses. Yield Optimization by Technological Development and by Genetic Strain Improvement. September, 1999.

be cultivated in large scale fermenters and the plastic can be recovered by first breaking the harvested cells and then using solvent to extract the bioplastic. Poor economics is the main constraint to commercializing bioplastic production using this method. New methods of manufacturing are needed to bring costs down, and researchers are now looking to grow PHA in "plant factories" as one way of addressing the cost issue.

The following are examples of major research themes which have emerged over the last 10 years:

6.5.5.1 Crop Production

New, More Efficient Harvesting, Storage and Separation Systems

- Iowa State and its partners are developing new harvesters that can separately collect wheat grain and stems in a single pass. This will extend the potential raw material base for PLA production by creating both starch (wheat) and sugar (straw) chemical platforms for the production of lactic acid.[262]
- Biomass Agri-Products and its partners are developing and demonstrating new harvest, storage and separation systems to collect both the corn ear and stalk (stover) in one pass. The stover will be stored in a silo (wet basis) to reduce fire risk, lengthen storage life, and control feedstock degradation. This project will also extend the potential raw material base for PLA production by creating both starch (corn) and sugar (stover) based chemical platforms.[263]

Expanding Feedstock Availability

- The Departments of Chemical Engineering and Biotechnology at the Technical University of Denmark, the Riso National Laboratory, and the Centre for Agro-Industrial Biotechnology at the University of Southern Denmark have developed a process for converting plant juice (a waste stream from pressing grass, clover and alfalfa into pellets for cattle feed), potato processing waste, and wheat straw into lactic acid.[264]
- Research is also being conducted in the US to convert lignocellulosic wastes into lactic acid. Cargill Dow and their partners Iogen, Shell Global Solutions, and CNH Global NV will develop and pilot a demonstration biorefinery in collaboration with corn, wheat and rice grower organizations, national labs, and universities. This study will integrate agricultural process systems and fermentation technologies in an effort to cost effectively produce sugars for use in lactic acid (and ethanol) production.[265]

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[262]Multi-Component Harvesting Equipment for Inexpensive Sugars from Crop Residues. Office of Industrial Technologies, US Department of Energy. Fact Sheet. October, 2002

[263]Collection, Commercial Processing, and Utilization of Corn Stover. Office of Industrial Technologies, US Department of Energy, Agriculture Bio-based Products FY 01 R&D Projects. Reported on Iowa Industries of the Future web site, http://www.ciras.iastate.edu/IOF/agresearch.html

[264]Garde, A., Schmidt, A.S., Jonsson, G., Andersen, M., Thomsen, A.B., Ahring, B.K. and Kiel, P. Agricultural Crops and Residuals as a Basis for Polylactate Production in Denmark. The Food BioPack Conference. Copenhagen, Denmark. August 27-29, 2000.

[265]Awardees for US Department of Energy, Energy Efficiency and Renewable Energy, Integrated Biomass R&D Solicitation. Reported on the US Biomass Research and Development web site, http://www.bioproducts-bioenergy.gov/, 2003.

- Metabolix and its partners are attempting to genetically engineer switchgrass to produce PHA that can be processed into film, fibres, coatings, moulded objects, and other chemicals. The switchgrass remaining after PHA extraction will be burned as a fuel.[266]
- GBF Gescellschatt fur Biotechnologische Forschung mbH (Germany), and other consortium partners, have focussed on further reducing the costs of propanediol production by trying to expand the feedstock base beyond glycerol to include cheaper, more abundant renewable resources like glucose, starch, and sucrose. To achieve this goal, researchers are genetically engineering bacteria and microorganisms to convert glucose and starch into propanediol.[267]

Molecular farming of PHA

- Various research projects in Europe are trying to find a less expensive manufacturing process for PHA by identifying the individual genes, and gene sets, in the bacteria that are responsible for the production of PHA (e.g. 3HB, 3HV, and 4HV-PHA) and then expressing them in plants like tobacco, rape, pea and potato. This new manufacturing process has come to be known as molecular farming.[268]

6.5.5.2 Processing

New Processing Technologies to Overcome Water Sensitivity of Starch and Protein Based Plastics

- Chemical modification using esterification and twin screw extruder - It has been suggested that one possible route to reducing the water sensitivity of starch based plastics is to develop continuous or semi-continuous methods for the partial chemical modification of starch (using esterification with acetic or propionic acid) in a modified twin screw extruder. Another approach could be to blend naturally derived hydrophobic proteins or natural wax-like materials in the extruder.[269]
- Water-resistant starch laminate films - AVEBE (The Netherlands), under the trade name Paragon®, is currently commercializing starch-based laminate films using a bio-based adhesive layer to bond the coating to the starch. This process retains the renewable, biodegradable qualities of the packaging but adds water barrier functionality.[270]
- Water-resistant starch foamed trays using expanded bead technology - The Department of

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[266]The research project is called "Biomass Biorefinery for Production of Polymers and Fuel" and was funded by the Office of Industrial Technologies, US Department of Energy in 2001. It is a 5 year, 14.8 million co-funded project.

[267]EU Fifth Framework Programme. Project QLK5-1999-01364 PROBIO: 1,3-Propanediol - A Versatile Bulk Chemical From Renewable Resources by Novel Biocatalysts and Process Strategies. June 2001. Progress Report Abstract.

[268]See, for example, EU Eclair Programme. Project AGRE-0006 - Novel Biosynthetic Routes for and Biodegradation of Polyhydroxy Alkanoates Made by Genetically Engineered Strains of Bacteria and Plants and FAIR-CT96-1780 - PHAtics: Sustainable Production in Biodegradable Polyesters in Starch-Storing Crop Plants.

[269]Lawther, M., and Fischer,G. Potential of Starch Based Packaging for the Food Industry. The Food BioPack Conference. Copenhagen, Denmark. August 27-29, 2000.

[270]Tuil, R. Van, Schennink, G., Beukelaer, H. de, Heemst, J. Van and Jaeger, R. Converting Bio-based Polymers into Food Packaging. The Food BioPack Conference. Copenhagen, Denmark. August 27-29, 2000.

Polymers, Composites and Additives, ATO (The Netherlands) has developed a water-resistant starch based tray using an expandable bead technology. This technology facilitates a one step production process for foamed containers that produces a product with properties comparable to extruded polystyrene foamed trays and expanded polystyrene thin walled products.[271]
- Cross-linked protein films - INRS-Institut Armand-Frappier and others have been using heat and irradiation to produce cross-linked films (based on a 50-50 combination of calcium caseinate and whey protein isolate) that are more puncture and moisture resistant.[272]
- Starch-fibre composites - ARD-Agro-Industry Research and Development (France) and CERME - Materials and Packaging Research Centre, ESIEC (France) have demonstrated that cellulose fibres used as a reinforcement in starch-based thermoforming applications not only adds impact strength, but reduces the impacts of water sensitivity associated with higher levels of relative humidity during storage.[273]

Metabolic Pathway Engineering
- Scientists from Genencor and DuPont have used metabolic engineering to developed a single microorganism containing all the necessary enzymes to convert glucose from corn starch to propanediol in one step. This has resulted in a five-hundred fold increase in productivity.[274]

Modification of Wheat Proteins Using Physical, Chemical, and Enzymatic Processing
- An EU consortium studying packaging films using industrial gluten (enriched gliadin and glutenin fractions) has examined a range of physical, chemical, and enzymatic techniques for modifying wheat proteins.[275] Their research found, for example, that:
  - chemical reagents (anhydrides, aldehydes) can improve water resistence,
  - enzymes (transglutaminase) can cross-link deamidated gluten to increase film stress and strain,
  - tetraethylene glycol and glycerol function as efficient plasticizers,
  - stearic acid applied to the wheat gluten film reduces water vapour permeability, and
  - the application of heat to the gluten film increases film strength.

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[271] Ibid.

[272] Lacroix, M. Letendre, M., Le, T.C., Vachon, C., Uattara, B., Mateescu, M.A. and Patterson, G.D. Structure and Functionality of Cross-Linked Milk Protein Films. The Food BioPack Conference. Copenhagen, Denmark. August 27-29, 2000.

[273] Fringant, C., Moro, L. and Averos, L. Stability and Mechanical Improvement of Starch Based Biodegradable Materials Suitable for Thermoforming Packaging. The Food BioPack Conference. Copenhagen, Denmark. August 27-29, 2000.

[274] Genencor and DuPont Reach 2nd Technical Milestone in Making Key Polyester Ingredient from Glucose. Genencor International press release. November 22, 1999.

[275] EU Fair Programme. Project FAIR-CT96-1979 Wheat Gluten as Biopolymer for the Production of Renewable and Biodegradable Materials. Final Report Abstract, December, 2000.

6.5.5.3 New Market Applications and Utilization

Edible Packaging

- There is a growing interest in vegetable (corn zein, wheat gluten, soy protein, etc) and animal proteins (milk proteins, collagen, gelatin, etc) for use as edible packaging.[276]

Water and Heat Proof Packaging

- Unlike starch and protein-based bioplastics, PHA are water resistant and they can be further modified chemically to have new properties. Scl-PHA have been used to make single-use bottles to hold shampoos, cosmetics, and biodegradable motor oil and as a water resistant coating for paper cups and food trays. However, the production of Scl-PHA using a fermentation process is not cost competitive with PP. Metabolic engineering of oil seeds or prairie switch grass may offer a more cost competitive route.[277]

High Value Added Niche Markets

- Mcl-PHA can be chemically modified to produce cheese coatings, pressure sensitive adhesives, a binder in paints, and a material for disposable diapers. Mcl-PHA do not compete directly against traditional petrochemical polymers. Because they can be modified, they can be tailor-made for different high-value added specialty niche markets.[278]

Composite Fillers

- Goodyear uses corn starch and fibre to replace conventional carbon black and silica in its new BioTRED GT3 tires. Goodyear claims its lower rolling resistance improves fuel consumption by 5% and reduces CO_2 emissions by 7.5 g/km.[279]

Food Safety Research

- Because starch and protein based bioplastics are moisture sensitive to both the environment and the foodstuffs they contain, they can potentially lose their barrier and/or mechanical properties. Bio-based materials may also be more subject to microbial activity as a result of damage (e.g. pin holes), aggressive foodstuffs (i.e., with high microbial activity) or being prone to digestion by microorganisms. Plastics made from starch and proteins could also be subject to insect and rodent abuse. Bio-based plastics also contain natural and synthetic components e.g. additives, plasticizers, cross-linking agents, antioxidants, preservatives, etc. which are not common in conventional packaging materials and may contaminate or interact

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[276]Guilbert, S. Potential of Protein Based Biomaterials for the Food Industry. The Food BioPack Conference. August 2000. Also see G.W. Padau et al., Zein-Based Biodegradable Packaging for Frozen Foods. The Food BioPack Conference. Copenhagen, Denmark. August 27-29, 2000.

[277]Weusthuis, R.A., van der Walle, G.A.M. and Eggink, G. Potential of PHA Based Packaging Materials for the Food Industry. The Food BioPack Conference. Copenhagen, Denmark. August 27-29, 2000.

[278]Ibid.

[279]Driveline, May 17, 2001; Tyres Online, July, 2001.

adversely with the foodstuff. All these areas are in need of further research.[280]

6.5.6 R&D Analysis

6.5.6.1 Canadian Strengths

Canada has several companies developing bioplastic products and technologies, but they tend to be in niche market areas that will not have a significant impact on CO_2 reduction. Examples of Canadian companies include:

- BioMatera Inc. (Montreal, QC) - which 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, and cosmeceutical and tissue regeneration matrices. Other potential applications include food packaging, plastic bottles, suture threads, biodegradable inks and paints, fibres, films, resins, and nanobiomaterials.[281]
- Bioenvelope Technologies (Laval, QC) - which produces an edible film from milk products or other vegetable proteins that is vaporized onto fresh and frozen food products to increase their shelf life, and act as a moisture barrier and food ingredient separator.[282]
- Nexia Biotechnologies (Vaudreuil-Dorion, QC) - which produces BioSteel®, a spider silk protein produced within its transgenic BELE® (Breed Early, Lactate Early) goat system. Nexia's patented technology allows them to insert the gene for producing spider silk into a goat's mammary gland cells. Nexia is focussing on two medical device markets: wound closure systems (e.g. sutures, patches and glues), and ligament prosthetic devices. Another application area is industrial fibres including fishing line and soft body armour protection for military and law enforcement personnel.[283] The projected world markets for high performance fibres in the composite, ballistic, protective clothing, and ropes and cables sectors in 2005 is less than 35,000 tonnes.[284]

Bioplastics is also gaining momentum in Alberta:

- The Alberta Bioplastics Network (ABN) has recently been formed. It is a multi-institutional research network with a mandate to promote the use of Alberta crops as feedstocks for

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[280]See Simoneau, C. Bio-based Packaging Materials: Food Contact, Safety and Legislation and Hgaard, V.K., Udsen, A-M., Mortensen, G., Hoegh, L., Petersen, K. and Monahan, M. Potential Food Applications of Bio-based Materials: An EU-Concerted Action Project in The Food BioPack Conference. Copenhagen, Denmark. August 27-29, 2000.

[281]BioMatera: A New Generation Of Biomaterials: Fact Sheet. June 20, 2002.

[282]Bioenvelope has entered into a scientific collaboration with the Institut National de la Recherche Nationale - Institut Armand-Frappier (INRS-IAF).

[283]Nexia has signed a collaboration agreement with Accordis Specialty Fibres Ltd. to develop a spider silk spinning process to produce BioSteel®.

[284]Nexia Biotechnologies Inc. - Prospectus. Dec. 8, 2000. Other military applications could include soft armour for mobile shelters, parachute fabrics, composite armour to protect satellites, aircraft and land vehicles.

specialty chemicals and polymers. Members include the Alberta Crop Industry Development Fund (ACIDF), AVAC Ltd., Alberta Agricultural Research Institute (AARI), the Agriculture and Food Council (AFC), Alberta Agriculture Food and Rural Development (AAFRD), Alberta Economic Development (AED), Agriculture and Agri-Food Canada (AAFC), Environment Canada (EC), and the Alberta Canola Producers Commission (ACPC).[285]

- Suresh Narine, University of Alberta, is the Chair of the Network and is coordinating a study of biodegradable polymers from Alberta oil seeds including fundamental science, pilot scale development, economic feasibility, and market analysis.[286]
- Another emerging group in Alberta is the Alberta Consortium for Industrial Crops, which is focussing on the genetic modification of plants to produce bioplastics.[287]

The University of Saskatchewan is also studying the chemical pre-treatment and polymerization of flax fibres for use in plastics as fillers and strength addition.[288]

6.5.6.2 Bottlenecks (R&D Challenges)

The main challenge for these small companies is not basic research at this point but scaling up to commercial production and focussing on product development research that will expand their market opportunities. In some cases, this may require the co-development of new products with downstream product manufacturers.[289]

SMALL START UP COMPANIES NEED HELP SCALING UP PRODUCTION, AND DEVELOPING NEW PRODUCTS AND MARKETS

6.5.6.3 Gaps in Research

The gaps in research are largely product specific for existing companies. For example, in the case of Nexia Biotechnologies, there is a need to scale up spinning equipment for their BioSteel®. This has led Nexia to form a corporate partnership with The College of Textiles at North Carolina State University, which is a world class centre for textile research and development.[290]

6.5.6.4 Themes for Future Research

Many of the major research themes have already been discussed above under sections pertaining

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[285]ACIDF Newsletter, December, 2002. Suresh Narine (ACIDF) is the chair of the fundamental science focus area. Connie Phillips, Centre for Agri-Industry Technology (AAFRD) is chair of the scale up technology focus area. Edward Phillipchuk (AAFRD) is chair of the marketing, investment and business development focus area; and Narine Gurprasad (EC) is chair of the environmental and economic policy and regulations area.

[286]This is a $175,000 study that is in progress. Refer to project #2002C069R.

[287]ACIDF Newsletter, December, 2002.

[288]Comments from Ron Kehrig, Bio-Products Saskatchewan,Winter, 2003.

[289]Bioenvelope Technologies Annual Report, 2002.

[290]Nexia Biotechnologies Inc. Prospectus. Dec. 8, 2000.

to crop production (6.5.5.1), processing (6.5.5.2) and new market applications and utilization (6.5.5.3). Most of these themes require continued, long-term support.

More specifically, we want to draw attention to one of the major issues that has emerged from the transgenic engineering of oilseed plants for PHA plastics. There is currently a negative correlation between the production of PHB (a short chain PHA bioplastic) in plants and plant health. As the concentration of PHB increases, plant fertility decreases, plant growth is retarded, leaves suffer from chlorosis, seed production is decreased, and other metabolic changes take place which may cause additional harm if the plant is placed under stress conditions.[291]

Even if these problems are overcome, there remain additional research challenges. For example, elevating the level of PHB in the plant's seeds has not yet yielded sufficiently high concentrations to be commercially viable. There also remains the problem of how to cost effectively separate the seed oil, PHB polymers and the meal in a large scale production system involving identity preservation.[292]

Finally, current bioplastic applications in Canada are focussed on market niches. There is a need to focus on industry-led, large scale starch, PLA, PHA, and soy protein product applications if CO_2 reduction potential is to be realized in Canada. To achieve this goal, Canada must engage some of the large multi-national companies in a technology roadmapping exercise relevant to the Canadian context.

6.5.6.5 Specific Recommendations

Southwestern (SW) Ontario is one location where large-scale production of industrial bioplastics may have potential. This region has easy access to large volumes of starch and protein-based raw materials either grown locally, or shipped easily from the US Midwest and Western Canada by boat or rail. SW Ontario also has several large starch and citric acid processing facilities, so a starch-based supply chain infrastructure is currently in place. Finally, SW Ontario is close to markets, especially the automotive and plastics industries which are both located in SW Ontario. In addition, almost 180 million people are located within a one day drive from SW Ontario. These factors all contribute to a set of strategic competitive advantages for SW Ontario, particularly with respect to large scale bioplastics processing. However, one of the main missing pieces is an interested multi-national private sector partner(s) to provide industry direction and focus for future bioplastics research. A cluster-based industrial strategy focussed on bioplastics should be developed with private sector involvement.

The Alberta Bioplastics Network may lead to another potential bioplastics cluster in western Canada. Alberta is actively involved in oil seed production and is close to markets on the US and Canadian west coasts. But like Ontario, they will also need active industry involvement to be able to identify market needs, and find the investment capital to scale up from the laboratory to

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[291]See Nola Immel's web site at the University of Saskatchewan. http://www.usask.ca/agriculture/plantsci/classes/plsc416/projects_2002/immel/problems_production.html

[292]Ibid.

commercial production.

6.6 Adhesives

6.6.1 Sector Overview

In the first half of the 20th century, bio-based adhesives enjoyed the lions share of this diverse and ever changing business. However, with the development of superior performing and in some cases cheaper petrochemical-based alternatives, the original starch and protein-based glues almost disappeared from the market. With revived interest in replacing non-renewable with renewable ingredients, a reversal in product formulation has started to occur.

CAN BIO-BASED ADHESIVES CHANGE A SAGGING INDUSTRY FOR CANADA?

The global adhesives industry amounted to just over $20 US billion in sales in 1998. US and Canadian manufacturing represented about 40% and 1.4% respectively of this total. The overall average annual growth rate of the industry is about 3%.[293] The Canadian adhesive and sealants industry is divided into industrial and consumer categories. The industrial segment is estimated to account for about 80% of the Canadian market with the paper/cardboard and wood industries making up the vast majority of this category. Total Canadian shipments of adhesives in 1999 were $473.5 CDN million, and 2,362 people were employed at 46 establishments.[294] In 2001, Canada exported a total of $167.5 million to the US while importing $441 million. This negative balance of trade has been fairly consistent over the past 4 years.[295]

Adhesives in the broadest context could include a wide range of products such as finished paper where modified starches provide significant functional properties to the end product. Similarly, starch and cellulosic materials are used in cementitious products to not only extend the product, but also to add desirous functional properties. However, the range of adhesives for Canadian reporting and statistical purposes generally includes the following:

Natural adhesives	Synthetic resin adhesives	Caulking compounds
Vegetable glue	Linoleum cement	Medical adhesives
Mucilage	Neoprene rubber adhesives	Polyvinyl acetate adhesives
Rubber adhesives	Sealing compounds	Tile cement

One group of materials which are not normally included in the adhesives totals are the formaldehyde

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[293]ChemQuest Group (Cincinnati) reports that the world market in 2000 was 19 million dry lbs with a value of $30 billion US. Regional breakdown shows: Europe 40.5%, US 34.7%, rest of world 24.8%.

[294]Note: Industry Canada does not class resins as adhesives, thus product used in the laminated board industry is not included in these totals.

[295]http://strategis.ic.gc.ca/SSG/bt01165e.html#1

resins. Although these materials are not in favor due to health concerns, they are still used extensively in the manufacture of plywood and other exterior sheeting products.

With regard to adhesive manufacturing in North America, shifts have occurred over the past decade as a result on the introduction of free trade. Where in the past, most companies produced the same products both in Canada and the US, free trade has resulted in consolidation of production in one country or the other. Corporate decisions have been based for the most part on economies of scale but to a lesser extent on legislative differences relating to emission standards for volatile organic compounds (VOC).[296]

The industry has also undergone change as a result of advances in manufacturing technologies. In certain situations, adhesive companies are now able to ship dry (as opposed to liquid) ingredients to their customers for final formulation and use. This has been made possible through the development of water-based adhesives for selected applications. Where this choice has been made, the reduced costs (mainly savings in shipping) help offset some, or all, of the performance deficiencies in the water-based products. However, in 1998, 59% of the North America wood-based adhesives were still amino resins (urea formaldehyde, melamine-formaldehyde, etc.) and another 32% was phenol-formaldehyde.[297] In spite of on-going efforts to find suitable replacements for these known to be harmful substances, their industrial performance is difficult to match.

While the market for low-cost adhesives and sealants is likely to remain flat or decline, specialty high performance adhesives are thought to hold good prospects for growth. For example, sales of hot-melt packaging adhesives suitable for high-speed processing are expected to continue to grow at, or above, the 10% rate seen in recent years.

THE ADHESIVES INDUSTRY CONTINUES TO EMBRACE CHANGE

Another trend worth noting is industry leaders' increasing interest in new adhesives applications. In addition to developing environmentally friendly products, cutting costs, and expanding markets for existing products, the technologically sophisticated companies are developing new adhesives for potentially lucrative applications. These include areas such as the replacement of mechanical fasteners (screws, bolts, welds, etc.) in the construction and automotive industries, as well as new high performance adhesives for electronic and medical uses. These newer markets are growing at a rate of 5-10% per year.[298] Unfortunately from Canada's perspective, these newer products are likely to be researched and manufactured close to head offices ostensibly located in the US, Japan or the EU.

For both environmental and cost reasons, the adhesives industry is looking seriously again at bioresources as alternate feedstock to petrochemicals. Raw materials of interest include: casein,

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[296]The list of VOC includes: 2-ethyl-1-hexanol, styrene, n-butyl ether, propylene glycol, and cyclohexanes.

[297]Sellers, T. Wood adhesive innovations and applications in North America. Forest Products Journal, Vol. 51, No. 6, June 2001, p. 12.

[298]Hume, C. Adhesives and Sealants, (Industry Trends), *Chemical Week*, March 21, 2001.

collagen and proteins from animal wastes; starch, protein, oils, cellulose, hemicellulose, lignin, natural rubber, rosins, terpenes, silicate and bitumen from plants; and an array of adhesive materials derived from marine species. While products which were around a half century ago have either disappeared, or are only used in limited application, new generation bio-based materials have started to appear. Starch, due to its availability and flexibility as a raw material continues to draw the greatest attention.[299]

Perhaps the greatest technical challenge facing many segments of the bio-based adhesives industry is the variability and quality of the raw material. Where the target material is a co-product generated from another manufacturing process, the quality of the ingredient can often be adequately controlled. However, where the material comes directly from the field in the case of certain plant-based sources, weather and handling related factors must be taken into consideration. A quality consistent and cost competitive supply of raw material is essential from the manufacturers perspective.

6.6.2 Major Players in Bio-based Adhesives Research

THE CANADIAN ADHESIVES INDUSTRY IS CURRENTLY DOMINATED BY FOREIGN COMPANIES

The companies and organizations listed below have been selected based on their perceived potential for impact on the bio-based adhesives industry in Canada and represent only a small percentage of the total number of organizations with interest and involvement in this far reaching industry. Detailed information on each of the organizations listed and other adhesives companies can be found at their respective web sites.

6.6.2.1 Companies[300]

- **Nacan Products Limited** is a leading Canadian supplier of adhesives, resins and starches to a wide variety of markets. The Resin Division, located in Brampton, ON, supplies resins and specialty chemicals to the paint, paper, construction, adhesive and cosmetic industries to name a few. Nacan Products is part of the US based National Starch and Chemical Company with over 8500 employees world wide and annual sales of almost $2.5 billion.[301]
- **Technical Adhesives** – One of two Canadian owned companies of significant size operating in Canada. Primarily markets hot melt and pressure sensitive adhesives to the packaging industry. The company has R&D interests, but limited budget.
- **3M** – This vertically integrated Minneapolis based company is a world leader both in the production of adhesives and end products which contain one, or more, of their unique adhesives. Their gross sales from Canadian production are in the $1 CN billion range with about 60% sold domestically. The company operates 4 production plants distributed across the country and employs over 2000 people. Both the Canadian head office and an active

[299] Smith, R.W. Overview of the Field of Natural Adhesives. Adhesives Age, October, 2002.

[300] For a full listing of companies active in the Canadian adhesives industry see Appendix C.

[301] http://www.nacan.com

research program are located in London, Ontario. The company has been an industry leader in innovation and has made good progress in reducing their emissions of VOC, but the reduction of GHG remains their greatest challenge. Product reformulation to be more environmentally friendly, equipment redesign and recovery and reuse of waste product are among the current fields of their research.[302]

- **H.B.Fuller** – This multinational company with corporate offices in St. Paul, MN does about $1.3 US billion in sales internationally in adhesives, sealants and coatings which would make it one of the top 5 companies in the world in these sectors. The company sells a wide range of products, including some which are bio-based and is committed to research as seen in the following excerpt from their web site: "Our 225,000 ft^2 Research and Development facility, also located in St. Paul, Minn., is staffed by more than 120 chemists and engineers grouped by industry and technology. Our core technologies are based in emulsion polymerization, water-based adhesives formulation, thermoplastic hot melt technology, and thermoset technology based on epoxy, polyurethane, acrylic, and silicone chemistry. In 2001, H.B. Fuller was granted 19 U.S. patents and filed for an additional 22."[303]
- **Borden Chemical, Inc.** – This multinational company with head office in Columbus, OH, operates five manufacturing facilities in Canada producing a range of chemicals, including resins and adhesives. Focus in Canada is primarily on production and marketing of formaldehyde resins to the construction sheeting industry.
- **Dow Chemical** – A major producer of a wide range of industrial products, including resins and adhesives. Dow recently purchased the Isoboard strawboard plant located in Elie, MB. Dow imports all of the isocyanate resin used in this plant.
- **ChitoGenics** – This newly established business is North America's leading developer of carboxymethyl derivatives of polyglucosamine. This chemical, extracted from chiten found in shellfish, is used as a medical adhesive. The manufacturing plant is located in Dartmouth, Nova Scotia.

6.6.2.2 Industry Associations

Canada

- **Adhesives and Sealants Manufacturers Association of Canada** (ASMAC)[304] represents the Canadian adhesives companies interests primarily with regard to public and regulatory issues. ASMAC does not get involved in research matters.
- **The Canadian Chemical Producers' Association** (CCPA) represents over 73 chemical manufacturing industries with over 200 plants across Canada -- which collectively produce more than 90 per cent of all chemicals in Canada. CCPA is also the driving force behind the Responsible Care® initiative, a global effort aimed at addressing public concerns about the manufacture, distribution, use and disposal of chemicals.[305]

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[302] http://www.3M.canada.com

[303] http://www.hbfuller.com/

[304] PO Box 296, Station A, Etobicoke, Ontario M9C 4V3 Tel: (416) 410-6116

[305] http://www.ccpa.ca

The US

- **Adhesives and Sealants Council, Inc. -** Mission statement - "ASC strives to create membership value by serving as a primary resource and confluence for education, interaction, and information exchange for and about the adhesive and sealant industry."[306]
- **Laminating Materials Association** - is a non-profit trade group representing all decorative overlays and edgebanding in North America.[307]
- **Structural Board Association -** For over 25 years, the Structural Board Association (SBA) has been representing Oriented Strand Board (OSB) manufacturers worldwide. Providing a variety of research and support services, the SBA is comprised of producer, associate, allied and research members.[308]
- **Center for Adhesive and Sealant Science** (CASS) **-** was established in 1982 as a result of a competitive bid process for both educational and R&D purposes. Since that time, it has become one of the most advanced programs in the world in adhesives and sealants research. The Center is comprised of researchers from 16 participating colleges and departments at Virginia Tech. Synergies are found among CASS, Virginia Polytechnic Institute, and the Adhesion Society, Inc., all located on the same campus.[309]
- **The Adhesion Society Inc.** - The mission of this organization is to promote and recognize the advancement of adhesion science and technology, and to promote education and training in this field. The society stages short courses and annual meetings and publishes events proceedings and quarterly newsletters. Two sub-groups of the Society are the Particle Division and the Pressure Sensitive Adhesives Division. The Society is operated out of the Virginia Polytechnic Institute in Blacksburg, VA.[310]

The EU

- **British Adhesives and Sealants Association** (BASA) - "BASA is the UK's only trade body representing the interests of industrial adhesive and sealant manufacturers, and the only large trade association in Europe totally dedicated to the adhesives and sealants industry. BASA has more than 80 members which together represent 85% of all UK industrial adhesive and sealant manufacturers".[311]
- **Association of European Adhesives Manufacturers** (FEICA) - is the multinational association of the European adhesives industry representing the national adhesives industry associations.[312]

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[306] http://www.ascouncil.org

[307] *e-mail: info@lma.org*

[308] http://www.osbguide.com/about.html

[309] http://www.cass.vt.edu/aboutcass.htm

[310] http://www.adhesionsociety.org/

[311] http://www.basa.uk.com/

[312] http://www.cefic.be/sector/profile/07-d.htm

6.6.2.3 Universities

Canada

> **CURRENT BIOADHESIVES RESEARCH EFFORTS IN CANADA IN THE PUBLIC SECTOR IS ALMOST NON-EXISTANT**

- **The University of Waterloo's Institute for Polymer Research** (IPR) - Although the IPR has not worked on bio-based adhesives, it appears to have potential to do so in collaboration with researchers familiar with the physical and chemical properties of the target raw materials. Their web site indicates: "The Institute carries out applied and fundamental research in areas that are of vital interest to the plastics, coatings, adhesives and elastomers industries. This includes work in such diverse fields as molecular weight characterization, thermal characterization, emulsion polymerization, polymer processing, polymerization kinetics, copolymerization, reactive extrusion, polymer-based catalysts, polymer photochemistry and development of new monomers and polymers. Major funding support in recent years has helped provide state-of-the-art research equipment and facilities."[313]
- **McMaster Institute of Polymer Process Technology** (IPPT) has done only limited work on adhesives in recent years. However, the combined strengths in bioprocess engineering, polymer chemistry, medical research and paper manufacturing gives this group significant capabilities to work in the bio-based adhesives field should the need arise.
- **McGill University – McGill Polymer** is a joint project of the departments of Chemistry and Chemical Engineering. A broad range of important aspects of polymers and plastics technology are covered, including adhesives.

The US

- **University of Delaware**, **Center for Composite Materials, Affordable Composites from Renewable Sources** (ACRES) - The ACRES research group, a multi disciplinary effort encompassing genetic engineering and composites manufacturing science, under the direction of Dr. Richard Wool, works with soy-based liquid molding resins and manufactures composites with natural fibers such as hemp, chicken feathers, and flax as well as the usual, glass, carbon, and synthetic fibers. In late 2001, the U.S. Department of Energy (DOE) awarded an $11 million grant (over four years) to the ACRES group under the umbrella of the Affordable Resins and Adhesives from Optimized Soybean Varieties (ARA) program.[314]
- **The Thames' Research Group, Department of Polymer Science, The University of Southern Mississippi** - This experienced group has pioneered much research in paints, coatings, adhesives and sealants fields. The TRG works closely with researchers at the USM School of Polymers and High Performance Materials on both basic and applied research.[315]

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[313] http://www.ipruw.com/about/about.htm

[314] http://www.ccm.udel.edu/research/acres/

[315] http://www.psrc.usm.edu/TRG

– **Virginia Polytechnic Institute, Center for High Performance Polymeric Adhesives and Composites -** The primary objective of the Center is to establish and integrate fundamental concepts for the design, synthesis, processing and manufacturing of polymeric adhesives and composites in order to understand and control their properties and performance in engineering applications. It seeks to do this by developing a better understanding of the basic science and technology of these materials at the molecular, microscopic, and macroscopic levels to allow correlations and predictions of macroscopic physical behavior. The Center's activities are solidly grounded in mechanics and materials science disciplines and draw heavily on contributions from them. However, its focus is limited to polymer based materials.[316]

Soybean Growers are leading the way in adhesive research funding in the US

– **Iowa State University, Centre for Crop Utilization Research, Biocomposite Group** – Has an active program in finding industrial uses for a wide range of agricultural materials. A significant effort has focussed on bio-based adhesives from soybeans.[317]

The EU

– **Composites and Adhesives Group, Department of Mechanical Engineering, University of Bristol, UK -** The Composites and Adhesives Group is a consortium of ten university researchers which, under the leadership of Professor R.D. Adams, carries out academic, as well as industrially oriented research in polymer matrix composites and structural adhesives.[318]

– **The Northern Germany EU Innovation Relay Center** for research and technology is available as a partner for questions relating to European research and technologies. The "Adhesives in Electronics" thematic network, which has been supported since March 1998 by the Brite-EuRam Program of the European Commission (DG XII), coordinates the research and development activities of currently 48 companies, research institutes, and universities from 14 European countries with respect to adhesives and related technologies in electronics and microsystems technology. This network is coordinated by VDI/VDE-IT, the management consulting subsidiary of both the VDI and the VDE, two of the largest engineering institutions in Europe.[319]

6.6.2.4 Government

Canada

– **National Research Council, Institute for Construction Research** – Located at the NRCC headquarters in Ottawa, engages in basic and applied research in a wide range of building materials including sealants and adhesives.

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[316] http://strategis.ic.gc.ca/SSG/1/mp00634e.html

[317] http://www.biocom.iastate.edu/

[318] http://www.men.bris.ac.uk/emrc/compad.html

[319] http://www.vdivde-it.de/homepage/engl/spectrum_services/networks.html

The US

– **Forest Products Laboratory**, USDA Forest Service, Madison, Wisconsin - Work is in progress on understanding the basic principles of adhesives – how they work and how they fail. This information is being used in studying bio-based materials which are candidates for replacement of petroleum based products.[320]
– **USDA National Center for Agricultural Utilization, Plant Polymer Research Unit**, Peoria, IL - One of the main thrusts of this group is the basic and applied research relating to the use of agricultural materials in industrial applications. Specific applications include water-resistant starch-based foams, starch and protein based biodegradable films, biodegradable composites for plastics applications, and adhesives.[321]

6.6.3 Key Opportunities

Opportunities for replacement of petrochemical derived materials with bio-based materials are numerous in the adhesives sector. The following examples may help the research community and governments in focussing their interest and investment.[322]

OPPORTUNITIES ABOUND, BUT AT WHAT COST AND WHAT RETURN?

– **Wood Products Adhesives** - Currently in North America 95% of the adhesives used in the wood industry are formaldehyde or isocyanate based. These two substances are manufactured from petroleum feedstock, and to varying degrees deemed hazardous by some authorities. Several bio-based feedstocks have shown potential to replace some or all of the formaldehyde and isocyanate adhesives. These feedstocks include: proteins, starches, tannin, lignin, casein, pyrolysis oils and animal blood. Given the scope of Canada's wood industry, very substantial opportunities await the company or companies able to capture this expected new business. Additionally, there may be potential to use bio-based adhesives in conjunction with straw to produce an annually renewable product.[323]
– **Medical Adhesives** – Niche markets are emerging for specialty water-based adhesives in a range of medical fields where ingredients derived from plant, animal and marine sources are receiving high attention.[324]
– **Mechanical Fasteners** – In recent years, with the development of adhesives with high bonding strength and durability, mechanical fasteners such as screws, bolts and even welded joints can in certain instances be replaced by industrial adhesives. The automobile industry has shown great interest in the time and cost saving on the assembly line, the reduction in vehicle weight and the elimination of some of the "road noise" in the vehicle. Research

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[320] http://www.fpl.fs.fed.us/

[321] http://www.ncaur.usda.gov/ppl/

[322] These opportunities will be discussed in more detail in section 6.6.5 and 6.6.6.

[323] Sellers, T. Wood adhesive innovations and applications in North America. Forest Products Journal, vol. 51, No.6, June 2001, p.12.

[324] Wilker, J. Adhesives from the Sea. Adhesives Age. October, 2002.

opportunities exist in the development and testing of adhesives and sealants for use in cold climates.

- **Other Specialty Adhesives** – A wide range of new areas of adhesives research are being mentioned in the literature utilizing biomaterials such as: lignin, tannins, caseins, soy flour and protein, animal blood, and pyrolysis oils as possible replacements for petroleum based materials.
- **Starch Based Adhesives from Grains and Pulses** – Although the use of starch for ethanol production may take significant quantities of this abundant resource, there will no doubt be many locations and opportunities for the development of alternate end products from starch and/or starch derivatives. With the combination of its availability and recovery in fairly pure form, there has been intensive focus on the use of starch from corn which has produced a wealth of information in the public domain which might be used by Canadian researchers. Information on wheat, barley, potatoes, and peas is available from Europe where these crops are often used in preference to corn. The use of domestically produced starch adhesives in Canada's competitive paper, cardboard and packaging industries suggests there should be a natural link between these two sectors.

6.6.4 Potential Impact on GHG

Although significant advances have been made in replacing some of the VOC in adhesives, sealants and paints over the past decade, more remains to be done. Until that time, these industrial chemicals will continue to contribute to diminished air quality, particularly in industrial regions where organic vapours contribute significantly to low level smog. The air deterioration problem may also persist in homes and offices in Canada where air exchange in winter time is minimal due to increased efforts in minimizing heat loss.

CONVERSION TO BIO-BASED ADHESIVES MAY RESULT IN ONLY MODEST GAINS IN GHG REDUCTION BUT SIGNIFICANT GAINS IN AIR QUALITY AND HUMAN SAFETY

If progress is made in replacing not only the solvent carrier, but also the active ingredients in adhesives, significant reductions in petrochemical feedstocks can occur. Fortunately there is a high level of collaboration among advanced nations on finding solutions to these technical challenges. However, in a global context, due to the relatively small amount of adhesives produced in relation to fuel production and use, the overall impact on atmospheric CO_2 levels would be relatively small even if totally environmentally friendly adhesives were developed.

6.6.5 Current Research

As previously mentioned, much of the research over the past decade has focussed on the reduction or modification of the highly effective but environmentally troublesome VOC found in many adhesives. These compounds, which are mainly petrochemical-based, have become the standard of performance in the sheeting board industry over the past 50 years as they provide superior drying and bonding characteristics. With the evidence brought forward in the late 80's that VOC contribute not only to GHG build-up, but also to low level chemical smog and the serious health hazards this can bring, governments in advanced nations have introduced strict controls on the use of these compounds. In most cases, industry was given advanced warning of the pending legislation and, for the most part, companies have been successful in meeting this challenge through the adoption of more appropriate production procedures and in some cases, reformulated products. However, research is ongoing to find even better solutions to these challenges.

There is also a great deal of product and process development research in progress both in public and private laboratories. Unfortunately, very little of this is occurring in Canada.

The following are examples of some of the research currently taking place in the US.

- The Thames' Research Group is currently working on an in-house project which is just entering the scale-up stages. The project involves the use of soy protein as the replacement for urea formaldehyde resin in fibreboard. Commercialization of this technology could occur by the end of 2003.[325]
- The University of Kentucky Department of Agronomy is genetically engineering soybeans to produce higher oil content and epoxy fatty acid levels. These acids can be used in not only adhesives, but oil-based paints, lubricants, insect repellants, pesticides and herbicides. The research is being funded by the United Soybean Board.[326]
- Purdue University is currently researching synthetic peptide models, protein adhesive precursors extracted from mussels and glue extracted from live mussels. Preliminary testing on porcine skin has proven quite positive.[327]
- Vertec BioSolvents, Inc. of Downers Grove, IL has recently introduced to the market environmentally friendly solvents derived from corn and soybeans. The primary ingredient is ethyl lactate an ester of natural lactic acid. These biosolvents are finding use in both the paints and coating industry and adhesives.[328]
- Iowa State University, with funding from the Iowa Soybean Promotion Board has over the past 10 years investigated the use of hydrolyzed soy protein in conjunction with chemicals used in traditional adhesives. Findings indicate up to 70% of the phenol formaldehyde in certain wood adhesives can be replaced with no loss of functionality.[329]
- Researchers at the University of Delaware have shown the potential use of both triglycerides and individual fatty acids in a range of adhesive applications. Fatty acid esters can be produced which in turn can then participate in free radical polymerizations. Cross-linking

RESEARCH TOPICS AND INVESTMENT OPPORTUNITIES ABOUND, BUT WHO WILL INVEST IN THIS RESEARCH?

[325] Evans, J. Director of the Thames' Research Group, University of Southern Mississippi, Hattiesburg, MS – Personal communication.

[326] http://www.uky.edu/Ag/NewCrops/soybeans.html

[327] Walker, J. Adhesives From the Sea: Characterization and Application of Mussel Glues. Adhesives Age. October, 2002, p 15.

[328] Henneberry, M. Green Solvents: Agrochemicals in Place of Petrochemicals. Adhesives Age. October, 2002, p 13.

[329] Myers, D. Soy-based Adhesives: Past, Present and Future. Adhesives Age. November, 2002, p 31.

of the polymers results in three dimensional polymers which perform on a par with petroleum-based polymers used in pressure sensitive adhesives.[330]

- Virginia Tech is currently investigating the potential use of polymeric isocyanate as a new rapid cure adhesive to replace formaldehyde-based product.[331]
- The Forest Products Laboratory of the USDA Forest Service has focussed attention recently on the use of small diameter trees. One option under assessment is their use in finger joined lumber. Studies to date have shown this technology to be very successful in fabricating beams and other larger dimension wood products with excellent structural properties. Bio-based adhesives are being considered for replacement of the isocyanate and formaldehyde based glues traditionally used in this application.[332]

6.6.6 R&D Analysis and Recommendations

6.6.6.1 Canadian strengths and weaknesses

Strengths:

- Canada has an impressive number of researchers versed in traditional agriculture and forestry breeding and scientific disciplines relating to the analysis and handling of plant and animal products destined for food and feed markets. Much of this knowledge would be transferable to the non-food/non-feed bioproducts field. Many of these resources lie in private companies and therefore are not readily accessible. However, there are still considerable human and physical resources residing in Canadian universities and government laboratories which are available to a bioproducts program.
- As a large producer of processed wood products, Canada has a significant strength in wood chemistry and physics.
- In addition to the human strengths, significant research infrastructure in the form of basic laboratory and pilot plant equipment resides in public sector facilities spread across the country.
- Canada has several world class medical research centres. If linked with researchers possessing expertise in polymer chemistry, potential exists to develop new adhesives aimed at the growing medical market.
- Canada's strong position in automobile, airplane and recreation vehicle manufacturing provides an opportunity for collaborative research on the development of special application industrial adhesives in the transportation industry.
- Canada's strengths in manufacturing, particularly in farm machinery, provides opportunity for collaboration on the use of adhesives in this industry. (possible involvement of the Prairie

SYNERGIES RESULTING FROM CROSS-DISCIPLINE COLLABORATION ARE NEEDED IF CANADA IS TO COMPETE IN THIS FAST MOVING TECHNICAL FIELD

[330]Bunker, S. Pressure-sensitive Adhesives from Plant Oil. Adhesives Age. November, 2002, p33.

[331]http://www.chem.vt.edu/PMIL/index.htm

[332]Frihart, C. USDA - Forest Service. Madison, Wisconsin - personal communication.

Agricultural Machinery Institute)

Weaknesses:

- The sparse adhesives research effort to date in Canada in both the public and private sectors as well as universities represents a significant hurdle to overcome.
- The lack of head offices of adhesives companies causes a significant barrier to private sector investment in R&D in Canada (research is traditionally done at, or near, head office).
- A perception among many that our business environment, our sparse population and our limited technological resources preclude our chances of success in innovative product lines.
- Limited public and private sector capital to invest in long term research where there is any chance of failure

6.6.6.2 R&D Challenges/Bottlenecks

- Replacing formaldehyde and isocyanate products may be a greater challenge than some might think. Their relatively low cost, proven performance and established market position make entry of competitive products very difficult unless superior performance and/or lower price can be demonstrated. This represents a serious hurdle to overcome.
- Water based adhesives generally take longer to dry than solvent based adhesives. This usually means added energy costs to dry the product and/or extended production lines to accommodate the longer set time. Manufacturers are reticent to incur these added costs.
- There is an inherent challenge in finding material which will not break down under intended use, but which is biodegradable or recyclable at the end of its manufactured use. This combination is not easily achieved.
- There is an ongoing challenge in using bioresources in production line operations given the usual quality variability issues.
- With the high level of foreign ownership, it will be a challenge finding companies willing to invest in longer term research in Canada.

6.6.6.3 Gaps in Research

From a Canadian research perspective, the gaps are numerous and substantial. An expanding volume of R&D information is building for use of soy and corn in adhesives. This information may be valuable to southern Ontario, but there is little information of this nature on the crops grown elsewhere in Canada.

Although Canadian scientists exhibit considerable strengths in the basic sciences and selective applied sciences, there are significant limitations in applied adhesives technologies. Clearly the focus at this time needs to be on strategic development of our capabilities and on pursuing collaborative opportunities rather than pursuing home grown research in attempts to catch up to our major competitors.

6.6.6.4 Themes for future research

- Future wood adhesives research opportunities have been identified by Professor Terry

Sellers of Mississippi State University to be in the following fields:[333]

1) cure on command: latency, fast cure at moderately elevated temperatures, and accelerator or cross-linker encapsulation;
2) combination adhesives technologies convergence where the benefits from each combine into one;
3) adhesive primers and surface treatments that are relatively inexpensive and subject to normal engineering applications;
4) environmentally benign adhesive systems, with data to prove it; and
5) life cycle predictions with associated costs.

- In addition to (or perhaps in place of) these "cutting edge" fields of research, Canadian researchers may provide the greatest contribution through collaboration with US and EU researchers to assess the potential use of competitively priced Canadian feedstocks such as canola, barley, wheat, flax, etc.

6.6.6.5 Specific Recommendations

- Although each of the opportunities identified in Sec. 6.6.3 appear to show potential for development, given the wide range of end products, the plethora of potential raw ingredients, the extent of the patent literature, the costs associated with the development and approval processes for new adhesives, and the competitive business climate, not only from new bioproducts from the US and UK but from the well established petrochemical industry which will not readily relinquish markets, Canadian research funding agencies should collaborate with other groups and agencies, and with private companies, in attempts to identify where public research funding would be best directed.
- Given the major catch-up situation facing Canada in terms of adhesives research, it is recommended that at least in the immediate future consideration be given to the allocation of any public funds which are available to "desk" research rather than bench or pilot plant research. Initial focus could be on feedstock availability and on market opportunities. Selected opportunities could then be subjected to a technical analysis, with those showing at least a theoretical potential for developmental success undergoing in depth analysis to identify specific research goals, priorities, collaborators and approach.

REWARDS COULD BE SUBSTANTIAL IF THE RIGHT PROJECT IS CHOSEN FOR THE RESEARCH

- There is potential for a major research program focussed on the use of bio-based adhesives to supplement and/or replace both formaldehyde and isocyanate based resins in panel board manufacturing.
- Another specific field of research worth consideration is that of investigating the use of the fairly extensive research on soy protein in bioadhesives but using canola, field pea or barley protein as the starting material.
- Similarly, the use of derivatives from wheat, barley or potato starch in place of corn starch in adhesives formulations may be worth investigating.

[333]Sellers, T. Wood adhesive innovations and applications in North America. Forest Products Journal, vol. 51, No.6, June 2001, p.12.

- Effort should be made to find synergies with other processing options. For example, barley protein may find use in specialty adhesives markets while the 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.
- Given Canada's world class expertise in both medical and fisheries technologies, it would be logical to actively search out opportunities in the medical adhesives field where natural marine adhesives have shown considerable promise.
- Consideration should also be given to building basic scientific understanding and strengths in selected research fields which could support future commercialization efforts in this sector.

6.7 Biocomposites

6.7.1 Sector Overview

The use of natural fibres in the automotive sector has begun to develop and gain significant momentum in Europe. While interest in North America in this sub-sector is also starting to build, greater focus has been on the construction biocomposites sub-sector.

Biocomposites made from flax crop residues and industrial hemp fibres have the potential to reduce GHG emissions by lowering component weight, reducing the use of energy-intensity products (e.g. glass fibres, cement). Yet to be definitively reported is the life cycle analysis of these biofibres when compared with petrochemical-based fibres for the target applications.

Several regions in Canada may have strategic advantages in the biocomposites area, but further research, development and demonstration is required all along the supply chain to reduce prices, improve quality, ensure fibre availability, and demonstrate the viability of current fibre processing technologies and new product development.

AUTOMOTIVE AND CONSTRUCTION BIOCOMPOSITES - NEW MARKET OPPORTUNITIES FOR CANADIAN FARMERS?

6.7.2 Key Opportunities

The production of natural fibres in the EU in 1999 was almost 100,000 tons, with flax accounting for about 2/3 of production, and hemp the other 1/3.[334] Currently, glass fibres account for almost all of the fibre reinforcement used in Europe (approximately 600,000 tonnes per annum)[335] but natural

[334]Karus, M., Kaup, M. and Lohmeyer, D. Study on Markets and Price Situation of Natural Fibres (Germany and EU). nova Institute. March 2000. A report commissioned by the Fachagentur Nachwachsende Rohstoffe e.V.

[335]Hill, C.A.S., Hughes, M. and Hague, J.R.B. The Role of Fibre Defects in the Deformation and Fracture of Bast Fibre Reinforced Thermosetting Polymer Matrix Composites. EcoComp, University of London, UK, September 3-4, 2001.

fibres show notable progress to be a viable replacement in several markets.

About 22,400 tonnes of natural fibres where used in EU automotive composites in 1999, with Germany accounting for about 70% of the market.[336] Other potential biocomposite markets include aerospace, construction, and transportation.[337]

Interest in biocomposites has been driven in the EU by the Directive on End of Life Vehicles, which requires that 85% of a modern European car must be made from recyclable materials in 2005.[338] Daimler Chrysler has developed a number of automotive products based on flax fibre composites. Ford's materials engineering department in Cologne Germany has done development work in the area of injection moulding using flax and polypropylene (PP) for radiator grills, front ends, and engine shields for the Ford Focus. Owens Corning is also exploring the possibility of supplying natural fibre mats for moulding applications and fibres for injection moulding.[339] BMW, Fiat, Olympia Motors, and other automotive companies in Europe are also engaged in developing natural fibre composites.[340]

The use of natural fibres in the North American automotive industry has begun, but is substantially behind the progress developed in Europe. One leading constraint in North America is the instability of bast fibre/decortication operations.

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[336]Ellison, J. The Use of Natural Fibres in Nonwoven Structures for Automotive Component Substrates. Renewable Resources - Becoming a Reality. London, UK, December 11, 2001. A meeting organized by the SCI Crop Protection Group in collaboration with the Central Science Laboratory. For more details, see Ellison, G.C., McNaught, R. and Eddleston, E.P. The Use of Natural Fibres in Nonwoven Structures for Applications as Automotive Component Substrates. UK Ministry of Agriculture Food and Forestry, February, 2000.

[337]Riedel, U., Nickel, J. and Hermann, A.S. High Performance Applications in Aerospace and Related Industries. IENICA 1999. However, given the difficulty in recycling natural fibres, some experts are pointing to other markets which may not be so demanding, such as footwear insoles (12 million pairs per year) and carpet underlays (300 million sq metres per year). See, for example, Ellison, J. The Use of Natural Fibres in Nonwoven Structures for Automotive Component Substrates. Renewable Resources - Becoming a Reality. London, UK, December 11, 2001.

[338]Auto manufacturers are interested in natural fibres for improved weight reduction, developing a "green" image, recycling/disposal, eliminating the difficult handling of fibreglass, greater design flexibility and modularity, improved crash protection, and overcoming limitations in the supply of fibreglass. See Thomason, J.L, and Cheney, T. Injection Mouldable Long Fibre Reinforced Polypropylene for Automotive Applications. EcoComp, University of London, UK, September 3-4, 2001. For a detailed study on biocomposite markets and current technologies see Ellison, G.C., McNaught, R., and Eddleston, E.P. The Use of Natural Fibres in Nonwoven Structures for Applications as Automotive Component Substrates. The Textile Consultancy Limited. Ministry of Agriculture Fisheries, and Food. United Kingdom. February, 2000. For a discussion of natural resins that can be used in the polymer matrix see Schuh, Thomas. Renewable Materials for Automotive Applications. IENICA 1999.

[339]Thomason, J. L. and Cheney, T. Injection Mouldable Long Fibre Reinforced Polypropylene for Automotive Applications. EcoComp. University of London, UK, September 3-4, 2001.

[340]Pejis, T. Markets and Trends in Ecocomposites for Automotive Applications and Beyond. EcoCom, University of London, UK, September 3-4, 2001.

6.7.3 Potential Reduction of GHG Emissions

Life Cycle Analysis (LCA) tries to quantify the environmental impacts associated with a process or product, including energy consumption and emissions associated with a product's production processes, use, and level of recyclability. In this context, the results of LCAs of traditional automotive composites made from glass fibre/PP are problematic because of the higher weight associated with glass fibre, and the complex problems involved in trying to recycle them.[341]

According to Professor Heinrich Flegel, Director of Production Technology at the Daimler Chrysler Research Centre in Ulm, Germany: "*Use of natural fibres reduces weight by 10% and lowers the energy needed for production by 80%, while the cost of the component is 5% lower than the comparable fibreglass-reinforced component.*"[342]

Natural fibre reinforced/PP composites are also a challenge to recycle. However, temperature and pressure control in the extruder, and screw geometry, can be used to avoid embrittlement. And under the right conditions, thermoset composites using natural fibres can be recycled by grinding, and then re-introducing the grind into the mix as a filler.[343]

6.7.4 Major Players

Europe

Examples include: Natural Fibres Organization (UK); The Textile Consultancy Ltd. (UK); Solvay S.A. (Belgium); Department of Natural Materials and Packaging IF Tulln (Austria); Biocomposites Centre, University of Wales in Bangor (Wales); Department for Materials Research Centre Riso (Denmark); SICOMP AB (Sweden); Wolfson Centre, Brunel University (UK); Department of Fibres and Cellulose, Agrotechnological Research Institute, (ATO-DLO); Nonwovens Research Group, School of Textiles, University of Leeds (UK); nova-Institut (Germany); Preform Biocomposites (Germany).

United States

Examples include: Lear Corporation; Center for American Flax Fiber; Biocomposites Group, Iowa State University; Center for Composite Materials, University of Deleware; Composite Materials and Structures Centre, University of Michigan; Department of Wood Science, North Carolina State University.

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[341] See for example, Giudice F., La Rosa, G. and Risitano, R. G. Evaluation of Recyclability of Thermosetting Composites: Recycling GRP for Pultrusion Process. EcoComp, University of London, UK, September 3-4, 2001.

[342] Daimler Chrysler Corporation news release. July 17, 2000.

[343] Jakwerth, G. Recycling of Natural Fibre Composites in the Automotive Industry. 4th International Wood and Natural Fibre Composites Symposium, April, 2002. See David Plackett's trip report posted on the Danish Polymer Centre at http://www.polymers.dk/research/posters/tripreport_plackett.htm.

6.7.5 Current Research

Research is being conducted at all stages of the supply chain, but most of the R&D in the biocomposites area focuses on improving the processability and performance of natural fibre composites.

Plant fibres can compete against glass fibres on stiffness, but they lack tensile strength, compressive strength, and especially impact strength compared to glass fibre composites.[344] Moisture can also be a problem when using natural fibres as a reinforcement in polymer composites. Moisture causes the fibres to swell, and after prolonged exposure, they can be subject to rotting from fungi attack. As a result, the durability and mechanical properties of the composite can be compromised. In the case of automotive parts made from natural fibre composites, this has restricted products to interior components of the car not subject to moisture effects.

Some of the main themes include:[345]

6.7.5.1 Crop Production

Harvest, Transportation, and Storage

- Agricultural biomass is difficult to harvest, store and process. Materials tend to be bulky, subject to degradation while in storage, and are at risk of catching fire. Protecting the stored fibres from moisture using tarps is also expensive. The Biocomposites Group, Center for Crops Utilization Research, Iowa State University is studying wet storage or ensilage as an alternative method to storing fibre. It is also investigating composting technologies to pre-treat and dry the fibre prior to further industrial processing.[346]

New Fibre Varieties

- An EU consortium has formed to develop a new hemp variety that promises to produce improved fibre quality and better decortication (less energy needed to isolate the fibres). The team is researching a range of issues including growing conditions for seed multiplication and fibre production; harvesting methods, and isolation and optimization of fibre separation; and the molecular basis for improved decortication and fibre performance. The knowledge gained from this project will be used to design new custom-made hemp varieties for tailor-

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[344] Specht K. Structural Optimized Natural Fibre/PP Composites for Automotive Interiors. 4th International Wood and Natural Fibre Composites Symposium, Kassel, Germany, April 10-11, 2002. See David Plackett's trip report posted on the Danish Polymer Centre at http://www.polymers.dk/research/posters/tripreport_plackett.htm.

[345] Ibid. Also see Ellison, J. The Use of Natural Fibres in Nonwoven Structure for Automotive Component Substrates Renewable Resources - Becoming A Reality. December 11, 2001 and Garkhail, S.K and Pejis, T. Micromechanical Models as a Guide for Future Optimizations of Natural Fibre-Reinforced Plastics. EcoComp University of London, UK, September 3-4, 2001.

[346] Kuo, M. L., Meyers, D. G., Richard, T., and Stokke, D.D. Composite Materials: New Opportunities for Bio-based Products. 5th International Biomass Conference of the Americas. Orlando, Florida, 2001.

made industrial applications.[347]

- Another EU consortium is using proteomics to isolate genes involved in the biosynthesis of cell wall lignins and hemicellulose in tobacco. Variations in these components can affect fibre quality and cellulose availability. This knowledge can be used to direct molecular breeding programs and genetic modification to improve flax fibre quality.[348]

New Fibre Treatments

- Well studied techniques used in the composites industry to treat technical fibres such as E-glass can also be used to improve the mechanical behaviour of natural fibres. These techniques include a broad range of physical, chemical, thermal and mechanical treatments. Physical methods include stretching, calandering, thermotreatment, electric discharge (e.g. cold plasma), and mercerization. Chemical treatments include dewaxing, acetylation, chemical grafting, delignification, bleaching, and the use of coupling agents and compatibilisers (e.g. isocyanates, triazine, organosilanes, MAPP). Other methods include steam explosion (to remove most of the lignin and hemicellulose, which are highly hygroscopic) and a new pretreatment process called Duralin.[349]
- The Duralin process involves a novel three stage pre-treatment of flax fibres prior to decortication. The first stage (hydro-thermolysis) involves heating green flax straw in water at 160-180 degrees Celsius, followed by drying, and then curing by heating the fibres in dry steam at 160-180 degrees Celsius. During the thermolysis stage, the hemicellulose is converted into aldehydes, and the lignin into phenol moieties. During the curing stage, the aldehydes and the phenol moieties combine to form a water resistant resin. The fibres also have higher crystallinity after curing. This process selectively reorganizes the chemistry of flax and shive fibres. The benefits of the process include: the ability to avoid dew-retting, easier decortication, higher fibre yield, less swell in moisture, higher temperature stability, and better quality consistency. The fibres can be used for polymer composites, while the shives can be used as a filler in certain composite products. The seeds can also be used and the process water can be converted to methane.[350]
- The Biocomposites Group at Iowa State University has found that refining agricultural residues into a flour form makes it easier to bond fibres to conventional and soy-based adhesives. This approach may provide a solution to the high cost of isocyanate binders,

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[347] EU Contract QLK5-1999-01505. HARMONIA: Hemp as Raw Material for Novel Industrial Applications. Progress report abstract, January, 2001. For more details, see their web site at http://www.eu-harmonia.org/

[348] EU Fifth Framework Programme, project QLK5-1999-31493. Integrated Control of Polysaccharide and Lignin Biosynthesis to Improve Cellulose Content, Availability and Fibre Quality.

[349] Stamboulis, A. Interface Modification for Natural Fibre Composites: A Review. EcoComp, University of London, UK, September 3-4, 2001. See also Wayenberg, I. Van de, Ivans, J., Katholieke, I. Verpoest, Coster, A. de, Kino, B., and Baetens, E. Influence of Processing and Chemical Treatment of Flax Fibres on Their Composites. EcoComp, University of London, UK, September 3-4, 2001 and Cantero, G., Arbelaiz, Llano-Ponte, R., and Mondragon, I. Effect of Fibre Treatment on Wettability and Mechanical Behaviour of Flax/Polypropylene Composites. EcoComp, University of London, UK, September 3-4, 2001.

[350] Pott, G. T., Ceres B.V. Reduction of Moisture Sensitivity in Natural Fibres. EcoComp, University of London, UK, September 3-4, 2001.

which have caused economic challenges to agri-fibre board plants like Isobord and others.[351]

6.7.5.2 Processing

Use of Natural Resins in the Polymer Matrix[352]

- ACRES at the University of Delaware is developing green resins from soybean oil triglycerides and synthesizing new polymers suitable for liquid moulding processes like RTM. This process, involving the epoxidization of soybean oil, has been used to produce panels for John Deere tractors and hay balers.[353]
- The Biocomposites Group at Iowa State University has been studying soy-based adhesive resins as a binder for the composite materials industry. The resin consists of defatted soybean flour cross-linked with synthetic phenol formaldehyde. Soybean flour is less expensive than purified soy protein.[354]
- Perform Biocomposites in Germany has developed a new polymer based on triglycerides and polycarboxylic acid anhydrides called PTP®. It has properties similar to conventional epoxy resins. The company is processing PTP with natural fibres such as flax or hemp to make hardwearing and sturdy parts for interior linings of cars, trains or for furniture. The company has been working with BMW since 1995.[355]
- SICOMP AB (Sweden) and Fortum Technology (Finland) have been studying flax/polylactic acid (PLA) composites. Initial results indicate this polymer matrix has a composite strength 50% greater than flax/PP composites that are typically used today in many automotive panels. PLA has good processability and can be processed much like PP-based composites. Additional research is required to improve the adhesion between flax and PLA.[356]
- Fasal has produced a thermoplastic granulated material containing waste wood in chip form (or sawdust), maize and natural resin (polyesteramide by Bayer, called BAK). The product

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[351]Kuo, M. L., Meyers, D. G., Richard, T., and Stokke, D.D. Composite Materials: New Opportunities for Bio-based Products. 5th International Biomass Conference of the Americas. Orlando, Florida, 2001.

[352]For a discussion of various biopolymer matrices used in biocomposites, see Riedel, U., Nickel, J. and Hermann, A.S. High Performance Applications in Aerospace and Related Industries. IENICA 1999.

[353]Pejis, T. Markets and Trends in Ecocomposites for Automotive Applications and Beyond. EcoComp, University of London, UK, September 3-4, 2001.

[354]Kuo, M. L., Meyers, D. G., Richard, T., and Stokke, D.D. Composite Materials: New Opportunities for Bio-based Products. 5th International Biomass Conference of the Americas. Orlando, Florida, 2001.

[355]See Schmidt, B., and Langer, E. Biomass for Industry: German Strategies for the 21st Century. 5th International Biomass Conference of the Americas. Orlando, Florida, 2001.

[356]Oksman, K., Skrifars, M., and Seliri, J-F. Natural Fibres as Reinforcement in Polylactic Acid Composites. EcoComp, University of London, UK. September 3-4, 2001. Other fibres such as kenaf and jute are also being studied as part of a natural fibre PLA matrix. See Nashino, T., Hirao, K., Kotera, M., and Nakamae, K. Kenaf Reinforced Biodegradable Composite and Plackett, D., Andersen, T., Loegstrup P., Batsberg W. and Nielsen, L. Biodegradable Composites Based on L-Polylactide and Jute Fibres. EcoComp, University of London, UK, September 3-4, 2001.

is called Fasalex.[357]

- Other bio-based resins that could be used in composites include cellulose ester (Bioceta), and PHB (Biopol)[358] and polylactic acid.[359]

New Processing Technologies

- Natural fibre nonwovens are widely used in compression moulding processes, but the technology is limited to the production of simple shaped articles. More complex articles require the use of injection moulding[360] or new innovations in extruder technology.[361] The automobile industry is moving towards injection molded products requiring a shorter fibre.[362]

Development of New Analytical Tools

- The separation of hemp and flax fibres from the shorter shives involves a mechanical process called decortication which "breaks" the fibre stems to facilitate separation. This action can create "kinking" in the fibres leading to subsequent fibre-matrix debonding and matrix fracture. These issues affect impact strength, an issue central to automotive safety. After an automobile is recycled, there are questions about the strength of the new recycled materials. New analytical tools such as half fringe photoelasticity[363] and Raman spectroscopy[364] allow researchers to study these issues at the micro-structural level.

6.7.5.3 Market Utilization

New Product Applications

- Wood fibre composites made from >50% wood (waste wood or wood flour) and recycled plastics (HDPE) are finding markets in residential and marine decking, railing systems, doors, window frames, exterior siding, and roofing shingles. Although these products are

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[357]Pejis, T. Markets and Trends in Ecocomposites for Automotive Applications and Beyond. EcoComp, University of London, UK, September 3-4, 2001.

[358]For additional details about natural resin based composites see EU Contract FAIR-CT98-3919, New Functional Biopolymer - Natural Fibre - Composites from Agricultural Resources. Final report, July, 2001. The report examines 5 different fibres combined with 4 sorts of matrices with additional combinations created by modifying both the fibres and the matrix materials using PLA, starch with synthetic polymers, and proteins.

[359]Herrmann, Axel. High Performance Applications from Plant Fibres in Aerospace and Related Industries. IENICA 1999.

[360]Thomason, J.L, and Cheney, T. Injection Mouldable Long Fibre Reinforced Polypropylene for Automotive Applications. EcoComp, University of London, UK, September 3-4, 2001. Also see Powell, R.M. The Limits of Design Potential in Plant Fiber Products. IENICA 1999.

[361]Potente, H., and Reckert, F. Direct processing of Materials Containing Starch By Using an Innovative Extrusion Technology. EcoComp, University of London, UK, September 3-4, 2001.

[362]Lloyd, E., personal communication, March 25, 2003.

[363]Hill, A.S., Hughes, M. and Hague, J. R.B. The Role of Fibre Defects in the Deformation and Fracture of Bast Fibre Reinforced Thermosetting Polymer Matrix Composites. EcoComp, University of London, UK, September 3-4, 2001.

[364]Eichhorn, S.J. and Young, R.J. Deformation Micromechanics of Natural and Regenerated Cellulose Fibre Composites. EcoComp, University of London, UK, September 3-4, 2001.

more expensive, they offer significantly greater moisture resistance, durability and significantly reduced maintenance. As such these products enjoy lower life cycle costs and while at the same time not carrying the environmental concerns of pressure treated lumber.[365] Bast crops, including both bast fibre, as well as core (i.e. shive or hure) portion are being considered for these product applications.[366]

- Another possible area is natural fibre reinforced polyurethane (PUR) products which are currently used in door panels and parcel shelves in the automotive industry. One new product is a hybrid paper honeycomb/glass fibre mat/PUR composite used as a load floor in vehicle trunks. The PUR component uses flax, sisal or hemp mats that are dried for 2-3 minutes at 120-130 degrees Celsius to reduce moisture down to 1% before high-pressure spray application of PUR. The PUR is then cured by heat (>120 degrees C) and pressure. The components are then laminated under vacuum and covered with TPO foil or other material.[367]

6.7.6 R&D Analysis and Recommendations

6.7.6.1 Canadian Strengths

Canada has several strengths. Unlike the US, Canada has legalized the commercial production of industrial hemp, which is a promising reinforcement fibre in the emerging biocomposite markets in both the automotive and construction sectors.

UNLIKE THE US, CANADA HAS LEGALIZED THE PRODUCTION OF INDUSTRIAL HEMP

Ridgetown Agricultural College, Kemptville Agricultural College and various hemp companies and grower associations have sponsored industrial hemp research programs in Ontario since 1995 and have developed considerable agronomic expertise.[368]

Two Ontario firms, Kenex Ltd., Hempline, Inc., have focussed on hemp fibre processing, and are strategically located in southwestern Ontario close to important downstream manufacturers in the plastics and automotive industries.

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[365]Pejis, T. Markets & Trends in Ecocomposites for Automotive Applications & Beyond. EcoComp, University of London, UK, September 3-4, 2001.

[366]See for example, Blossom, S. Hemp Construction technologies. EcoComp, University of London, UK, September 3-4, 2001.

[367]Willmeroth, G. Natural Fibre Reinforced Polyurethane (PUR) in the Automotive Industry. 4th International Wood and Natural Fibre Composites Symposium, Kassel, Germany, April 10-11, 2002. See David Plackett's trip report posted on the Danish Polymer Centre at http://www.polymers.dk/research/posters/tripreport_plackett.htm.

[368]For example, see Baxter B., and Scheifele G., Growing Industrial Hemp in Ontario, Ontario Ministry of Agriculture and Food Fact Sheet, August, 2000. And Scheifele, G. Agronomic Field Studies To Determine Factors Affecting Hemp Stalk Production in Northern Ontario, Ontario Ministry of Agriculture and Food Fact Sheet, February, 2000.

The Automobile of the 21st Century (AUTO21), a Federal Network of Centres of Excellence, is located in Windsor, and a consortium led by Francois Trochu, at the Ecole Polytechnique, is investigating polymer composites involving the use of natural fibres. This research program will be developing product formulations; conducting manufacturing trials and rheological studies; performing computer simulations of manufacturing; performing evaluations of test specimens; optimizing processes and formulations; and conducting material characterizations and test specimen production using hemp, flax, kenaf, and wood.[369]

Alberta is another regional centre with biocomposite expertise in hemp, flax, and cereal straw. Hemp agronomic studies have also been conducted by Alberta Agriculture, Food and Rural Development[370] Expertise also exists at the Forest Products Group and the Department of Renewable Resources, University of Alberta with respect to the prototyping of hemp panels, and nonwoven products.[371]

Hemp is a potentially important crop for increasing biodiversity, and reducing greenhouse gas emissions. Hemp scores high on a scale of "biodiversity friendliness", higher than other Canadian crops including potatoes, flax, cereal (corn, wheat, barley, oats) and oil seed (soybean, canola) crops.

Saskatchewan represents a third potential regional centre for biocomposite production. A flax straw processing plant (Durafbre), located near Canora SK, has until recently produced an animal bedding (Flaxsorb) and a natural fibre reinforcement (NatureGlass) to replace glass fibres in the automotive composites market. In April 2002, Cargill decided to pull out of the operation. The processing plant has since been purchased and the new owner intends to pursue composite markets in the construction sector, where the product specifications may be more closely matched to the capabilities of the Canora decorticating plant.[372]

The University of Saskatchewan is also applying for a National Centre of Excellence for natural fibres.[373] The University is currently working on an ASTM natural fibres sub-committee and is also working with the USDA on NIR methods of fibre content measurement.[374]

Overall, Canada has developed considerable skills and knowledge in the natural fibre composites area, using oilseed flax fibre crop residues and industrial hemp fibres.

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[369]Project C3, Polymer Composites. AUTO21.

[370]Blanch, M. and V. and Toogood, John. Review of Three years of Hemp Trials on the Blanch Farm. Alberta Hemp Symposium Proceedings, 1998. Labrecque, Lawrence. Farming for the Future Application - Hemp Trials. Alberta Hemp Symposium Proceedings, April, 2002.

[371]See, for example, Wasylciw, W. and Domier, K.W. Manufacture of Hemp Panel Prototypes. Alberta Hemp Symposium Proceedings, April, 2002. Manitoba also has considerable agronomic experience with hemp cultivation but their experience supports the cultivation of oilseed varieties rather than fibre. See, for example, 1996 Hemp Evaluation Trails. Manitoba Agriculture and 1997 Hemp Trials Report. Manitoba Agriculture.

[372]Personal communication with new owner.

[373]Comments from Ron Kehrig, Bioproducts Saskatchewan.

[374]Ibid.

6.7.6.2 Bottlenecks (R&D challenges)

There are four key bottlenecks to the development of natural fibre composites:

- price (prices have to come down to compete with current competitors and imported hemp/flax from Europe);
- availability (flax crop residues are plentiful, but hemp production is constrained until markets develop);[375]
- quality (natural fibres lack impact strength because of poor bonding between fibre and polymer matrix); and
- proven fibre processing technology (e.g. Hempline is operating at a prototype scale and is seeking investments to scale up its fibre processing capacity).

6.7.6.3 Gaps in Research

More specific gaps in R&D include[376] the need to:

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[375]There is a "chicken and egg" relationship between feedstock availability and market development. Industry is reluctant to commit to large capital expenditures on manufacturing equipment if there isn't a large supply of cheap, high quality, easily available feedstocks. On the other hand, there is reluctance on the part of farmers to plant crops that do not have an assured market. In the case of new crops like hemp, the expected markets have been very slow to develop. In general, the markets for natural fibres have declined over the last two decades. World markets for cotton, flax, hemp, wool, and rayon have all declined in absolute terms since the early 1990s (see Industrial Hemp in the United States: Status and Market Potential. USDA. January, 2000). While some markets for hemp, e.g. in the automotive biocomposites area, have increased in Europe it is largely due to significant government subsidies at all stages of the supply chain, and recent suggestions to cut back EU subsidies could significantly harm this emerging industry before it becomes established (see Study on Markets and Price Situation of Natural Fibres (Germany and EU) Nova Institute, March 2000). Even with public subsidies, market demand for hemp fibres in the automotive industry in Europe (1999) was only 1,700 tonnes compared to a demand of almost 20,000 tonnes for other natural fibres like jute, sisal, flax, and kenaf. Even in Germany, where there is considerable support for hemp fibre production, the automotive industry still (as of 1999) used 50,000-60,000 tonnes/year of recovered cotton fibres and 50,000-70,000 tonnes/year of wood chips. In Canada, one of the major tier one suppliers is Magna International, which uses mostly wood in fibre composites. Unlike some areas of Europe, wood residues in Canada are cheap and plentiful. This limited market demand may have been a contributing factor in the decision of Cargill and the Province of Saskatchewan to close down the Durafibre plant in Canora Saskatchewan, which was processing flax residues for the automotive market. Although natural fibres have drawn a lot of interest on the part of auto manufacturers in North America, this interest has not yet been translated into important market opportunities. There still remains a significant amount of comparative fibre research to be conducted (see for example the AUTO21 study in Canada and the Qinetiq-led Biomat project in Europe). Some of this research will go on for about four years before automakers and their tier one suppliers make commitments affecting future production. While this research work proceeds, hemp fibre processors will be constrained in their ability to scale up production because neither banks nor farmers will want to make capital investments until the auto industry in North America can offer long term contracts for hemp/flax fibres. Yet, without a viable infrastructure in place, it will be difficult for the auto industry to commit to using natural fibres like hemp or flax. In the end, governments may have to assist hemp and/or flax fibre processors (and possibly specialized hemp/flax harvesting equipment manufacturers) with capital assistance, loan guarantees, tax exemptions, and other financial forms of assistance in order to successfully launch the industry.

[376]See, for example, Scheifele G., Determining the Feasibility and Potential of Field Production of Low THC Industrial Hemp for Fibre and Seed Grain in Northern Ontario. Ontario Ministry of Agriculture and Food. March, 1999. Small, Ernest and Marcus, David. Hemp: A New Crop with New Uses for North America. In Trends in New Crops and New Uses. Janick, J., and Whipkey, A. (eds.) ASHS Press, Alexandria Virginia. 2002.

- improve fibre yields and quality by focussing additional agronomic research on developing improved and less costly Canadian fibre seed varieties, finding optimum seeding rates, and improving fertility management appropriate to different regions.
- improve the economics of large-acreage, commercial harvesting by developing new or modified harvesting and baling equipment
- improve fibre processing, cleaning and fibre separation
- reduce the damage caused to the fibre through the decortication process
- improve the bond between natural fibres and the polymer matrix[377]
- improve short fibre injection moulding systems by controlling fibre size and developing new compounding technologies
- develop bio-based resins for the polymer matrix to increase GHG reduction potential[378]
- in addition to continued study of automotive composites, there is also a need for new product development in the construction composite sector e.g. new forms of natural fibre-based insulation, fibreboard, fibre-reinforced cement, drywall, and ceramic tiles.[379]
- ensure quality control throughout the supply chain.[380]

6.7.6.4 Themes for Future Research

Most of the research in Canada on natural fibres has focussed on agronomic research. However, for the biocomposite sector to develop, research, development and demonstration funding will be required all along the supply chain including the development of better fibre varieties appropriate to different regions in Canada; improved crop harvesting, storage, and transportation equipment; new fibre pre-treatment strategies; development of bio-based polymer matrices; new processing technologies; and more product development studies.[381] The research themes summarized in earlier sections on crop production (6.7.5.1), processing (6.7.5.2), and market development and utilization (6.7.5.3) provide examples of the types of future research themes that could be funded in Canada.

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[377]A company in Manitoba (Acsion Industries, Inc) tried to use a combination of chemicals and electron beam treatment to cross-link flax fibres and shives (obtained from Durafibre) to polypropylene. Unfortunately, the attempt failed. See Stepanik, T. Use of Electron Beam Processing to Improve The Mechanical Properties of Flax Plastic Composites. ARDI Project results, July 2000. The University of Saskatchewan is also studying the chemical pre-treatment and polymerization of flax fibres for use in plastics as fillers and fibre reinforcement.

[378]This point has been made by Dr. Thomas G. Schuh, Manager, Polymer and Composite Application. Daimler-Chrysler AG, Stuttgart, Germany in Renewable Materials for Automotive Applications. IENICA, 1999. One polymer he identified is polymide 11 (PA11), made from castor oil. Also see Riedel, U., Nickel, J. and Hermann, A.S. High Performance Applications in Aerospace and Related Industries. IENICA 1999 for a discussion of various biopolymer matrices being tested in the aerospace industry.

[379]For a discussion, see Small, Ernest and Marcus, David . Hemp: A New Crop with New Uses for North America, in Trends in New Crops and New Uses. Janick, J. and Whipkey, A. (eds.) ASHS Press, Alexandria Virginia. 2002.

[380]See, for example, Kessler, R.W., Kohler, R., and Tubach, M. Strategy for a Sustainable Future of Fibre Crops. IENICA, 1999.

[381]These kinds of themes are a specialized subset of challenges facing new crop development in general. For a broad discussion of the challenges facing new crop development see Blade S.F., and Slinkard A. E., New Crop Development: The Canadian Experience, in Trends in New Crops and New Uses. Janick J., and Whipkey A., (eds.) ASHS Press, Alexandria Virginia. 2002.

6.7.6.5 Specific Recommendations

This area could benefit from the adoption of a long range strategic plan, similar to Alberta's Agricultural R&D Strategic Plan.[382] Several of their guiding principles for the R&D system would be very helpful to the development of biocomposites.[383] Some of these principles, modified to apply to Canada as a whole, could be summarized as follows. R&D should be:

- market driven toward end products that meet long term strategic goals (e.g. 2010);
- focussed on fostering research, development, and commercialization
- future-focussed and built on provincial or regional strengths and comparative advantages
- encourage collaboration across geographic, sectoral, institutional, and disciplinary boundaries.

CANADA NEEDS A STRATEGIC R&D PLAN FOR BIOCOMPOSITES

At the moment, hemp, flax, and wood appear to be in competition for the same biocomposite markets. Some national process that brought all the players together to look for synergistic solutions might prove beneficial to everyone. The AUTO21 project could provide the foundation for that type of process.

6.8 Biolubricants

6.8.1 Sector Overview

Biolubricants and hydraulic fluids represent an important opportunity for reducing GHG emissions. Considerable research has been conducted over the last 10 years in North America and Europe where complete supply chains have been created in many countries.

Canada is one of the leaders in the development of high oleic canola and high erucic rapeseed oils that are used to make industrial lubricants and other products in the plastics and cosmetics industries. A complete supply chain for high oleic canola has been established. Expansion of this supply chain to include high oleic soybean and high erucic rapeseed oils may also be possible.

CANADA IS A LEADER IN DEVELOPING HIGH-OLEIC AND HIGH-ERUCIC OIL SEEDS

A national R&D program in support of this sector is needed, and could provide important economic as well as environmental benefits to the nation.

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[382]Agriculture and Food Strategic Research and Development Plan for Alberta, (2002-08 and Beyond). Alberta Agriculture, Food and Rural Affairs, October 16, 2002.

[383]Ibid., p. 12.

6.8.2 Key Opportunities

Vegetable oils can be used to make a broad range of lubricant products, including: food-grade machinery oils, chain bar lubricants, gear and transmission fluids, hydraulic fluids, farm tractor oils, drilling oils, outboard marine two-stroke engine oils, metal cutting oils, etc.

Biolubricants are expected to penetrate at least 20% of the European lubricants market by 2010.[384] Markets have not developed at the same pace in the US, but a broad range of companies are now manufacturing biolubricants in the US and sales are expected to increase. The United Soybean Board has rated lubricants and hydraulic fluids as one of the top five industrial market opportunities in the US for soybeans.

BIOLUBRICANT MARKET SHARE EXPECTED TO HIT 20% IN THE EU BY 2010

The 1994 sales of lubricants in Canada were about one billion litres. Only about 200,000 litres were produced from vegetable oils.[385] Typical customers were logging companies, municipalities, parks, and golf courses. The market for vegetable oil-based lubricants were expected to increase to 1 million litres by the year 2000.[386] Despite the small current market, the potential is large.

Each application area has unique performance requirements.[387] Because vegetable oil-based lubricants generally have lower performance characteristics than their petroleum-based competitors, the initial market focus has been on "total loss" lubricants like chain bar oil and two-stroke engine oils, and on food-grade machinery oils. These applications take advantage of the lower eco-toxicity and more favourable biodegradability characteristics of biolubricants.

Other application areas demand higher performance. To expand market opportunities in these areas requires on-going research and development into plant biotechnology and improved processing of specific esters that meet more demanding market requirements. From a GHG reduction perspective, one market segment that justifies more R&D is the huge motor and gear oil market, which accounts for about half of the total lubricant market.[388]

[384]Johnson, D. Renewable Raw Materials: A way to reduce greenhouse gas emissions from EU industry? DG Enterprise/E.1 July 2000.

[385]Reaney, M. and Blondeau J. Biooils Market Study. Saskatchewan Canola Development Commission. 1996.

[386]Ibid.

[387]For example, see the Lubrizol Corporation web site at http://www.lubrizol.com/default.htm

[388]See The IENICA National Report for Germany, 1999.

6.8.3 Potential Impact on GHG Reduction

A European study of the savings potential in annual EU CO_2 emissions from the use of renewable raw materials lists lubricants at the top, tied with surfactants:

- Lubricants - 2 million tonnes CO_2 reduction;
- Surfactants - 2 million tonnes CO_2 reduction;
- Solvents - 1 million tonnes CO_2 reduction;
- Biopolymers - 600 million tonnes CO_2
- Biocomposites - unknown (but could be significant, if applied to insulation)

The time frame to reach these savings was estimated at 10-20 years.[389]

6.8.4 Major Players

Europe

Examples of companies that produce biolubricants, bioadditives or are co-ordinating R&D include: Carl Bechem Gmbh (Germany); Fuchs Petrolub AG (Germany); Koipesol Semillas S.A. (Spain); Rheine Chemie Rheinau GmbH (Germany); Tessol GmbH (Germany).

Examples of key universities, government labs, research institutes and NGOs include: AGRICE (France); FNR (Germany); Stanzione Sperimentale Oli e Grassi (Italy); Tekniker (Spain); and John Innes Centre (UK).

United States

Examples of companies selling biolubricants, hydraulic fluids, greases, cutting oils, etc. include: Renewable Lubricants, Inc. (Hartville, OH); Terresolve Technologies (East Lake OH); Environmental Lubricants Manufacturing Ltd. (Waverly, IA); Gemtek (Phoenix, AZ); HydroSafe Oil Division (East Lansing, MI); International Lubricants (Seattle, WA); Uniqema (New Castle DE); Cargill (Minneapolis, MN); John Deere (Moline, IL); West Central Soy (Ralston, IA); Lubrizol Corporation (Wickliffe, OH).

Examples of universities and research institutes include: ABIL, University of Northern Iowa (Waverly, IA); Chemical Engineering Department, Penn State University.

6.8.5 Current Research

Plant biotechnology is being used to increase seed oil yields and design oils with fatty acid profiles

[389]Johnson, D. Renewable Raw Materials: A way to reduce greenhouse gas emissions from EU industry? DG Enterprise/E.1 July 2000.

that more closely meet industry specifications.[390]

Genetic modification is also being used to create oil seed varieties that can reduce the costs of manufacturing, either by reducing the number of manufacturing steps in the production process, or by reducing the additives required to enhance performance. Advances in these areas are important because they can close the price gap between petroleum and bio-based products.

Transgenic engineering is being used to transfer genes from special crops and wild plants to domesticated crops such as soybean, canola, or corn. The fatty acid profiles of thousands of wild plant species with novel and industrially useful profiles have been identified. The transfer of genes from these wild plants to conventional crops is being pursued to avoid the costs and time delays (approximately 20 years) involved in domesticating wild species. Among the fatty acids that have been identified are: unusual chain lengths, hydroxy-, epoxy-, acetylenic-, and conjugated fatty acids with double bonds at unusual positions. However, the oil yields from these wild species tend to be too low for commercial production and additional research effort is required to increase the yield levels from a few percent to over 80%, which would be necessary for crop commercialization.[391]

Another approach to improving the performance of biolubricants is the use of performance additives. These additives are mixed with vegetable oils to achieve cold stability, oxidative stability, hydrolytic stability, viscosity, anti-corrosion, etc. One of the emerging areas of research and development is biodegradable additives. There is concern that the additives, as well as the base oil itself, should meet biodegradability and eco-toxicity standards in order to preserve the environmental qualities of the vegetable oil-based lubricant.

Europe currently has the lead in the development of biolubricants. About 75% of Europe’s vegetable oil-based lubricants come from natural oils that are improved with the use of additives and 25% are produced by using chemical processes.[392] Advances in chemistry, catalysts, and bioreactor design will begin to change this ratio. In the future, as much as 75% of vegetable oil-based lubricants could be synthetically manufactured because of the need to develop oils with higher performance characteristics.[393]

The design of better testing protocols using laboratory equipment is another important research area. It is very expensive to test vegetable-based lubricants in the "field." One test in a real engine costs ~$30,000, and in a hydraulic pump, it could cost ~$100,000. Usually, a number of these tests are

[390]It should be emphasized that in specific situations there may be several alternatives to plant biotechnology. The oil industry, for example, has easy access to cheap vegetable oils from all over the world. These oils can often be chemically modified or separated to fulfill market requirements for bulk products. See, for example, the Conclusion and Discussion to the CTVO-net Workshop: Lubricants and Hydraulic Fluids.

[391]See for example, IENICA National Report for the United Kingdom, 1999 and Bundiolli P., and Igartua A., “Lubricants and Hydraulic Fluids” in CTVO-net Final Conference Proceedings, June 2000 for a discussion of using domesticated crops, and the need (or lack of) for new chemical formulations derived from new crops.

[392]Bundiolli, P., and Igartua, A. “Lubricants and Hydraulic Fluids” in CTVO-net Final Conference Proceedings. June 2000.

[393]Ibid.

needed when trying to overcome a list of problems. Only a few laboratory tests simulate field performance satisfactorily. This is another area of research.

There is also a need to conduct lifecycle analyses and cost benefit assessments for various lubricant products. Lifecycle analysis is a process used to evaluate the environmental impacts of a product, process or activity over the entire life cycle including extraction and processing of raw materials; manufacturing, transportation and distribution; use, re-use, maintenance; recycling, and final disposal. These studies could place the higher prices (2-21/2)[394] of biolubricants into a broader perspective. For example, about 47% of lubricants are released directly into the environment. When the environmental, health and safety costs (which are typically treated as "externalities") are folded into a cost benefit assessment, the price advantage for petroleum-based lubricants becomes less favourable. A number of industry sectors are now becoming concerned about potential clean-up costs and legal liabilities associated with total-loss oils.

In general, lubricant research falls into a number of broad themes:

6.8.5.1 Crop Production

Plant Biotechnology

- High Oleic Acid Seed Oils - In the US, DuPont has developed a high-oleic acid soybean oil that can be used for both food and non-food (e.g. lubricant) use. High-oleic canola, corn and sunflower varieties are also being developed for lubricant use.[395]
- High Lauric Acid Seed Oils - Calgene has developed, in cooperation with Proctor & Gamble, a high lauric acid (40%) canola variety that can be used for both food and industrial uses. High lauric canola can be used in food applications like confectionary coatings, frosting and icing. It can also be used as a replacement for coconut and palm oil in making lubricants as well as detergents, soaps and cosmetics.[396]
- High Erucic Seed Oils - An EU consortium led by Koipesol Semillas S.A (Spain) has been studying Ethiopian mustard (B. Carinata) as a source of erucic acid since 1998. They have concluded that it can be grown in both wet/cool areas and dry/hot areas; it is not demanding of nitrogen and sulphur because its deep tap root makes good use of fertilizer used from previous crops; and it works well in crop rotation with cereal crops.[397] One interesting application area for high erucic acid is automotive transmission fluid where it could extend the life of the fluid. International Lubricants Inc. (Tacoma, WA) sells a transmission fluid

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[394]See Harvesting Lubricants. The Carbohydrate Economy. ILSR. 2000.

[395]High oleic oils (83-100%) makes it possible to synthesize derivatives directly from the triglyceride. See Conclusion and Discussion to the CTVO-net Workshop: Lubricants and Hydraulic Fluids, June 2000.

[396]Riley, P. A. and Hoffman, L. Value-Enhanced Crops: Biotechnology's Next Stage. Economic Research Service, USDA. March, 1999. However, the EU position on this is that lauric acid from rapeseed is not economical. See, for example, Askew M., Background Scenario and Executive Summary to European Overview. IENICA Report. August, 2000.

[397]EU FAIR Programme project. FAIR-CT96-1946: *Brassica Carinata*: The Outset of a New Crop for Biomass and Industrial Non-Food Oil. Final report, July, 2001.

called LubeGard® which uses erucic oil.[398] Witco Corporation (Greenwich, CT) has also developed a slip agent for water-based inks from n-hydroxyethyl erucamide, which is derived from erucic acid.[399]

- Metabolic Engineering of Domesticated Starch Crops - Potatoes, for example, could be metabolically engineered to produce as much as 10 tonnes/ha, or about six times the oil yield from existing crops, or about the same as a palm oil field.[400]

New Oilseed Crop Development

- Europe has studied the agronomic, technical, and economic aspects of crambe, meadowfoam, lesquerella, lunaria, calendula and other special crops. Typically these studies look at oil quality as well as the suitability of using the residues as animal feed to improve the economics. Crambe is the closest to commercialization. It has high erucic content which makes it suitable for use as a lubricant, especially in metal processing industries involving lubrication, quenching, cutting, etc. [401] However, it is not yet economically viable, its meal contains glucosinolate levels too high for animal feed (although these bioactives could be separated and used as biocides or breed out of the plant[402]), and market applications are required for the residual straw. Most of the other special crops provide low oil yield, and/or have poor agronomic performance.[403] Even the size and stability of Crambe yields must be increased in order for the crop to have greater commercial value.[404]

6.8.5.2 Processing

Performance Additives

- Lubrizol Corporation is a major source of performance additives for both petrochemical and vegetable-based lubricants and hydraulic fluids. They have developed the 7600 Series of additives, concentrates and base fluids to improve the performance of vegetable oils. Their

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[398]Carstensen, M. Biochemicals for the Automotive Industry. Institute for Local Self Reliance. 1997.

[399]Carstensen, M. Biochemicals for the Printing Industry. Institute for Local Self Reliance. 1997.

[400]See Stymme, S. Vegetable Oils to Replace Mineral Oil in Chemical Industries. NUTEK 2000.

[401]High erucic rape seed oil in the EU contains 52% erucic acid compared to 58% for Crambe. However, oil production from rapeseed is 1270 kg per ha compared to only 800 kg per ha for Crambe. See Marvin, H.J.P and Mastebroek, H.D. Breeding of Crambe and Lunaria. 1st CTVO-net Workshop: Lubricants and Hydraulic Fluids, February 19, 1999.

[402]This was studied in the EU FAIR Programme project FAIR-CT95-0260: High Quality Oils, Protein and Bioactive Products for Food and Non-Food Purposes Based on Biorefining of Criciferous Oilseed Crops.

[403]EU ECLAIR Programme project AGRE-0046: Vegetable Oil for Innovation in Chemical Industries (VOICI). ECLAIR Programme. AIR3-CT94-2480: Crambe abyssinica - Production and Utilization - A Comprehensive Programme. Air Programme. AIR2-CT93-1817: Vegetable Oils With Specific Fatty Acids (VOSFA): Agricultural and Industrial Development of Novel Oilseed Crops.

[404]High erucic rapeseed oil in the EU contains 52% erucic acid, compared to 58% erucic acid for Crambe. However, oil production from rapeseed is 1270 kg per ha compared to only 800 kg per ha for Crambe. See Marvin, H. J. P., and Mastebroek H.D., Breeding of Crambe and Lunaria. 1st CTVO-net Workshop: Lubricants and Hydraulic Fluids, February 19, 1999. Also see FAIR-CT98-4333: DiCra: Diversification With Crambe: An Industrial Oil Crop.

line includes pour point depressants, antioxidants, thickeners, concentrates and enhanced base oils.[405]

- Rheine Chemie Rheinau GmbH (Germany) has identified a pool of potential biodegradable additives. Gemtek (US) produces a full line of total-loss lubricants and hydraulic fluids that use vegetable seed oil telomers, other seed esters, and rarified waxy substances as additives.[406] Tessol GmbH (Germany) also produces additives from plant sources. This is an area of future research, particularly for lubricants that are used in extreme working conditions.[407]

New Extraction, Separation and Purification Procedures

- AGRICE in France has recently funded a study that couples a twin screw extruder with innovative ultrafiltration and chromatography techniques. The first phase of the study will optimize the screw profile design and twin screw extruder configuration to use of oleic sunflower oils. The second phase will study the conditions for ultrafiltration separation and chromatography purification.[408]
- Dr. Frische at Alzenau (Germany), in cooperation with a worldwide manufacturer of centrifuges, has developed a new process called Friolex®. This process uses centrifugal separation to produce high quality oils such as *90plus*, a high-oleic sunflower oil with more than 90% oleic acid, less than 3% linoleic acid, and less than 2% stearic acid. It's content of free fatty acid is below 0.1%. Because of this special composition, *90plus* has very attractive properties: high oxidative stability and improved high and low temperature behaviour. This allows the oil to be used for high performance applications like lubricants, but also for cosmetic products, and starting materials for chemical synthesis.[409]

Bioreactor Design

- Experimental work is being conducted in Italy to develop new bioreactor designs that will be able to accept multiple raw material inputs and produce multiple outputs (lubricant types).[410]

Biorefinery of Value Added Co-products

- EU industry, the Danish Government, and the European Commission funded the Bioraf Denmark Foundation to pilot an integrated, "whole crop", approach to processing wheat and rape. It was hoped the synergistic benefits of these "biorefineries" would result in smaller processing facilities, located closer to the source of raw materials. Transportation costs would be reduced as bulk products like straw would be used locally for energy and fibre with

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[405]See Lubrizol's web site http://www.lubrizol.com/EnvironmentalFluids/7600index.htm.

[406]Gemtek Product LLC web site. See references to Safe Lube line of products http://www.gemtek.com/industrial/index.htm.

[407]1st CTVO-Net First Workshop on Lubricants and Hydraulic Fluids, February 17, 1999.

[408]A New Procedure for the Extraction and Purification of a Lipochemical Base from Oleic Sunflower, 2001. AGRICE Project # 0101085.

[409]See Schmidt, B. and Langer, E. Biomass for Industry: German Strategies for the 21st Century. 5th International Biomass Conference of the Americas. Orlando, Florida, 2001.

[410]Bundiolli, P. Basics Of Oleochemistry for Lubricant Production. 1st CTVO-net Workshop on Lubricants and Hydraulic Fluids, February 19, 1999.

only the more valuable “minor” co-products being shipped off to other regions. Current efforts at biorefining oilseed rape have resulted in added values of more than 100% over traditional refining, but it also comes with added refining costs. Although three generations of the biorefinery have been implemented, the model has not yet proven economical (competitive) for the processing of bulk crops like wheat or oilseed rape.[411]

- Another biorefinery approach uses methyl esters as an intermediate starting material (and its chemical derivatives) to produce a broad range of products, including: biodiesel, glycerol, lubricants, solvents, plasticizers, soaps, detergents, emulsifiers, cosmetics, and pharmaceuticals. The transesterification process involves the use of acids, alcohols, and alkali or metal catalysts. This approach can be augmented by using plant biotechnology. For example, the EU has developed high oleic, low stearic acid sunflower seed oils. These new oils open up additional chemical processing opportunities, leading to new biolubricants with improved performance attributes.[412]

6.8.5.3 Market Utilization

Testing Protocols and Machinery

- Professor Joe Perez in the Chemical Engineering Department at Penn State is developing test methods to screen new automotive lubricants to reduce the number of expensive, full-scale engine tests required during development. He is also researching the thermal and oxidative characteristics of renewable biodegradable basestocks to enable their use as hydraulic and engine lubricants.[413]
- The Institute for Local Self-Reliance reports that Agro Management Group (AMG) is working with Savant Inc. to establish new testing protocols for vegetable-based motor oils. Savant Inc. is an independent testing laboratory that has developed testing methods for the American Petroleum Institute (API) and the American Society for Testing Materials (ASTM).[414]
- It is also difficult to prove that vegetable oil is less hazardous to the environment than synthetic materials because there are no simple means to test the long-term effect on the environment. According to S. Erhan of the USDA, "*Recently adapted (nationwide) laboratory tests (in the US) controversially suggest with very questionable reliability that many synthetic and petroleum materials have biodegradability nearly as high as that of vegetable oils.*" Scientists in Europe have also reported problems in this area and have called for public funding to resolve the issue.

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[411]Commercial Success of ECLAIR Programme AGRE-0061: The Whole Crop Biorefinery Project (Bioraf).

[412]See, for example, Commercial Success of ECLAIR Programme. AGRE-0039: Seed Oils for New Technical Applications. Also see Bundiolli, P. Basics Of Oleochemistry for Lubricant Production. 1st CTVO-net Workshop on Lubricants and Hydraulic Fluids, February 19, 1999, and A Heterogeneous Catalyst Transesterification Process for Manufacture of Isopropyl Esters of Fatty Acids from Vegetable Oil or Methyl Esters, 2001. AGRICE Project # 0101034.

[413]See the Department of Chemical Engineering at Penn State web site http://fenske.che.psu.edu/.

[414]Lubricants from Vegetable Oils. The Carbohydrate Economy. ILSR. 2001.

Product and Market Development

- In France, AGRICE has funded numerous projects aimed at developing lubricant applications and end use markets. Examples include:
  - *Food industry applications* - an in-depth study of the food industry to identify factors that could be used to promote the use of biolubricants, including an analysis of the technical, economic, and regulatory environment.[415]
  - *Industrial lubricant grease* - a study designed to replace petroleum-based lubricants made from metallic soaps with biolubricants made from oleic sunflower oils.[416]
  - *Industrial demoulding applications* - the development of water-soluble, vegetable oil-based derivatives that meet the technical requirements of industrial demoulding operations, including the study of health and hygiene (skin irritation, inhalation of solvents), and environmental impacts (biodegradability, VOC reduction, CO_2 emissions)[417]
  - *Automotive industry steel stamping applications* - a project designed to replace chrome-plating and use of polluting oils with a carboxylation coating process.[418]
  - *Forest industry applications* - an analysis of the technical performance, and human and environmental safety requirements, of lubricants used in the forestry industry; followed by a comparative analysis of vegetable-based and petrochemical-based lubricants; efforts to promote the concept to consumers and equipment manufacturers; and the establishment of specifications relevant to the use of lubricants in the forestry industry.[419]
  - *Motor oil applications* - a study aimed at developing biolubricants for use in farm tractors; including an investigation of seed oils, extraction, refining, lubricant characterization, perfection of esters, establishment of crop cultivation, formulation of motor oils, establishment of industrial crushing and refining, endurance tests, and gaining approval status for using the new vegetable-based lubricants.[420]
  - *Textile industry applications* - a study to explore the feasibility of replacing textile greasing oils, which are used in fibre treatment; including establishing biolubricant formulae, conducting pilot studies, field testing, monitoring waste water, and conducting a technical, economic and environmental assessment.[421]

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[415] Lubricants Derived from Agricultural Products for Use in Food Industries, 1998. AGRICE Project # 9801075.

[416] Preparation of Lubricant Grease Compounds from Oleic Sunflower Oils Via 9/10 Hydroxystearic Acids. AGRICE, 2001. Project # 0101035.

[417] Vegetable Oil Derivatives Used in Formulation of Demoulding Agents That Are Soluable or Self-Emulsifying in Water-Based Media, 2001. AGRICE Project # 0101038.

[418] New Methods for Zinc Surface Treatment Via Organic Compounds Derived from Vegetable Oil, 2000 AGRICE Project # 0001043.

[419] Natural Biodegradable Lubricants in Forestry, 1998. AGRICE Project # 9801025. Specific application areas include: chain saws and felling saws; hydraulic fluids used in all equipment with a hydrostatic circuit; two-stroke engine oils; and engine grease.

[420] A New Generation of Biolubricants for Use in Farm Tractor Motors, 1999. AGRICE Project # 9901075. Also see Analysis of the Stability and Oxidation Resistance of A Biolubricant, 1999. AGRICE Project # 9901076.

[421] Evaluation of Textile Greasing Oils Formulated From Vegetable-Oil Compounds, 1999. AGRICE Project # 9901071.

- *Railway and viticulture applications* - a study focussed on developing biolubricants for railway switches and equipment in a train switching yard, and lubricant and hydraulic fluids for grape picking machinery, forklifts and lifting equipment.[422]
- *Construction demoulding and casting applications* - a study to quantify the technical and economic benefits of using biolubricants to remove poured concrete and ceramic structures from moulds used in the construction sector.[423]

- ABIL at the University of Northern Iowa, is also a leader at developing lubricant markets for a new genetically modified, high-oleic soybean oil.
  - *Transformer cooling oils* - The ABIL technology and patents to BioTrans has been purchased by Cargill Industrial Oils and Lubricants, which will produce the oil for Electric Research and Manufacturing Cooperative (ERMCO). Over 40 million gallons of transformer oil is used in the US every year.[424]

Field Testing

- Some form of field testing will probably always be necessary to determine how a product actually performs under real world situations. The FNR in Germany, for example, has funded research to field test lubricants in a variety of settings and found that biodegradable lubricants can react negatively with other system components made from petrochemical feedstocks. Rubber rotor seals made from petrochemicals, for example, tend to degrade after contact with biolubricants. Biodegradable lubricants also have problems working successfully with heavy equipment. More research is required in this area.[425]

Life Cycle Analysis (LCA)

- LCAs of rapeseed oil used for chainsaw oil[426], and sunflower oil used for industrial lubricants[427], have both found that vegetable oils have lower environmental impacts than minerals. The impacts from manufacturing are very low compared to the impacts from crop production, where the use of fertilizers and pesticides contribute to CO_2 emissions and nitrification.

On-Site Farm Production

- ABIL at the University of Northern Iowa, received funding from the USDA to establish three on-farm sites for the production of rail flange and fifth wheel hitch grease. The farms crush and process the soybean oil on-site and convert it into grease. The soy meal is used to feed hogs. The owners of Lanehaven Farm, Inc. estimate the grease production operation adds 30-50 cents per bushel above the market price of soybeans. The process is fairly simple. The

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[422]Implementation and Follow-Up of a Biolubricants Demonstration Network: Application in Viticulture and Transportation/Logistics, 2001. AGRICE Project # 0101040.

[423]Forming and casting Oils, 1998. AGRICE Project # 9801063.

[424]Cargill press release, July 16, 2002.

[425]See IENICA Report for Germany, 1999, p. 8.

[426]Wightman, P. Environmental Benefits to Be Derived From the Use of Vegetable Oils in Place of Existing Petrochemical Materials. CTVO-net Workshop on Paints and Coatings, November, 1998.

[427]Igartua, A., Aranzabe, A., Mendoza, G., Barriga, J., Marcaide, A., Gonzalez, A., Fessembecker, A., Bock, H., Tavernier, G., Andret, M. Vegetable Oils: Lifecycle of Seed Obtention and Production, Behaviour During Use, Biodegradability and Toxicity, Recycling. CTVO-net Workshop. CTVO-net Workshop on Lubricants and Hydraulic Fluids. February 17, 1999.

soybeans are first crushed using extruder/expeller units and then the oil and meal are separated. The oil is processed on-site to grease using grease manufacturing equipment and the meal is fed to the pigs. The processing equipment is sized to fit small, medium and large-sized operations.[428]

Breakthrough Concepts and Technologies

- Great advances may also come from breakthrough concepts and technologies. One example is where a new lubricant and an new engine design were co-developed. Fuchs Lubricants in Germany has developed a new lubrication concept for diesel engines in conjunction with Daimler Chrysler. The new engine design uses rapeseed oil as both a fuel and an engine lubricant. The lubricant gradually, and continuously burns off with the fuel. It leaves no residue, and produces few pollutants. The concept was patented in 1997 and was first piloted with a VW Passat. It has since been extended to power generation equipment.[429]
- *Wood preservatives* - ABIL at the University of Northern Iowa, used soybean oil to replace mineral oil as a lubricant for wood bearings used on farm machinery grain augers and found that the surface area would become polymerized. This led to a new wood preservative process where wood is placed in a chamber, the air is removed by a vacuum procedure, and then soybean oil is applied under heat and pressure to impregnate the wood. This process can be applied to utility poles and railroad ties to prevent creosote or arsenic from leaching from the wood.[430]

6.8.6 R&D Analysis and Recommendations

6.8.6.1 Canadian Strengths

Canada has no organized national program to promote the development of biobricants and hydraulic fluids, even though Canada has pioneered the development of high oleic canola oils (largely through conventional breeding). Canada currently grows about 500,000 acres of high oleic canola (out of 10 million acres)[431] and has a strong biotechnology infrastructure capable of developing improved varieties using genetic modification.

Some important pockets of R&D activity, and sources of comparative advantage, have been identified:

- The Saskatchewan Canola Development Commission has funded research on biolubricants and maintains an interest in the area.[432]

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428 ABIL Advocate, Winter/Spring, 2002.

429 See The IENICA National Report for Germany, 1999.

430 ABIL Advocate, Fall, 2001.

431 Corbett, P. Research in the Area of High Oleic Oils. Diversification of Canadian Oil Seeds: Part 1 Adding Value to the Oil. PBI Bulletin, 2002, Issue 1.

432 See for example, Reaney, M. and Blondeau J. Biooils Market Study. Saskatchewan Canola Development Commission. 1996.

- The National Research Council's Plant Biotechnology Institute in Saskatoon has a Seed Oil Modification Group (now called the Seed Oil Biotechnology Group) that has genetically modified rapeseed for super-high erucic oils.[433] High erucic rapeseed oil can be used in the making of lubricants (e.g. slip oil in plastic bags), emollients, cosmetics, plastic film, synthesis of nylon 13,13, and in photographic materials.[434] PBI was awarded $544,000 from the the Saskatchewan Agri-Food Innovation Fund to develop elite canola breeding lines for ultra-high levels of erucic acid.[435]
- The Department of Plant Science at the University of Manitoba was the first to develop high erucic acid rapeseed (HEAR) varieties in Canada.[436]
- Gary Stringam, at the University of Alberta is studying the introgression and molecular characterization of multiple disease resistance traits from *Brassica carinata* to *B. napus*.[437]
- Canada already has an identity preservation infrastructure in place for canola. About 500,000 acres of IP canola were grown in Canada last year and more is expected next year.[438]
- Lubrizol Corporation has developed the 7600 Series of additives, concentrates and base fluids to improve the performance of vegetable oils. Their line includes pour point depressants, antioxidants, thickeners, concentrates and enhanced base oils. Lubrizol has three manufacturing plants in Canada located at Niagara Falls, London and Newmarket, Ontario. The Niagara Falls facility has a staff of 30 and provides contract blending, manufacturing, terminalling, warehousing, and analytical services.
- Greenland Corporation (Calgary, AB) produces lubricants and hydraulic fluids from canola oil.[439] They have also partnered with TriboSpec Corporation (LaSalle, QC), an independent manufacturer and distributor of lubricants in Canada and the US.[440]

6.8.6.2 Bottlenecks

There are no major bottlenecks. A complete supply chain has already been developed in Canada.

As the Ag-Based Industrial Lubricants (ABIL) Program at the University of Northern Iowa has

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[433]Reported in Agricultural Biotechnology: Research and Development in Saskatchewan, 5th Edition, 2001.

[434]Taylor, D. C., Katavic, V., Zou, J., MacKenzie, S. L., Keller, W. A. Improvement of Oil Content, Erucic Acid Content and Seed Yield in Field Tested Transgenic Rapeseed. Diversification of Canadian Oil Seeds: Part 1 Adding Value to the Oil. PBI Bulletin, 2002, Issue 1.

[435]Crawford, C. November, 2001. Discussion Framework: Developing Bio-based Industries in Canada, Agriculture and Agri-Food Canada, 2001.

[436]Canola Research: Time is Money and Money is Time. Faculty of Agricultural and Food Sciences. University of Manitoba press release. August 23, 2001.

[437]This is a $399,749 project that is in progress. Refer to project #2002A103R.

[438]IP Canola Offers Premiums, Headaches. Western Producer, March 28, 2002. Note that one of the farmers interviewed complained that CanAmera Foods high-erucic-acid variety resulted in low yields, and time lost cleaning stray seeds from equipment.

[439]http://www.greenpluslubes.com/

[440]http://www.tribospec.com/

demonstrated, a centre of expertise with a modest capital investment in production equipment can produce a wide range of biolubricants for market testing. In the latest ABIL project, rail flange and fifth wheel grease can actually be made on the farm and sent to a centre like ABIL for quality testing prior to being sold to market. Agriculture itself can be a major purchaser of its own products. Governments could also support the development of a biolubricant supply chain by encouraging their use in environmentally sensitive areas.

6.8.6.3 Gaps in Research

There may be additional research required in Canada to improve the economics of lubricant production using new advances in chemical processing and reactor design. More detailed studies of end use applications may help to expand markets. Lifecycle analyses should be performed to provide policy justification for more supportive federal and provincial policies.

6.8.6.4 Themes for Future Research

The development of new canola and rapeseed varieties with high oleic and high erucic content, that are drought tolerant, and have lower fertilizer and pesticide requirements, should be a priority. Drought tolerant varieties are needed because of the changing climate on the prairies. Recent droughts have reduced seed yield significantly. Reduced fertilizer and pesticide use is needed to improve lifecycle impacts and establish the basis for increased public policy support for vegetable oil based lubricants.

6.9 Platform Chemicals

6.9.1 Sector Overview

The area of platform chemicals is a broad and complex area. Because of time and resource restrictions, all we can provide in this report is a general overview of the opportunities and barriers within a Canadian context.

There are a number of potential platform chemicals that can be produced from agricultural feedstocks, including: citric acid, lactic acid, levulinic acid, succinic acid, and 1,3-propanediol, to name some of the more commonly discussed platforms. Each of these platforms has created immense interest in Europe and the US, but the applicability to the Canadian context remains unclear.[441]

The sections below briefly discuss some of the opportunities that platform chemicals may offer for industrial uses of agricultural feedstocks, and some of the key barriers to commercializing any R&D discoveries in Canada.

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[441] A recent study by ACTIN has concluded that crop-derived bulk chemicals offer little short-term promise because of the cheap cost of petrochemicals. Crops may be more cost competitive in the area of specialty chemicals and biomaterials. See Oliver B. N., Realizing the Economic Potential of UK-Grown Crops Industrial Crops: A Review by ACTIN. April, 2001.

We conclude by discussing the methyl ester platform as one area where Canada might wish to conduct research. The Federal Government has recently announced that it intends to support biodiesel production in Canada. The Ontario Government has removed the provincial excise tax on biodiesel and BIOX Corporation is working with Rothsay in Ontario to finance the construction of Canada's first commercial biodiesel plant. Biodiesel is one of the main products produced from methyl esters. Further research, development and demonstration of other co-products from methyl esters could help to support this emerging industry.

6.9.2 Citric Acid

Citric acid is the largest volume organic acid, accounting for about 85% of the fermentation-based organic acid market.[442] It is also a well established platform chemical made from starch and sugar feedstocks. The three major players in the US are Archer Daniels Midland, Cargill, and Haarmann and Reimer Corporation (H&R), a subsidiary of Bayer.

Jungbunzlauer (JBL) has recently constructed a citric acid plant in Port Colbourne Ontario. JBL produces a range of citric acid products that are targeted at industrial, personal care and pharmaceutical markets, including: adhesives, agrochemicals, metal treatment and electroplating, packaging, paper, photo-chemicals, plastics, textiles, films, detergents, cleaners, dental/hair/skin care, nail polishes and toiletries.[443]

Citric acid also has many food uses. For example, JBL has citric acid products that serve the food and beverage markets. Their food markets include: baby food, bakery, cheese and diary, confectionary, desserts, flavours, frozen and convenience foods, ice cream, meats, seafood and fish. Beverage markets include: carbonated drinks, fruit juices and drinks, health and sports drinks, instant drinks, ready to drink teas, soft drinks, still beverages, wines and wine coolers.[444]

Food and beverages account for 59% of JBL's sales. Detergents (13%), pharmaceuticals (9%), industrial (8%), and others (11%) account for the balance.[445]

Citric acid production in the US is characterized by large-scale operations and vertical integration, which take advantage of economies of scale.[446] Any research and development in this area should be industry lead, to ensure that new discoveries have an opportunity to be commercialized.

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[442]Industrial Uses of Agricultural Materials, August 6, 1997. USDA.

[443]http://www.jungbunzlauer.com/products/

[444]Ibid.

[445]http://www.jungbunzlauer.com/company/

[446]Industrial Uses of Agricultural Materials, August 6, 1997. USDA.

6.9.3 Lactic Acid

Lactic acid can be produced either from the fermentation of carbohydrates (starches, sugars, lignocellulosics) or synthesized by hydrolysis of lactonitrile. Lactic acid is also a well established market with major players that include Purac (Netherlands, US), which is the largest lactic acid producer in the world, Archer Daniels Midland (US), Musashino Chemical Laboratory Ltd.(Japan), and Galactic (Belgium).[447]

In 1997, about 85% of lactic acid demand was for food-related applications, e.g. as a food acidulant, flavour enhancer, preservative, texture enhancer, antibacterial agent, and meat preservative. It's industrial uses accounted for 15%, and included use in shampoos and soaps, and as a building block for polylactic acid (PLA).[448]

Lactic acid is currently in a growth cycle as a result of the recent Cargill Dow advances in polylactic acid production and others who intend to enter the field, like Chronopol (US), Mitsui Chemical (Japan) and possibly Galactica (Belgium).[449]

Cargill Dow (Minnetonka, MN) is clearly the front runner in establishing lactic acid as a platform chemical. They spent $750 million in developing their PLA plant in Blair, Nebraska and plan to spend $250 million more over the next few years on commercial development, product technology development, and converting biomass directly to PLA.[450] Cargill Dow not only see market opportunities for converting lactic acid into polylactic acid (used to make bioplastic fibres, packaging, fibre-fill), but also opportunities for ethyl lactate (a solvent), acrylic acid (used to make acrylate polymers and plastics), propylene glycol (anti-freeze, plastics), 2,3 pentanedoine (used as a flavour agent, biodegradable solvent, photoinitiator, and chemical intermediate), pyruvic acid (food acidulant), and pharmaceuticals.[451]

Ontario was considered as a potential site for a polylactic acid plant but lost out to Blair, Nebraska, where energy prices and taxes were lower, and Cargill Dow could leverage existing capital investments. With the exception of the CASCO and JBL plants located in Port Colbourne, Canada does not have a well developed food processing industry that can provide the infrastructure for developing a platform chemical industry based on lactic acid. Major policy changes in taxation and incentives for foreign investment would have to be completed before Canada would become a realistic candidate. Research and development in this area may be premature unless it is industry driven, or forms part of a larger, regional cluster-based strategy.

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[447]Mirasol, F. Lactic Acid Prices Falter As Competition Toughens. CMR, March 1, 1999.

[448]Industrial Uses of Agricultural Materials, August 6, 1997. USDA.

[449]Wood, A. Whipping Up Demand for Lactic Acid Polymers. Chemical Week, January, 28, 1998.

[450]Walsh, K. Cargill Dow Opens PLA Plan. Chemical Week, April 10, 2002.

[451]Miller, D. J., and Doidge, B. Biochemicals From Corn: Developing A Biochemical Industry Based on Corn in Ontario. Ontario Ministry of Agriculture Food and Rural Affairs. March 31, 2000.

6.9.4 Levulinic Acid

Levulinic acid (LA) is another potential chemical "building block" or "platform chemical". It has a world-wide market of about 1 million pounds per year and sells for between $4-6 a pound.[452]

Levulinic acid can be used as a starting material to derive[453]:

- diphenolic acid (DPA) - which can be used as a monomer for polycarbonates and epoxy resins; used as a component in protective and decorative finishes; or brominated to create a fire retardant and environmentally friendly marine coating[454]
- delta-amino levulinic acid (DALA) - a biodegradable herbicide/pesticide
- methyltetrahydrofuran (MTHF) - a fuel additive
- succinic acid and its derivatives[455]
  - succinate salts can be used to produce deicing agents and its esters can be used in solvents and paints
  - itaconic acid can be used as an additive in polymeric fibre blends to add toughness and abrasion resistance
  - pyrrolidinones - are used as solvents, plasticizers, and coalescing agents for polymer emulsion coatings and polyvinyl pyrrolidinone (PVP)
  - PVP, in turn, is used in pharmaceuticals, cosmetics, toiletries, textiles, paper, beverages, and detergents
  - 1,4-butanediol - a polymer intermediate
  - tetrahydrofuran - a major solvent

The Office of Industrial Technologies, US Department of Energy, has estimated the commercialization of DALA could increase the market for levulinic acid to between 200 million and 400 million pounds per year. LA and all its derivatives could reach a world-wide market of 1 trillion

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[452] US EPA Summary of 1999 Green Chemistry Challenge Awards.

[453] For a detailed review of industrial applications see Ghorpade, Viswas and Hanna, Milford Industrial Applications For Levulinic Acid, Corn Chem International and Industrial Agricultural Product Center, University of Nebraska, Lincoln. Contact Corn Chem International, 908 Summerfield Ct. Lawrence Kansas, 66049. Phone: 785-830-9409 or see their web site at http://www.levulinic.com/industrial-use-levulinic.htm.

[454] Elliott, D. C., Fitzpatrick, S.W., Bozell, J.J., Bilski, R.J., Moens, L., Frye, J.G., Wang, Y., and Neuenschwander, G.G. Production of Levulinic Acid and Use as a Platform Chemical for Derived Products in 4th Biomass Conference of the Americas, 1999, Vol. 1, p. 595-600. Elsevier Science, Oxford, United States.

[455] Miller, D. and Doidge, B. Biochemicals from Corn: Developing a Biochemical Industry Based on Corn in Ontario, March 21, 2000. Ridgetown College, University of Guelph.

lbs/yr.[456] The benefits are estimated to be 75.6 trillion BTU per year in energy savings.[457]

Biofine (now BioMetics, Inc[458]) has developed a cost effective thermochemical process for producing LA from paper mill waste for as little as one tenth the cost of current manufacturing processes.[459] Apparently, the process can be used with almost any biomass including un-recycled waste paper, mill sludge, municipal solid waste, waste wood and agricultural residues. Large-scale commercialization using the Biofine process is expected to produce levulinic acid for as little as \$0.32 per pound, at the 50 dry ton/day scale or 4-5 cents per pound at the 1,000 ton/day scale.[460]

Biofine has developed a high-temperature, dilute-acid hydrolysis process that converts cellulose into soluble sugars and then into levulinic acid. Byproducts from the process include furfural, formic acid, and condensed tar.[461] The process won the Presidential Green Chemistry Award for small business in 1999. It currently operates a small 1-ton-per-day pilot-scale levulinic acid conversion plant at South Glen Falls, New York.[462]

With the help of \$15 million in funding from the US Department of Energy and New York State, BioMetics Inc. hopes to build a demonstration plant that would convert waste paper (i.e., fast food containers, wrapping paper, beverage cartons) that can't be recycled into LA. The plan is to convert 2,000 tons per day into 20 million gallons of LA per year. The cost of production is expected to be 5 cents a pound.[463]

The US Department of Energy's Pacific Northwest National Laboratory (PNNL) has developed a multi-step catalytic process that converts LA into methyltetrahydrofuran (MTHF), a fuel additive,

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[456] Elliott, D. C., Fitzpatrick, S.W., Bozell, J.J., Bilski, R.J., Moens, L., Frye, J.G., Wang, Y., and Neuenschwander, G.G. Production of Levulinic Acid and Use as a Platform Chemical for Derived Products in 4th Biomass Conference of the Americas, 1999, Vol. 1, p. 596. Elsevier Science, Oxford, United States.

[457] Manufacturing of Industrial Chemicals From Levulinic Acid: A New Feedstock for the Chemicals Industry: Inexpensive Biomass Material to Be Developed Into A Variety of Products. Project Fact Sheet. Office of Industrial Technologies, Energy Efficiency and Renewable Energy, US Department of Energy, February 1999.

[458] Fitzpatrick, S. W. BioMetics Inc., 300 Bear Hill Road, Waltham Massachusetts, 20451, Tel: 781-684-8331.

[459] Science Daily News, June 30, 1999.

[460] US EPA Summary of 1999 Green Chemistry Challenge Awards. Also see Elliott, D. C., Fitzpatrick, S.W., Bozell, J.J., Bilski, R.J., Moens, L., Frye, J.G., Wang, Y., and Neuenschwander, G.G. Production of Levulinic Acid and Use as a Platform Chemical for Derived Products in 4th Biomass Conference of the Americas, 1999, Vol. 1, p. 595-600. Elsevier Science, Oxford, United States.

[461] US EPA Summary of 1999 Green Chemistry Challenge Awards.

[462] Manufacturing of Industrial Chemicals From Levulinic Acid: A New Feedstock for the Chemicals Industry. Project Fact Sheet. Office of Industrial Technologies, Energy Efficiency and Renewable Energy, US Department of Energy, February 1999.

[463] Mill Watch. January, 2000.

that can be used with ethanol and natural gas liquids to produce a cleaner burning fuel for cars and trucks.[464] MTHF is miscible with gasoline and hydrophobic, which allows it to be blended at the refinery, rather than later in the distribution process. MTHF, as a fuel additive, increases the oxygenate level in gasoline without affecting engine performance. It also has a high octane rating (87) and a lower vapor pressure, thereby reducing fuel evaporation and improving air quality.[465]

The process involves mixing levulinic acid with hydrogen inside a reactor containing a catalyst where a series of chemical reactions take place under 250 degrees Celsius and 100 atmospheres of pressure to create MTHF.[466] On a weight basis, the yield is 63 pounds of MTHF for every 100 pounds of LA.[467]

The US National Renewable Energy Laboratory has also developed a new process to develop delta-amino levulinic acid (DALA), a broad spectrum herbicide from LA.[468] Levulinic acid is brominated in MeOH to give 5-bromomethyllevulinate which is treated diformylamide anion. Acid hydrolysis of this intermediate produces DALA. Formic acid is the only byproduct.

Rensselner Polytechnic Institute is looking at LA as a starting material for the production of diphenolic acid, which can be used as a replacement for bisphenol A, which is used in commercial polymers.[469]

Companies and organizations involved in researching and trying to commercialize LA include Biofine Corporation, National Renewable Energy Laboratory, Pacific Northwest National Laboratory, New York State Energy Research and Development Authority, the Chemical Industry Services (a manufacturing agency representing 40 US chemical companies), Rensselner Polytechnic Institute, and Merichem Company.

The current status is as follows:

- conversion of biomass to levulinic acid - 1 ton per day pilot scale
- conversion of LA to MTHF and DALA - lab scale

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[464]DOE, Office of Industrial Technologies, Project Fact Sheet, January, 1999. Contact D.C. Elliott, PNNL, Batelle Boulevard, P.O. Box 999, MS K2-12, Richland, Washington 99352, USA Tel: 509-375-2121 E-mail: dougc.elliott@pnnl.ov.

[465]US EPA Summary of 1999 Green Chemistry Challenge Awards.

[466]Science Daily News, June 30, 1999.

[467]PNNL News, October 26, 1998.

[468]Contact Joseph Bozell, National Renewable Energy Laboratory (NREL), 1617 Cole Boulevard, Golden Colorado 80401. Phone: 303-384-6276 E-mail: joe.bozell@nrel.gov

[469]Elliott, D. C., Fitzpatrick, S.W., Bozell, J.J., Bilski, R.J., Moens, L., Frye, J.G., Wang, Y., and Neuenschwander, G.G. Production of Levulinic Acid and Use as a Platform Chemical for Derived Products in 4th Biomass Conference of the Americas, 1999, Vol. 1, p. 595-600. Elsevier Science, Oxford, United States.

There is interest at NREL and PNNL to move to industrial scale but efforts to engage the US pulp and paper industry in a partnership have not been successful at present.[470]

More recently, Corn Chem International and the Industrial Products Center, University of Nebraska have patented a process that creates levulinic acid from starch slurry using a reactive extrusion process. The extrusion "takes place in a twin-screw extruder having a plurality of temperature zones wherein the starch slurry is preconditioned, extruded, filter pressed, reboiled, vacuum distilled, condensed, centrifuged, whereby the waste stream is reprocessed upstream to the preconditioning stage.[471]

For levulinic acid production to be viable in Canada would require the participation of the Canadian forestry industry. It is also unclear whether the limited access to concentrated, high volumes of cellulosic materials in Canada may restrict the economic viability of this platform.[472]

6.9.5 Succinic Acid

The Department of Energy's Oakridge National Laboratory, Argonne National Laboratory, National Renewable Energy Laboratory, and the Pacific Northwest National Laboratory have been developing a fermentation process for producing succinic acid from corn glucose. Succinic acid can act as a possible platform chemical for the production of commodity plastics, synthetic fibres, food additives, and solvents for paints and paint removers.[473]

The technology to convert glucose into succinic acid from corn fermentation using mutant bacteria was licensed to Applied CarboChemicals. The acid is separated, purified, and then converted chemically into 1,4-butanediol, tetrahydrofuran, n-methyl pyrrolidone and other chemcials.[474]

Two attractive chemical derivatives are polyvinyl pyrrolidinone (PVP) used in pharmaceuticals, toiletries, paper, beverages and detergents and itaconic acid, which is used in polymeric fibre blends to add toughness and abrasion resistance. The market for PVP is estimated to be 50 million lbs/yr and itaconic acid is estimated to be 20 million lbs./yr world-wide.[475]

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[470]Interview with Joseph Bozell, National Renewable Energy Laboratory (NREL), DOE.

[471]US Patent No. 5,859,263.

[472]Canada does not have many locations capable of supplying 1,000 tonnes per day of biomass. See Chornet, E., D'Amour, R., Chornet, V., and Abatzoglou, N. Refining Low Grade Non-Homogeneous Biomass Feedstocks; Bioenergy and a Co-product Strategy. 5th International Biomass Conference of the Americas, 2001.

[473]Industrial Uses of Agricultural Materials, USDA, October, 25, 1995.

[474]Converting Corn into Marketable Chemicals. Tech Transfer Highlights, Volume 8, Number 1, 1997. Argonne National Laboratory.

[475]Miller, D. J., and Doidge, B. Biochemicals From Corn: Developing A Biochemical Industry Based on Corn in Ontario. Ontario Ministry of Agriculture Food and Rural Affairs. March 31, 2000.

Succinic acid, and its derivatives, could replace many of the benzene class of commodity petrochemicals.[476] The potential US market is 1 billion pounds per year at a value of about $1.3 billion dollars.[477]

A single biological/chemical plant using the new technology could save the same amount of energy required to heat 80,000 single family homes for the year.[478]

More recently, Oakridge National Laboratory, Argonne National Laboratory, Arkenol Inc and Applied CarboChemicals have been trying to convert lignocellulosic sugars into succinic acid to improve the economics.[479]

Succinic acid can also be made from levulinic acid (see above) or it could be produced as a co-product in ethanol processing.[480]

The development of plant-derived succinic acid lags behind lactic acid by about 5-7 years. And the economics, at this point, 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.[481]

6.9.6 1,3 Propanediol

Until fairly recently (1992), 1,3-propanediol sold for between $15-30/kg., and as a result, was used in only high value, low volume applications. Shell Oil Company has since developed a breakthrough technology, based on the hydroformylation of ethylene oxide, which has reduced the commodity cost to less than $1.00/lb. Shell has built a 70,000t per annum plant that uses 1,3-propanediol to produce carpet fibers (poly trimethylene terephalate) called Corterra™.[482]

DuPont, working closely with Genencor International, has recently developed a microorganism that

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[476] Replacing Petrochemicals with Biochemicals: A Pollution Prevention Strategy for the Great Lakes Region. Institute for Local Self Reliance. October, 1994.

[477] Converting Corn into Marketable Chemicals. Tech Transfer Highlights, Volume 8, Number 1, 1997. Argonne National Laboratory.

[478] Converting Corn into Marketable Chemicals. Tech Transfer Highlights, Volume 8, Number 1, 1997. Argonne National Laboratory.

[479] Production of Succinic Acid from Wood Waste and Plants, US Department of Energy, Office of Industrial Technologies Fact Sheet. February, 1999.

[480] Ponnampalam, E. 2001. Integrating Emerging Technologies with Biomass Refining. Abstract from the 5th Biomas Conference of the Americas.

[481] Miller, D. J., and Doidge, B. Biochemicals From Corn: Developing A Biochemical Industry Based on Corn in Ontario. Ontario Ministry of Agriculture Food and Rural Affairs. March 31, 2000.

[482] Ibid.

can convert glucose directly into 1,3-propanediol with a 500-fold productivity increase over existing methods. DuPont has built a modern plant in Kinston, North Carolina to produce 3GT from 1,3-propanediol and terephtalate. DuPont's plan is to replace the petrochemical route to processing propanediol with a bioprocessing route once the process has become economically viable.

There is also interest in Europe in using bacterial strains to convert raw glycerols from biodiesel production into 1,3-propanediol. Recent work by the Institute of Technology, Federal Agricultural Research Centre (FAL), in Germany has found that bioconversion of raw glycerol using immobilized catalysts - C. butyricum entrapped in a hydrogel (LentiKats) - should make the process competitive and profitable.[483]

6.9.7 Methyl Esters

Methyl esters are a starting material for producing biodiesel, lubricants, and other fatty acid derivatives. It can be used as a chemical intermediate to produce a number of oleochemicals such as soap noodles, fatty alcohol, alkanolamides, alpha sulfo-methyl esters, sucrose esters, and other detergents.

Methyl esters are produced by transesterification, which is a reaction between an ester or triglyceride with another compound which could be an ester, alcohol, or acid, alkali or metal catalyst. They can also be produced by acid hydrogenation.

The transesterification process produces several important products including biodiesel and the main co-product of glycerol.[484]

The world production of glycerol now exceeds demand[485], and prices have dropped steadily since 1995. The price drop is a direct cause of increased supply from growth in biodiesel production.

In response, research has begun to focus on new applications for glycerol. Examples of existing applications include: cosmetics and soaps (16%), and pharmaceuticals (10%), esters (11%), polyglycerols (12%), food and drink (8%), cellulose films (3%), tobacco (3%), and paper (1%).[486]

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[483]See Wittlich, P., and Dieter-Vorlop, K. Microbial Conversion of Glycerol Towards 1,3-Propanediol. CTVO-net Workshop on Valorization of By-Products: Glycerol. January 21, 1999.

[484]Glycerol is produced, in the main, as a co-product from producing soaps (saponification of triglycerides); fatty acids (hydrolysis of triglycerides), biofuels, fatty alcohols, fatty esters, fat substitutes (esterification of troglycerides). It can also be produced intentionally from the synthesis of epichlohydrin from allylchloride and propylene or by the fermentation of sugars and starches. See, for example, Heming M.P.D., Glycerine Market Report. CTVO-net Workshop on Valorization of By-Products: Glycerol. January 21, 1999.

[485]Ibid.

[486]Heming, M.P.D. Glycerine Market Report. CTVO-net Workshop on Valorization of By-Products: Glycerol. January 21, 1999.

Glycerol has several promising applications:[487]

- replacement for synthetic polyols, e.g. ethoxylates used in making surfactants;
- the production of glycerol carbonate, which in turn can be used to produce glycidol, an important intermediate in the production of cosmetics and pharmaceuticals and the synthesizing of surfactants using very pure monoglycerides;[488]
- microbial conversion of glycerol to produce 1,3-propanediol.[489]

One interesting area for further research is the use of gylcerol in synthesizing epoxidization of vegetable oils and their derivatives into various industrial chemicals. Epoxidized soybean oil, for example, is being developed as plasticizers and additives for polyvinyl chloride (PVC). Lab and pilot scale studies in Europe suggest that epoxidized methyl esters made from either rape or high oleic sunflower oils can be synthesized into ether alcohols using glycerol as a reactant. The co-products from this process are now being investigated for applications as lubricants and detergents.[490]

All of these new processes have important implications for the expansion of biodiesel production into broader-based biorefineries.

It is important that these applications should be original, and innovative, not just simple substitutions, where they will have to compete against lower priced petrochemicals.

In summary, methyl esters can act as chemical intermediates to:

fatty alcohols	alkanoamides	sucrose mono and polyesters
soaps	alpha sulfo-methyl esters	fatty esters such as fatty isopropyl esters
plasticizers	lubricants	detergents
emulsifiers	cosmetology	pharmaceuticals

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[487]Summary of Discussion. CTVO-net Workshop on Valorization of By-Products: Glycerol. January 21, 1999.

[488]Mouloungui, Z. Network of Valorization of Glycerol: Synthesis Processes For The Production of Glycerol Carbonate, Glycidol and pure α-Monoglycerides. CTVO-net Workshop on Valorization of By-Products: Glycerol. January 21, 1999. The production process described by Mouloungui is ecologically friendly because the reactions take place without a solvent, the catalysts are reusable, and a polyvalent reactor is used which does not require further purification.

[489]See Wittlich, P., and Dieter-Vorlop, K. Microbial Conversion of Glycerol Towards 1,3-Propanediol. CTVO-net Workshop on Valorization of By-Products: Glycerol. January 21, 1999.

[490]Pages, X. Opening Epoxidized Oils with Glycerol. CTVO-net Workshop on Valorization of By-Products: Glycerol. January 21, 1999.

Appendices

Bio-Based Economy – Discussion Paper

Appendix A -- US R&D Capacity - Government Labs

Laboratory	Product Focus	Basic Science	Production	Processing	Market Utilzation
Department of Energy National Laboratories					
Argonne National Lab	< biochemicals e.g. vitamin C, ethyl lactate, succinic acid	< material characterization < structural genomics < proteomics < biochip manufacture and application < bioinformatics	< meteorological research < terrestrial ecology	< catalysis and biocatalysis < membrane separation	< LCA
Brookhaven National Lab	< bioenergy < biofuels	< genetic engineering to tailor plant storage compounds	< bioprocessing lab		< use of biodiesel in residential and commercial heating equipment
Idaho National Engineering & Environmental Lab	< biochemical building blocks for materials production, e.g. plastics, lubricants, etc.		< decision support systems for agriculture to optimize fertilization and watering processes < enhancement of agricultural residues e.g. by decreasing the silica content of wheat straw and using white-rot fungi to increase the percentage of cellulose	< extremphile enzymes < biofilters/bioreactors < multiPHAe continuous reactors using immobilized biocatalysts < extreme bioprocessing for high temperature, high pressure applications < advanced membrane separation technology < process control software < engineered enzymes	
National Renewable Energy Lab	< bioethanol < biodiesel < biochemicals from sugars < adhesives < platform chemicals (levulinic acid from sugar) < intermediate chemicals (levoglucosan from starch) < biodegradable herbicide (DALA)	biofuel strengths include: < genetic engineering < protein engineering < microbiology < fermentation < enzyme production and purification < biomass pretreatment and hydrolysis < analytical chemistry < and a world-class process development unit biochemical strengths include: < organic synthesis		< biomass characterization < biomass feedstock pretreatment < cellulase enzyme development < protein engineering < molecular modeling < strain development < developing designer strains for specific feedstocks, feed streams, and processes < process development and integration < process engineering	< life cycle analysis (for bioethanol using a number of different feedstocks and biodiesel from soybeans) < LCAs bioethanol from corn stover and biodiesel from and waste fats and grease are now underway

Laboratory	Product Focus	Basic Science	Production	Processing	Market Utilzation
		< catalysis < biocatalysis < protein engineering < new biomass separation technologies < ionic liquids < green chemistry < carbohydrate and lignin chemistry < thermochemical processing including combustion, pyrolysis, gasification		and analysis < 8,000 ft^2 bioethanol pilot plant, and protein engineering, purification, and metabolic pathway engineering facilities over 50 staff engaged in chemical and biological separations and conversions including: < research on the use of catalysis and metal complexes to modify the structure of sugars in a single step < new biocatalysts for sugar conversion < thermochemical processing of a large range of plastics < use of new media like ionic liquids as enabling technologies for conversion of lignin and carbohydrates to new materials	
Oak Ridge National Laboratory	< bioenergy < biofuels	< carbon sequestration	< woody crops (i.e. poplar, willow) including advanced silviculture, insect and disease prevention, traditional breeding, molecular genetics < herbaceous crops (i.e. switchgrass) including improved breeding and agronomic activities < systems integration analysis (biomass resource, environmental, economic) < operational support and evaluation < systems engineering (collection, storage and transportation) focussed on crop residues (straw		< environmental sustainability (soil, water quality, biodiversity) < ethanol market penetration < biomass power market penetration

Laboratory	Product Focus	Basic Science	Production	Processing	Market Utilzation
			and stover) < residue information (urban and industrial wastes, logging residues, etc.) < databases and data analysis tools		
Pacific Northwest National Laboratory	< biochemicals < fuel components			< addresses all processing steps from feedstock pretreatment to purified product recovery < novel catalytic processes that convert sugars, organic acids, levulinic acid, and oils to much higher value commodity and specialty chemicals < studying the use of fungi microorganisms to develop novel fermentation systems < discovery of new enzyme systems	
Sandia National Laboratory	< biomass combustion research			– a multifuel combustor has been used to study a wide range of gas, liquid, and solid fuels, including biomass flash pyrolysis oils, agricultural residues, and various woody and herbaceous fuels – extensive study of ash deposits formed during biomass combustion – current research is on the formation and control of NOx and fine particulates during combustion of biomass fuels when fired alone and during cofiring of biomass with coal	
US Department of Agriculture Research Centers					

Laboratory	Product Focus	Basic Science	Production	Processing	Market Utilzation
Eastern Regional Research Center	< ethanol < biodiesel, extenders and additives < lubricants < surfactants < industrial, biodegradable biopolymers < functional food ingredients < nutraceuticals < cosmetics (sun screens) < byproduct utilization, e.g. zein			< improving the economic competitiveness of ethanol through process efficiencies and co-products < new biocatalysis and/or biomimetric reagents < enzyme bioreactors < green extraction processes using supercritical fluids and high temperature/pressure ethanol < identifying and quantifying fine chemicals, phytosterols, tocopherol and sterol glucosides, in stover and residues from stover-to-ethanol production processes < estimate value and production costs for these coproducts are being determined	
USDA-ARS Forage Research, Lincoln, NE	< developing switchgrass into an energy crop		< breeding and genetics < management (seed quality, weed control, fertility management, harvest management) < feedstock quality < economics < soil quality < carbon sequestration		
ARS Soil and Water Conservation Research Unit			< crop and soil management < long-term affect of various production practices (tillage, crop sequence, N-fertilizer application, crop residue removal) on biomass production, grain yield, soil carbon content, and soil erosion < remote sensing		

Laboratory	Product Focus	Basic Science	Production	Processing	Market Utilzation
			equipment and decision support aids to help growers apply site-specific management practices to crops and soil < evaluating use of livestock manures as source of N and P for crops, developing methods for assessing soil health, and assessing the impact of crop residue removal on soil organic C content and crop productivity.		
Western Regional Research Center	< biofuels < starch derived biodegradable packaging < light-weight starch-based concrete < soil additives	< comparative genomics < wheat sequencing & bioinformatics < genetic biotechnology of multiple cereal crops		< directed molecular evolution of amylase enzymes and cold hydrolysis < use of ethanol as a solvent in grain fractionation < polysaccharide liquefaction < fermentation technologies < polysaccharide development	< characterization of the unique physical and chemical properties of wheat starch, modified starch, and blends of starch with other components, and using this characterization knowledge so that these materials can fill market niches
USDA Forest Service Forest Products Laboratory	< ethanol, biochemicals, and pharmaceuticals from wood	< engineered wood products and structures < moisture and indoor air quality < material design and performance < coatings and finishes < adhesives < wood preservation < biodeterioration < wood/nonwood composites.		< biopulping technologies	< carbon sequestration
USDA North Central Research Station	< bioenergy		< hybrid poplars < conducting breeding and selection programs to produce new crop tree genotypes		

Appendix B: - Biotech Accord Members/Website List (as of January 2003)

Ag-West Biotech Inc. – Peter McCann	www.agwest.sk.ca
BC Biotech – Paul Stinson	www.biotech.bc.ca
BioEast Genesis Group – David King	www.bioeast.ca
BioAlberta – Myka Osinchuk	www.bioalberta.com
BioAtlantech – John Argall	www.bioatlantech.nb.ca
BioNova – Marli MacNeil	www.bionova.ns.ca
BioProducts Canada – Randal Goodfellow	www.goodfellowagricola.com
BioQuébec – Perry Niro	www.bioquebec.com
BIOTECanada – Janet Lambert	www.biotech.ca
Biotechnology Human Resources Council – Claire Thifault	www.bhrc.ca
Health Care Products Association of Manitoba – Paul Doolan	www.hcpam.com
Ontario Agri-Food Technologies – Gord Surgeoner	www.oaft.org
Ottawa Life Sciences Council – Ken Lawless	www.olsc.ca
Prince Edward Island Business Development	www.peibusiness development.com
Toronto Biotechnology Initiative – Matt Buist	www.torontobiotech.org

Appendix C: – Canadian Adhesives Manufacturers

Company	Head office location	Location of plants
Chembond	Canada	Brampton, Ontario Brantford, Ontario
Dow Corning	USA	Mississauga, Ontario
Dural div. of Multibond	Canada	Etobicoke, Ontario
H.B. Fuller	USA	Boucherville, Quebec Port Credit, Ontario
GE Silicones	USA	Pickering, Ontario
Halltech	Japan	West Hill, Ontario
Helmitin	Canada	Montreal, Quebec Toronto, Ontario
Lepage div. of Henkel Canada	Germany	Brampton, Ontario
Mapei	Italy	Laval, Quebec Woodbridge, Ontario Delta, British Columbia
Mulco	Canada	Longueuil, Quebec
Nacan Products	United Kingdom	Toronto, Ontario Boucherville, Quebec
Reichhold Swift Adhesive Products	USA	Toronto, Ontario Pointe Claire, Quebec
Roberts Company Canada	USA	Brampton, Ontario
Technical Adhesives	Canada	Mississauga, Ontario
3M Canada	USA	London, Ontario
Tremco	USA	Toronto, Ontario Boucherville, Quebec

Source: Statistics Canada – Industry Canada website

REDUCING GREENHOUSE GAS EMISSIONS FROM THE TRANSPORTATION SECTOR: ROLES FOR BIO-PRODUCTS.

An Appendix to CCFIA Position Paper 3: An Assessment of the Opportunities and challenges of a Bio-Based Economy for Agriculture and Food Research in Canada.

Presented at a Conference on Greenhouse Gas Emissions from Canadian Agriculture: Narrowing the Knowledge Gaps.

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Ewen Coxworth and Tam McEwen.

Transportation Activities in Canada and Greenhouse Gas Emissions.

Transportation activities are an important source of greenhouse gas (GHG) emissions from the Canadian economy. In 2001, transportation GHG emissions accounted for 22 percent of the all emissions from the Canadian economy (Environment Canada, 2003). Furthermore, of the various sectors of the economy, transportation showed one of the largest increases (22 percent) in GHG emissions since 1990 (Environment Canada, 2003). In contrast, agricultural emissions (e.g., enteric fermentation, manure management and nitrous oxide emissions from soils) increased only slightly (one percent) in the period between 1990 and 2001 (Environment Canada, 2003).

Potential Roles for Bio-Products in Reducing Greenhouse Gas Emissions from Transportation.

There are two different, but complementary, paths by which bio-products might be employed to reduce GHG emissions from transportation activities:
(1) replace some portion of fossil fuels with renewable ones such as ethanol or biodiesel.
(2) make vehicles more fuel efficient by making them lighter (while maintaining safety) by greater use of plastics and plastic composites. Some of these plastics and fibre sources for the composites could be derived from agricultural raw materials.

Economic Comparison of Improving the Fuel Efficiency of Vehicles with Use of Alternative Fuels.

A recent study in California (California Energy Commission, 2003) found that most methods to improve fuel efficiency of vehicles resulted in positive direct net economic benefits to the California economy. Direct net benefit was defined as the combined costs and benefits associated with each petroleum reduction option. California imports much of its petroleum needs at the present time.

Costs and benefits analyzed included the following:
- Incremental costs associated with the purchase and use of new and/or additional technologies.
- Loss of government revenue due to reduced sales of fuel.
- Reductions in external costs associated with petroleum dependence, including energy security and economic costs.
- Savings associated with reduced operational costs, such as reduced fuel usage.
- Savings associated with avoided damages from pollution, including reduced health costs and damages from climate change impacts.

Technologies to improve fuel efficiency included improvements in engines and transmissions, aerodynamic styling, increased use of hybrid electric drive systems (both gasoline-electric and diesel fuel-electric drive systems), more use of diesel engines, compared to gasoline engines, and reductions in weight of vehicles. It was believed possible to more than double the efficiency of new cars and light trucks (including mini-vans and sports utility vehicles) by employment of various combinations of these technologies.

In contrast, this California study found that fuel substitution by alternative fuels, such as ethanol, biodiesel or compressed natural gas, generally resulted in slightly negative direct net economic effects. This was a reflection, among other things, of the higher costs (fuel, engine modifications, infrastructure) associated with these alternative fuels.

Potential Role of Plastic Composites in Reducing the Weight and Improving the Fuel Efficiency and Light Trucks.

Several studies (Lovins et al., 1993; Brylawski, 1999; Lovins, 2003) have shown that much of the fuel consumed by cars and light trucks is used to move the vehicle, not the passengers. Furthermore, these same studies have shown that the use of high performance plastic composites can halve the weight of the vehicle, without compromising safety or performance. In the extreme case of the Hypercar(R), the vehicle would be, by weight, one-half polymer, composite, and advanced composite, and about one-third metallic materials (Brylawski, 1999). In contrast, the average North American vehicle is three-quarters steel, iron, and aluminum, and less than ten percent polymers and plastic composites.

These studies have calculated that making vehicles lighter also reduces the size and weight of the motor and related components required for a same level of performance as a heavier vehicle of the same size. This helps to reduce costs. Furthermore, although plastic composites (particularly carbon-fibre composites) are more expensive than steel, far fewer parts are needed to make the body of the vehicle; this reduces assembly costs.

DaimlerChrysler, in partnership with Canadian parts suppliers Husky and Decoma, announced in 1999 that they had developed a plastic injection molding process that will “revolutionize the way cars and trucks are made”(Priddle, 1999). According to the announcement from DaimlerChrysler, full vehicle plastic bodies would have the potential to reduce tooling costs by up to 70 percent. A body would have 6-12 pieces instead of the 70-100 now. The plastic materials would be 100 percent recyclable. There would be no painting required, since the color would be incorporated in the plastic.

Jim Holden, president of DaimlerChrysler, sees plastic as “the leading technology to beat now” in an industry increasingly concerned with vehicle cost, fuel efficiency and emissions (Priddle, 1999). “Weight is the enemy” according to Holden. The public wants size, performance and horsepower. Automakers want to give it to them without accompanying poor fuel economy and higher emissions. Greater use of plastics, and the resulting reduction in weight, appears to offer a way to achieve these otherwise incompatible goals. The new plastic injection molding technology is first to be used in 2001 in the hardtops for the Jeep Wrangler.

Integration of Weight-Saving Plastic Composites with Other Technologies to Improve Fuel Efficiency.

Various studies (Lovins et al., 1993; Brylwaski, 1999; Lovins, 2003) have emphasized that integration of a number of methods to improve fuel efficiency and reduce greenhouse gas emissions is important in achieving the greatest improvement in fuel efficiency and reduction in costs. The integration of these technologies is illustrated by the Hypercar Revolution concept vehicle (Lovins, 2003; see also www.hypercar.com).

- This concept vehicle is similar in size to a mid-sized sports utility vehicle, such as the Lexus RX 330 (Carguide, 2004).
- Body is built mainly from a carbon fibre-plastic composite.
- Weight is 857 kg, compared to the Lexus RX 330 at 1844 kg.
- Has low aerodynamic drag.
- Has low-rolling-resistance tires.
- Designed to meet the US Federal 48 km/hr fixed barrier occupant safety standard in a head-on collision with a vehicle twice its weight, each car moving at 48 km/hr.

The choice of power system has a big effect on fuel efficiency and is synergistic with weight reduction. Thus the Hypercar Revolution concept vehicle was estimated to have the following fuel efficiency (combined city/highway), powered with various engine systems:

Powered by a hydrogen fuel cell hybrid system = 99 miles/US gallon (2.4 L/100 km).
Powered by a gasoline-electric hybrid system = approx. 70 mpg (3.3 L/100 km).
Powered by a conventional gasoline engine = approx. 35 mpg (6.7 L/100 km).
In comparison, the Lexus RX 330 is rated at 21 mpg (10.9 L/100 km).

Holden Ltd, an Australian affiliate of General Motors, has designed and built a gasoline-electric hybrid five-passenger car which uses plastic composites and aluminum to reduce the weight of the vehicle (Hybrid Vehicles, 2001a). The vehicle has about twice the fuel efficiency of a conventional family car.

Role of Hybrid Electric Drive Systems in Improving Fuel Efficiency, Reducing Greenhouse Gas Emissions and Reducing Air Pollution.

Gasoline-electric hybrid and diesel-electric hybrid drive systems combine features of internal combustion engines and electric drive/batteries. The internal combustion engine recharges the battery system through a generator, so these vehicles do not need to be plugged in, in contrast to a conventional electric drive vehicle. The combustion engine operates most of the time close to its optimum speed to minimize air pollutant emissions and improve fuel efficiency, with the battery providing some of the extra power need for acceleration. During braking, the battery is recharged, so that much of the energy lost during conventional braking is recovered in the hybrid system. Thus hybrid systems have high fuel efficiency in stop-and-go situations typical of urban driving.

The Toyota Prius and the Honda Civic Hybrid (both gasoline-electric hybrid systems) qualify for the Advanced Technology Partial Zero Emission Vehicle standards in the USA (Clean Fuels and Electric Vehicles Report, 2003a; English, 2004). It is noteworthy that these very low air pollutant emissions were achieved with regular gasoline. Thus the role of ethanol (for example) in reducing air pollution may decrease in time as such new drive systems become more common.

Similar large reductions in air pollutants have been reported with diesel-electric hybrid systems for buses and trucks. In one study (Hybrid Vehicles, 2001b) a bus equipped with a hybrid diesel-electric drive systems, plus a catalyzed particulate filter system, achieved major reductions in air pollutants compared to a conventional diesel engine powered vehicle: carbon monoxide, 99 percent reduction; nitrogen oxides, 56 percent reduction; particulates, 90 percent reduction; total hydrocarbons, no change from the conventional bus, but lower than emissions from a natural gas powered vehicle. It was not necessary to use renewable fuels, such as biodiesel, to achieve these large reductions in air pollutants. Furthermore, the hybrid system had a 30 percent improvement in fuel efficiency compared to a conventional diesel bus.

GHG emissions are expected to be proportional to fuel consumption. The Toyota Prius is roughly the same size as the Toyota Camry, one of the more popular mid-sized automobiles. The Camry’s fuel efficiency was 10.9 L/100 km in the city and 6.7 L/100 km on the highway (Carguide, 2004). The Prius is rated at 4.0 L/100 km in the city and 4.2 L/100 km on the highway (English, 2004). The Prius would thus be expected to have much lower GHG emissions in combined city/highway driving than the Camry.

Plans are underway by many automobile manufactures to extend the hybrid electric power system to larger vehicles. For example, a Lexus RX 330 SUV powered by a gasoline-electric hybrid system is to be built at Toyota’s Cambridge, Ontario, plant (Clean Fuels and Electric Vehicles Report, 2003b).

Integration of Measures to Improve Fuel Efficiency with Renewable Fuels.

General Motors collaborated with Argonne National Laboratory, BP, ExxonMobil and Shell to analyze the greenhouse gas emissions of various advanced fuels and vehicle drive systems (GM, 2001). Included in the analyses was ethanol made from lignocellulosic raw materials (e.g., waste wood, straw, chaff), estimated to have much lower GHG emissions than conventional gasoline or ethanol made from grain. Ethanol was used as an 85 percent blend with gasoline in both conventional and hybrid gasoline-electric drive systems.

GHG emissions (grams of carbon dioxide equivalents per kilometre driven) were estimated for a mid-sized passenger car as follows:

Conventional gasoline engine, conventional gasoline = 339
Conventional gasoline engine, 85% ethanol = 170
Gasoline-electric hybrid, 85% ethanol = 143
Conventional diesel engine, diesel fuel = 290
Diesel-electric hybrid, diesel fuel = 239
Fuel cell hybrid, hydrogen derived from natural gas = 186.

In this analysis, a gasoline-electric hybrid vehicle, fueled by 85 percent ethanol derived from lignocellulose, has lower GHG emissions (well-to-wheel) than a fuel cell hybrid drive system vehicle, powered by hydrogen derived from natural gas. In GM's analysis, use of a renewable fuel had a greater effect on GHG emissions than the shift from conventional gasoline engine to a gasoline-electric hybrid system. Developments in hybrid systems since the GM study was completed suggest that greater improvements in fuel efficiency, and corresponding reductions in GHG emissions, can be achieved by hybridization than was assumed by General Motors.

Comparison of the Amounts of Bio-Products Needed for More Plastic in a Hypercar Compared to Fuel Savings.

The Rocky Mountain Institute has estimated that the extra plastic needed for Hypercars would only increase U.S. plastic use by a few percent (RMI, 1995). Another approach is to calculate the extra plastic used in a Hypercar, compared to a conventional car, and contrast this with the fuel savings. The following calculations are based on the previous comparison of a Hypercar Revolution with a Lexus RX 330.

- The Hypercar Revolution contains 244 kg more plastic than a Lexus RX 330.
- Assuming a lifetime of 15 years, the Hypercar invests 16.3 kg more plastic per year.
- A Hypercar Revolution, powered by a gasoline-electric hybrid power system, and assuming 20,000 km driven per year, would consume 660 l/year of fuel.
- The Lexus 330 would consume 2180 L/year of fuel.
- Assuming the fuel for both vehicles is ethanol, only 30 percent as much land is required to provide raw materials to make ethanol for the Revolution as for the RX 330.
- An investment of 16.3 kg in bio-plastic (for example), when combined with other techniques to improve fuel efficiency, saves 1520 L of fuel per year.

Plastics and Fibres for Plastic Composites Based on Agricultural Raw Materials.

Brian Haas of John Deere's World-wide Combine Product Development Centre has described how John Deere has developed soybean and corn-based polyester and polyurethane plastics now used in their commercial combines and round balers (Maas, 2003). Research and development work was conducted with a number of universities and commercial companies involved in plastic manufacture. The University of Delaware's ACRES (Affordable Composites from Renewable ResourceS) centre developed a soybean oil-based polyester resin for use in fibreglass-reinforced plastic components. This work was supported by the United Soybean Board, representing over 600,000 farmer customers. Further development lead to a commercial polyester resin containing 17 percent soybean-based and 8 percent ethanol-based polyester resin; the remainder of the polyester was petrochemical-based. This was the initial level of renewable materials which could be used without causing material property degradation.

In similar fashion, a polyurethane was developed, based on a polyol derived from soybean oil. The final polyol used in the commercial product (employed in combine side panels and roof) contained 20 percent soybean-based polyol. The remainder was petrochemical-based to avoid material property degradation.

John Deere is also investigating flax fibre to replace glass fibre in plastic composites. If this is achieved, panels for combines and balers could, in the future, be made mostly from renewable resources.

John Deere is in communication with technical experts from Ford Motor Company to determine whether renewable resources such as corn and soybeans could be used as raw materials in the development of plastic composites for use in the automotive industry.

Studies are underway in many parts of the world to develop and improve natural fibres for application in plastic composites. Hill (1997) has reviewed a number of the advantages and disadvantages of natural fibres, and described chemical and physical treatments designed to improve the properties of natural fibres for industrial applications, including in plastic composites used in vehicles.

The CARC/BIOCAP report (2003) describes some of the advantages and disadvantages of natural fibres and plastics and current research and development activities (see section 6.5 and 6.7 in CARC/BIOCAP, 2003).

Greenhouse Gas Reduction Potential of Bio-Plastics and Natural Fibres Used in Plastic Composites.

Studies in the European union have found that a polyol made from rapeseed oil reduced greenhouse gas emissions by 1.5 tonne of carbon dioxide equivalents, per tonne of polyol, compared to a comparable polyol based on petrochemical raw materials (see section 6.5.3 of

CARC/BIOCAP, 2003). The polyol would be used to produce polyurethane plastic.

The DaimlerChrysler research centre in Germany reported that natural fibres (such as flax fibre) reduce the weight of a plastic composite by 10 percent, and reduced the energy required to produce the fibre, compared to glass fibre, by 80 percent (see section 6.7.3 of CARC/BIOCAP, 2003). As discussed earlier, weight reduction of a vehicle would be expected to improve fuel efficiency, and hence reduce greenhouse gas emissions.

The Dutch government has claimed the use of flax fibres in plastic composites for cars as part of its GHG emissions reduction plan (Schoenmaekers, 1997). A direct GHG reduction follows from the much lower energy input required to produce flax fibres. An indirect reduction follows from cars using flax fibre in composites being lighter than those using glass fibre, thus consuming less fuel. The Dutch government estimated a saving of 40,000 tonnes of carbon dioxide equivalent per year.

Examples of Canadian Research and Development Activities on Plastics and Composites Based on Agricultural Raw Materials.

Suresh Narine of the Agri-Food Materials Research Centre at the University of Alberta has developed and patented new technology for the production of plastics from canola oil and other vegetable oils (Gibson, 2003).

Alvin Ulrich of Biolin Research, Inc., at Saskatoon, is investigating flax fibre and the effects of choice of variety, growing conditions and harvesting system on flax fibre yield, quality and economics (Daniels, 2003).

The Automobile of the 21st Century (AUTO 21) is a Federal Network of Excellence centred in Windsor, Ontario. As part of the activities of the centre, Francois Trochu of the Ecole Polytechnique is leading a consortium investigating polymer composites involving the use of natural fibres (see section 6.7.6 of CARC/BIOCAP 2003).

Other Canadian research and development activities on bio-plastic and plastic-composites are described in the full report (CARC/BIOCAP, 2003).

Greenhouse Gas Emissions and Climate Effects on Crop Production. Implications for Use of Crops as Raw Materials for Bio-Products and Bio-Fuels Production.

Life-cycle analysis is frequently needed to determine whether bio-products and bio-fuels have lower total greenhouse gas emissions than petrochemical materials they may replace. For example, nitrous oxide emissions from canola and soybean production can be a significant factor in the total greenhouse gas emissions attributed to biodiesel made from these raw materials. Agronomic methods to reduce GHG emissions from crops would also reduce the total GHG emissions attributed to the final bio-product. One study in the USA calculated that one type of bio-plastic produced from corn plants actually emitted more GHGs than the petrochemical plastic to which it was compared (Gergross and Slater, 2000). Thus it is important to reduce GHG emissions from all steps in the process, including primary crop production.

Furthermore, drought can reduce the yield of crops and thus increase the total greenhouse gas emissions per tonne of crop produced. Drought could also negatively affect the supply of crop raw materials and their price. Thus methods to reduce the negative effects of drought on crop production would be important in future consideration of bio-product production, particularly in western Canada where drought is a frequent occurrence.

A recent study in western Canada evaluated the effect of various factors on nitrous oxide emissions from the production of spring wheat, canola and flax (Lemke et al., 2003). The effects of nitrogen fertilizer type, rate, placement and spring or fall application were studied. Four sites over three years were employed. In general, nitrous oxide emissions were considerably less than would be estimated by use of the IPCC guidelines. The implication is that in a fairly dry climate, the IPCC guidelines overestimate nitrous oxide emissions.

Drought conditions were experienced at several sites over the three years. Under these conditions yields were greatly reduced and GHG emissions from inputs into crop production, per tonne of crop produced, increased. Thus methods to reduce the effect of drought on crop production are very important in a region such as western Canada where drought is quite common, and the potential effects of climate change could be quite negative (Sauchyn, quoted by Duckworth, 2003).

Methods such as zero tillage and selection of more drought resistant crops are being studied in western Canada.

In addition, new discoveries on endophytic fungi show considerable promise for future investigations. It was discovered recently that a perennial grass growing near hot springs in Yellowstone National Park in Wyoming was remarkably tolerant of high soil temperatures (Redman et al., 2002). The grass survived soil temperatures as high as 50ºC. A fungus, a new *Curvularia* species, was found growing endophytically within the grass plants. The combination of plant and fungus gave high heat tolerance to the combination. However, neither plant nor fungus were heat tolerant when they were grown separately.

In further studies, it was found possible to inoculate crop plants with the same fungus (Redman and Rodriguez, 2003). Inoculated watermelon and tomato plants withstood soil temperatures as high as 50ºC. Inoculated wheat seedlings lasted 18 days without water. In contrast, uninoculated wheat plants died within 10 days. It will be very interesting in the future to field test such a fungus-crop association under drought conditions in western Canada. Equally interesting will be to test the integration of such an endophytic fungus treatment with selection of more drought-resistant crops and growing conditions.

Integrated Systems and Reduction of Greenhouse Gas Emissions from Transportation.

The studies described in this report are examples of the benefits of integrated systems:

(1) Integration of several methods to improve fuel efficiency, including vehicle weight reduction by greater use of plastics and plastic composites, further improves fuel efficiency and reduces greenhouse gas emissions, and may reduce overall costs..

(2) Integration of bio-based plastics with petrochemical-based plastics may allow use of bio-based materials without loss of performance characteristics in the final material. Further development of bio-based materials may allow an increase in the proportion of bio-based materials in the future.

(3) Improvements in the fuel efficiency of vehicles reduces the amount of renewable fuels required to achieve the same level of performance, e.g., less fuel per kilometre driven. This decreases the amount of land required to produce the biofuels to provide a given level of fuel service, e.g., renewable fuel required to provide a million kilometres of distance traveled. The cost of fuel per kilometre driven would be decreased also.

(4) Integration of various methods to reduce the negative effects of drought on crop production may reduce the severity of the drought effects.

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